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Catalyzing renewable energy deployment in the Mercosur economies: A synthesis of human capital, technological innovation and green finance

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ABSTRACT

It has become a global agenda for the transition toward sustainable energy systems; the Mercosur region faces unique opportunities and challenges in harnessing the potential of renewable resources. Against this backdrop, this study thoroughly investigates the determinants of renewable energy consumption (REC) for Mercosur nations. The research examined the influence of economic expansion, green finance, technological innovation, human capital, government effectiveness, and urbanization on the integration and transition of REC. Incorporating a comprehensive approach, the study integrated the CS-ARDL econometric model and panel data for over three decades (1990–2021). The analysis revealed that economic expansion, green finance, technological innovation, human capital and government effectiveness are advantageous and essential for advancing REC deployment in the Mercosur nations. In addition, the outcome espoused that urbanization is detrimental to the progress of REC. Moreover, there is a one-way causality between economic expansion, green finance, technological innovation and green finance to REC. Still, there is a bi-directional link between human capital, urbanization, and renewable energy consumption. The outcome of this paper contributes to the ongoing discussion on sustainable development, providing essential insight for stakeholders, policy-makers and researchers seeking to investigate the complexities of transitioning towards a more resilient and greener energy landscape.

1. Introduction

In the contemporary era, the central focus of many economies is to achieve sustainable development goals (SDGs), notably attaining economic stability and decent work as espoused in the 17 SDGs agenda [1]. The achievement of these SDGs is essential for protecting and improving the global ecological and socio-economic well-being of people [2]. As a result of the need for various economies to strengthen their economic expansion (EXP), energy usage from both non-renewable and renewable power sources has risen. Existing research has reported that non-REC has adverse environmental challenges, such as increased global climatic disruption and habitat deterioration [3,4]. As a result, energy analysts, ecological scientists, and scholars have proposed that renewable energy consumption (REC) is essential for simultaneously dissipating ecological issues and attaining higher EXP [5]. Moreover, the escalating environmental challenges and the finite nature of fossil fuels underscore the urgent demand and need for a transition energy source. As global industrial activities expand, the demand for energy has risen, exacerbating ecological deterioration and contributing to climate alteration through the emission of greenhouse gases [6]. The research problem of this research also lies in exploring how human capital, financial mechanisms, effective governance, economic expansion and urbanization transition can contribute to renewable energy transition and consumption. This transition is not merely an environmental imperative but also a socio-economic necessity, as it promises to reduce dependency on fossil fuels, mitigate climate change impacts, and ensure sustainable energy [7]. The shift towards renewable energy is thus a critical endeavour, requiring innovative solutions and widespread adoption to meet the world's current and future energy needs sustainably.

The International Energy Agency (2022) indicated that global REC is anticipated to increase by more than 60% by 2026, which might equal the total world's potential for conventional fuel and nuclear energy combined. Thus, the report by the International Energy Agency (2022) further indicated that collaborative efforts from the conference of the parties, "COP 26 climate change agenda," and stronger governance systems from various nations are the driving factors in achieving this

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List of abbreviation

REC: Renewable Energy Consumption	
EXP	Economic Expansion
GFN	Green finance
TNI	Technological Innovation
HUC	Human Capital
GEF	Government Effectiveness
URB	Urbanization
SDG	Sustainable Development Goals
Mercosur	Southern Common Market
STIRPAT	Stochastic Population, affluence, and technology
CS-ARDL:	Cross-Sectional Augmented autoregressive Distributed Lag
CST	Cross-Sectional Dependency Test
SHT	Slope Homogeneity Test
CIPS	Cross-sectional I'm Pesaran and Shin
CADF	Cross-sectional augmented Dickey-Fuller
ECT	Error-Correction Term
AMG	Augmented Mean Group
CCE-MG	Commonly Correlated Effect Mean Group
DH	Dumitrescu and Hurlin

REC target by 2026. Accordingly, to attain the target stipulated by the Paris Agreement and SDGs and other international ecological collaboration, it is crucial for nations to devise strategies that can enhance the smooth transition to a renewable power supply. Erstwhile analysis has demonstrated that due to the inescapable and unique structure of energy needs for production and manufacturing, it is pertinent to integrate clean energy sources and REC. Compared to conventional energy, including fossil fuel, renewable energy is considered sustainable, timeless, and cleaner [8–10]. Considering that REC has been identified as a mechanism to alleviate environmental degradation and address sustainable issues, it is imperative to investigate these cleaner energy sources' primary determinants and drivers. Analyzing these drivers can help provide appropriate policy directions to governments, energy policy-makers, and stakeholders in the REC plans.

The Southern Common Market (Mercosur) has been recognized as a territory with a wide socio-economic structure and ecosystem that can substantially contribute to the EXP and reduction in greenhouse gases [11]. Moreover, the Mercosur region, which comprises Argentina, Brazil, Paraguay, Uruguay, and Venezuela, was formed in 1990 with the intended purpose of promoting free and unrestricted commerce in commodities and services, as well as the free movement of people, capital, and ideas among the participating nations [12]. The study targeted the Mercosur economies for the following reasons. Among the Mercosur block, REC began around the 1970s; for example, Brazil initiated programs outlining biofuel and hydropower consumption. In Argentina, REC power sources, including biogas, waves, wind, biomass, and geothermal, were introduced as power generation sources for production. Nadaleti et al. [11] recounted a similar situation in Paraguay, Venezuela, and Uruguay in the early 2000s. Moreover, Koengkan & Fuinhas [13] asserted that the Mercosur region generates the most hydropower internationally, with this type of energy source contributing to more than 50% of the blocs' total power usage. Nonetheless, the rapid upsurge in power consumption among these nations has increased ecological pollution in the last decade. Hence, evaluating what factors account for effective REC among these economies is crucial. The argument stance of this study has been stipulated on six main macroeconomic variables that can influence REC.

The dramatic rise in economic expansion (EXP) and modernization phenomenon of these economies have contributed to the rise in energy demand. EXP has intensified throughout time, which has affected every aspect of nations' environment, social, and government structures. The influence of EXP on the consumption of REC can be both destructive and beneficial. Moreover, there are mixed findings regarding the association between EXP and REC. For instance, while some prior studies assert that EXP is advantageous to the deployment of REC [14–16], contrastingly, some empirical studies noted that EXP causes havoc to the transition to REC [17,18]. Since various economies have initiated REC production and distribution as the key driver for EXP, the coherence linkage between EXP-REC has received less attention, especially from the Mercosur regions. As a result, following the theoretical lens of the stochastic impacts by regression on population, affluence, and technology (STIRPAT) was employed in the current analysis to evaluate the interplay between EXP-REC among the chosen economies of this study.

The current analysis also investigates the influence of green financing (GFN) tools on the diffusion of REC in the Mercosur bloc. The interaction between GFN and the deployment of REC has not received much attention from environmental scientists [19]. The scanty academic research on this linkage presents a literature gap that must be addressed. Rasoulinezhad & Taghizadeh-Hesary [20] contended that GFN is essential in the REC transition because it can help safeguard the ecosystem and improve environmental health. In addition, Saeed Meo & Karim (2021) addressed the significant contribution of GFN in raising funds to support environmentally friendly initiatives, and their study proposed a causal connection between GFN and green energy. Therefore, using GFN tools is an indispensable and desirable option to draw private investment into eco-sustainable enterprises such as REC transition. As suggested by the prior studies, adopting GFN in the form of green bonds is a suitable initiative for cleaner energy and can decrease capital risk, increase investment returns, and attract international and domestic investment in REC projects [20,21].

Another essential mechanism to the development and transition to REC is the focus on technological innovation (TNI) investment opportunities. The improvement in technology lowers the cost of REC, which eventually enhances the amount of capital invested in this industry. As Yao et al. (2016) demonstrated, technology for storing energy offers a workable remedy for the intermittency nature of REC. As a result, investing in TNI is necessary to implement REC deployment effectively [22]. As the United Nations (2015) report suggests, in total energy production, potential loss occurs at the initial phase of transformation, extraction, transmission, transportation, and final consumption. As a result, certain synergies exist between REC and TNI. This is because technological advancement can help smooth renewable energy production and distribution. However, there is a major literature gap concerning the influence of TNI on the transition to REC among the Mercosur economies.

Moreover, prior studies have contended that human capital (HUC) is a fundamental component of deploying REC technologies [23]. This is because HUC provides a special function in synchronizing all factors of production, several of which inevitably depend on energy [24,25]. The HUC of a country determines and enhances the level of its economic outcome in the nation's power consumption pattern and production [24]. Moreover, Huang et al. [26] opined that HUC helps technological spillover from related energy sources to international and foreign direct investment, especially among emerging economies. However, the effect of HUC on REC transition is inconsistent in energy literature. For instance, a strand of empirical investigation asserts that HUC can improve REC's energy efficiency and growth [23,27,28]. Some findings also evidenced that HUC will indulge in excessive use of power for EXP, which might reduce efficiency [29,30]. Accordingly, this paper empirically tests the interaction between human capital and REC.

Furthermore, in implementing REC, one essential player that can facilitate the smooth transition is the government's role in implementing the right channel and framework required to expand a cleaner power supply. As a result, this paper evaluates the influence of governance effectiveness (GEF) on the development of REC in Mercosur economies. GEF describes a government system that allows for effective management of public resources, insists on institutional quality, and ensures the application of citizens' rights in a manner that is mainly free from the corruption and abuse of individual rights with due consideration for the rule of law [31,32]. As posited by extant analysis, the consideration of institutional and legal framework substantially influences the deployment and expansion of cleaner power sources [33,34]. Despite the significant upsurging role of GEF in the Mercosur economies, scanty analyses have explored the association between GEF and REC development in these regions. This investigation sought to empirically assess the impact of GEF on REC transition in the Mercosur.

The influence of urbanization (URB) on REC has received less attention in the energy-urbanization literature. Lantz et al. [35] echoed that, to enable sustainable power integration and management, the varying patterns of URB in the rural and urban centres should be considered during the transitional energy stage. Theoretically, the energy-urbanization linkage has been captured in the research by Poumanyvong & Kaneko [36]; their analysis suggested the transition and compact city theory, urban environment theory, and the theory of ecological modernization. The focal points of these theories are that URB's process changes various modernization structures, which results in energy efficiency through the fast pace of using ecologically friendly tools and technology [35]. Based on this theoretical background, this paper explores the influence of URB on REC.

The current analysis is motivated by the SDGs outlined by the United Nations (2016). Based on these SDG targets, this paper addressed these research questions: **RQ1:** To what extent does EXP, GFN, TNI, HUC, GEF, and URB drive the transition to REC in the Mercosur economies? **RQ2:** What causality exists among these research variables? **RQ3:** What policies are required to develop sustainable energy effectively in the Mercosur regions?

This paper sets itself apart from previous studies by offering a comprehensive synthesis of how human capital, technological innovation, and green finance can act as catalysts for renewable energy deployment in the Mercosur economies. Unlike prior research that often addressed these elements in isolation, our study integrates these crucial factors, highlighting the synergistic effects they can have on accelerating the transition towards renewable energy sources within this unique geopolitical and economic context. By focusing on the Mercosur region, the paper delves into specific challenges and opportunities, offering tailored insights that are especially relevant for these economies. This integrated approach not only provides a holistic understanding of the renewable energy landscape in Mercosur but also proposes a nuanced framework for policy and investment strategies, setting a new precedent for research in the field.

The contribution and novelty of this study are explained as follows. First, examining EXP, GFN, TNI, HUC, GEF, and URB on REC is scanty in the literature, especially in the Mercosur economies. Hence, this study provides insight into how these variables affect REC in these economies. Second, this analysis can serve as a policy document that can assist energy experts, scholars, and environmental scientists in understanding the drivers and barriers of REC advancement. Third, the paper applied the STIRPAT theory. Thus, the paper enriches STIRPAT theory and prior energy literature evaluating the transition to REC from other economies [20,32,37]. Fourth, the study provides policy measures to assist the enactment of new strategies to boost investment in sustainable energy, stimulate EXP and neutralize environmental deterioration. Lastly, applying the CS-ARDL estimation approach distinguishes the study from prior studies [38]. This estimating technique takes into account the constraints of CST and the SHT. Lastly, by analyzing the evolving landscape of sustainable finance instruments, including GFN and TNI, the study assesses their efficacy in mobilizing capital for renewable energy ventures in Mercosur nations. Through a comprehensive empirical analysis and policy initiatives, the paper evaluates the impact of these financial mechanisms on promoting long-term sustainability and fostering a conducive environment for renewable energy development.

The other part of the paper is presented as follows: The synopsis of the literature is in part 2, and the theoretical framework and empirical model are presented in part 3. The results and discussion of the paper are given in part 4. Part 5 involves the conclusions, policy direction, and future research study.

2. Related studies

2.1. Economic expansion and REC

Prior studies evaluating the link between EXP and REC have produced mixed outcomes. For instance, among the organizations for the OECD bloc, Mujtaba et al. [39] explored the nexus between EXP, capital formation, and REC from 1970 to 2016. The outcome of their research demonstrated that EXP improves the growth of REC. Wei et al. [40] reported on the interplay among EXP and REC progress. The results of the CS-ARDL model showed that EXP has an inverse correlation with REC. A similar investigation was organized in Europe for 34 years on energy cost, EXP, and REC. The results are that regions in Europe with high dependence on non-REC for EXP have rising energy prices. The conclusion from the article advised that nations should, therefore, transit in REC [41]. Furthermore, Makieła et al. [42] demonstrated that a country's EXP benefits the growth of REC among 133 nations. Several other literary investigations also concluded that EXP has a direct and substantial impact on the growth of REC [11,13,43,44].

2.2. Green finance and REC

With the recent development in the environment, social, and governance (ESG) report for sustainability, institutions have started to issue green bonds to depreciate carbon emissions. In the top ten green leading regions for 2002–2018 and employing the STIRPAT model, Rasoulinezhad & Taghizadeh-Hesary [20] demonstrated that GFN in the form of green bonds is an essential component in appreciating the desire for green energy projects. The Richardson model was employed to analyze 141 institutions in China on REC and how green development in GFN can promote investors' investments [45]. The results revealed that over-investment in REC lessens bank credit insurance. Similarly, Sun et al. [46] investigated the influence of GFN and REC in achieving emission neutrality in China. The findings indicate that the GFN policy effectively controls nitrogen and sulphur oxide. Previous investigations on green finance and REC [22,47] have demonstrated the significance of GFN in promoting the development of REC and ecological stability.

2.3. Technological innovation and REC

Technological innovation in REC is developing innovative plans to help reduce the cost of implementing REC projects. This may include using artificial intelligence and robots to manage various aspects of REC deployment and transitional agenda. Solarin et al. [48] empirical outcome revealed that TNI substantially influences the transition to green energy and REC. Data was collected by Shahzad et al. [49] from the BRICS bloc from 1993 to 2018. The findings demonstrated that TNI had a positive link with REC production. In Poland, the issues of REC were studied by Pietrzak et al. [50], and the results discovered that biomass, wind, and solar are the RECs that can be improved to achieve the country's carbon depreciation target. Using the bootstrapping autoregressive distribution lag, Suki et al. [51] researched Malaysia's TNI, REC, and ecological dilapidation. The results imply that REC lessens the emission of carbon in Malaysia. Again, with TNI, the quality of the environment is improved faster. Geng & Ji [52] researched six developed economies from 1980 to 2010. The patent count was used as a measurement for TNI. Their analysis demonstrated a bidirectional nexus between TNI and REC. Previous literary works have shown material influence between TNI and REC [22,53,54].

2.4. Human capital and REC

HUC is a crucial component of resources nations depend on to improve economic progress. The literary investigation has shown that economies with high HUC can reduce their dependence on non-REC. Wang et al. [32] explored HUC and energy consumption by employing the STIRPAT model. The finding exhibited a 1% rise in HUC and a corresponding 0.3 percent appreciation in REC. The conclusion from the results indicates that the positive effect was a result scale; however, regions with higher HUC in education help to depreciate consumption of non-REC. Edziah et al. (2021) tested the impact of HUC on energy efficiency in developing economies. The findings exhibited that HUC improves energy efficiency. The analysis controlled for URB and population, and the results remained unchanged as HUC appreciated energy efficiency. Zhu [25] explored the linkage between HUC and environmental protection in achieving SGDs. The outcome highlighted that HUC and REC production affected the attainment of SDGs in China. In addition, Acheampong, Erdiaw-Kwasie et al. [55] empirical investigation found that HUC was significant in Sub-Saharan Africa regarding accessibility to power and clean energy. However, connectivity to power and clean energy has deteriorated across South Asia. Moreover, investigations have shown that HUC influences REC growth [27,56,57].

2.5. Effective governance and REC

Past research has focused on controlling emissions and the relationship between EXP, UBR, and REC. However, recent investigations have considered the contribution of political, financial, and composite factors in achieving carbon neutrality and promoting REC. Between 1997 and 2015 panel data was gathered from OECD communities, and empirical results indicated that GEF in the form of political and economic risks corroborated the effects of REC (Q [32]). Similarly, institutional quality, economic progress, financial progress, and REC transition were explored in Tunisia. Employing the ARDL and nonlinear granger causality model, data covering 1984–2017 was used for the analysis. The findings demonstrated that GEF, in terms of institutional quality, had a positive affiliation with REC. This was verified by the nonlinear and two-way nexus between institutional quality and REC in Tunisia [33]. Moreover, Su et al. (2021) investigated geopolitics risk and its link with REC. The results revealed that the two are mutually linked in achieving depreciation in the pollution level. Also, the article indicated that geopolitical risk and the rise in fossil fuels have caused nations to innovate in their energy production methods. Similarly, research was carried out in 38 countries from 1990 to 2015 on the link between GEF and REC. The results indicated that GEF is associated with REC in the long run. The article suggested governments should include private institutions through incentives and subsidies to be involved in REC production [18]. In addition, Acheampong, Dzator et al. [55] evaluated the interconnection among REC and GEF in 45 regions in Sub-Saharan Africa. The finding highlighted a bidirectional correction between REC and GEF. These studies have also demonstrated that GEF and economic stability improve the REC [31,58].

2.6. Urbanization and REC

Developed and emerging nations' urban communities have seen rapid development changes and joined cooperation among countries on trade, technology transfer, and political factors. This has enabled enterprises to move from nations with high environmental taxes and settle in lower taxes regions with cheap and available raw materials. Urbanization involves appreciating the energy used [46]. Rehman et al. [59] explored UBR and REC. The empirical findings demonstrated that URB had an inverse relationship with REC. Similarly, Onifade et al. [60] explored energy transition and URB in the OPEC region. Analysis was carried out through the CS-ARDL regression methods on 11 regions. The results show that REC and UBR had a depreciation influence on emissions. Yang et al. [61] researched 30 provinces from 2000 to 2020 and showed that UBR had a material link with REC in China. Also, there was a positive connection between the two indicators. Using a large data set of 106 countries from 1990 up to 2014, Armeanu et al. [62] studies revealed a bidirectional nexus between UBR and REC. Recently, Su et al. (2022) analyzed the per capita of cleaner energy in 116 nations on the interaction between URB and REC. The findings collaborate with the previous investigation of a positive affiliation between URB and REC. Other literary works have demonstrated a material association between the two indicators [36,63].

2.7. Research gap

Based on the above literature review discussion, it is evident that few studies have evaluated drivers of REC among the Mercosur economies. Hence, the current analysis closes this researcher gap by evaluating the determinants of REC in these economies. These existing studies fall short of comprehensively exploring the interaction between EXP, GFN, TNI, HUC, GEF, URB and REC and the specific dynamic of the Mercosur region. Hence, bridging this gap is imperative for developing targeted policies and initiatives that harness the potential of sustainable finance, human capital, EXP, URB, and innovation to drive effective REC strategies in these economies.

3. Material and methods

3.1. Theoretical background

The effect of EXP, TNI, and urbanization on energy structure and sustainability are generally linked to the IPAT theory echoed by Ref. [64]. The expression (*I*) represents environmental influence, which is evaluated by a series of multiple factors, including *population* (P), *affluence* (A), *and technological* (T). Thus, York et al. [65] revealed that the IPAT theory has some drawbacks, which include the lack of dynamic evaluation and varying effects of influential variables. Hence the authors extended the IPAT approach into the STIRPAT framework. Plausible analysis has acknowledged that the STIRPAT model a core conceptual strategy to elucidate the interaction between factors that influence REC and the energy economy [20,32,37]. The mathematical expression for this model is presented in equation (1):

$$I_i = K\, P_{it}^{a} \times A_{it}^{b} \times T_{it}^{c} \times \mu_{it} \tag{1}$$

The study incorporated $a, b,$ and c as the coefficients of $P, A,$ and T in the framework to eradicate the inherent proportional restrictions. Also, the constant of the equation is denoted by the term $K,$ and μ depicts the error term of the model. At the same time, i and t illustrate the countries and timeframe for the investigation, respectively. As recommended by Khan et al. [66], the logarithm structure for the STIRPAT can be expressed in equation (2) as:

$$LnI_{it} = K_i + a(Ln\, P_{it}) + b(Ln\, A_{it}) + c(LnT_{it}) + \mu_{it} \tag{2}$$

Therefore, to extend the STIRPAT model, the study formulates the mathematical function that indicates the effect of EXP, GFN, TNI, HUC, GEF, and URB on REC, as illustrated in equation (3).

$$Ln\, REC_{it} = K_i + aLnEXP_{it} + bLnGFN_{it} + cLnTNI_{it} + dLnHUC_{it} + aLnGEF_{it} + aLnURB_{it} + \mu_{it} \tag{3}$$

Where EXP (economic expansion), GFN (green finance), TNI (technological innovation), HUC (human capital), GEF (government effectiveness), URB (urbanization), and REC (Renewable energy consumption). The term *Ln* represents the logarithm structure for the series. The equation's constant is denoted by the term $K,$ and μ depicts the error pattern in the model. Moreover, i depicts the Mercosur regions and t timeframe for the investigation (1990–2021).

3.2. Data source and management

The article evaluated data for the Mercosur regions of Argentina, Brazil, Paraguay, Uruguay, and Venezuela from 1990 to 2021. The exclusion of certain economies and study periods is attributable to a paucity of data for analysis—the REC, GFN, and TNI data obtained from the [67] data source. Urbanization and economic expansion data were gathered from Ref. [68]. Moreover, data for GEF was collected from Ref. [69], and HUC information was retrieved from Ref. [70]. A summary description of the measurement for all the series has been presented in Table 1.

3.3. Descriptive assessment

Table 2 reports the correlation matrix descriptive analysis for all the variables. The outcome confirmed that the Mercosur has a mean coefficient of LnREC (11.160), LnEXP (26.202), LnGFN (3.360), LnHUC (0.895), LnTNI (7.273), LnGEF (3.657) and LnURB (16.602). In addition, the maximum value for REC is 17.142, and the minimum value is 6.122, indicating a disparity in the deployment of REC among the Mercosur economies. All the series had a higher standard deviation value, implying that the data points' values largely drifted from their average values. This result also means a significant likelihood of heterogeneity and cross-sections among the series under consideration. The result from the kurtosis revealed that the study data is normally distributed. Moreover, the bivariate correlation analysis highlighted a positive correlation between LnEXP, LnGFN, LnTNI, LnURB, and LnREC. However, the outcome highlighted a negative linkage between LnHUC, LnGEF, and LnREC. Additionally, the VIF analysis demonstrated that all the series had a VIF below the suggested cut-off point 10 [71]. This result shows that the investigated variables are not multicollinearity-related. The preceding Figs. 1–7 illustrate the trend of all indicators explored in this study.

3.4. Econometric strategy

3.4.1. Cross-sectional dependence test and slope homogeneity test

For most empirical evaluations, CST and SHT are conducted to demonstrate whether co-integration verification is required to investigate the study variables further. Thus, CST and SHT help identify and solve panel data challenges, including common residual interdependencies, unobserved parameters, and spatial influence [72]. In addition, spatial spill over impacts might arise due to potential CST, including expanding economic expansion, modernization, and trade liberalization among the Mercosur regions. Therefore, three models were applied to the study data to address the panel CST. These CST tests include scaled LM- Pesaran [73], corrected scaled LM- Baltagi et al. [74], and [75])-LM. The general formulae for the CST are presented in Equation (3).

$$CST = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\sigma_{ij}^{t}\right) \tag{4}$$

Such that N specifies the dimension of the cross-section in the model. T also shows the time series aspects, and the estimated residuals of the indicators are depicted with δ_{ij}^{t}. It must be noted that regimes and shifts that identify the structural breaks are captured with this test, as espoused by Ref. [76,77].

Aside from testing the CST, this paper incorporated the Pesaran and Yamagata [78] test to evaluate the SHT, and the mathematical formulae have been displayed in Equations (6) and (7).

$$\widetilde{\Delta}_{\mathrm{SHT}=}(N)^{\frac{1}{2}}(2K)^{\frac{-1}{2}}\left(\frac{1}{N}\widetilde{S}-K\right)\Bigg) \tag{5}$$

$$\widetilde{\Delta}_{\mathrm{ASHT}=}(N)^{\frac{1}{2}}\left(\left(\frac{2k(T-k-1)}{T+1}\right)^{\frac{-1}{2}}\right)\left(\frac{1}{N}\widetilde{S}-K\right)\Bigg) \tag{6}$$

Where $\widetilde{\Delta}$SHT denotes the delta of the slope and $\widetilde{\Delta}_{\mathrm{ASHT}}$ represents the adjusted slope homogeneity.

3.4.2. Unit root test

Panel data analysis relies heavily on panel unit root tests, such as CADF and CIPS testing. These tests determine if the structures examined are constant throughout the model's sectional units [79]. These tests assist the analysis in determining whether to incorporate the indicators' integration order when non-stationarity is present, ensuring that any further analyses are predicated on the proper transformations. These tests are crucial diagnostic instruments since they enable the paper in the econometric modelling process and offer insights into the time series properties of indicators. Equations (6) and (7) provide the mathematical function for the CIPS and CADF.

$$CADF = \gamma x_{it} = \alpha_{it} + \beta_{it-1} + \delta_{I}T + \sum_{j=1}^{N}\gamma_{ij}\gamma x_{it-j} + \varepsilon_{it} \tag{7}$$

Where γ represents the disparities among the indicators, x_{it} captures the variables assessed in this research.

$$CIPS = \frac{1}{N}\sum_{i=1}^{N}\varphi_i\ (N,T) \tag{8}$$

Where N denote the research period, and T captures the cross-sections among the indicators.

3.4.3. Panel co-integration assessment

The research used the panel co-integration technique, which captures accurate estimations while considering the CST constraints. Accordingly, the paper incorporated the Westerlund [80] approach to evaluate the incidence of long-run association between the regressors and REC. The null hypothesis of this methodology is that no co-integration exists in the error-correction term (ECT) among the series [81]. One main benefit of the Westerlund [80] method is that it alleviates and controls the constraints of SHT and CST in the research model. Equations 9-12 show the computational expression for this co-integration test.

$$G_{\tau} = \frac{1}{N}\sum_{i=1}^{N}\frac{\eta_i}{S.E(\widehat{\eta}_i}} \tag{9}$$

$$G_{a} = \frac{1}{N}\sum_{i=1}^{N}\frac{T\eta_i}{1-\sum_{j=1}^{k}\widehat{\eta_{ij}}} \tag{10}$$

Table 1
Description of variables.

Series	Symbols	Variable Description	Source
Renewable Energy Consumption	REC	Renewable energy use based on per capital (% of total energy)	[67]
Economic Expansion	EXP	GDP growth per (annual %)	[68]
Human Capital	HUC	HUC measures human capital index (scale 0–1)	[70]
Green Finance	GFN	GFN measures environmental product protection by residents	[67]
Technological Innovation	TNI	Patent on related environmental technologies	[67]
Government Effectiveness	GEF	GEF reflects the opinions on the quality of public service (Index)	[69]
Urbanization	URB	URB represents % of urban population to the total population	[68]

Note: WID: World Development Indicators, UNDP: United Nations Development Programme, WGI: Worldwide Governance Indicators.

Table 2
Descriptive analysis, correlation, and VIF.

Indicators	Mean	Std. Dev	Min.	Max.	Kurtosis	Corr.	VIF
LnREC	11.160	2.080	6.122	17.142	3.053		2.855
LnEXP	26.202	1.747	23.519	28.256	1.327	0.257***	1.726
LnGFN	3.360	6.461	2.095	4.890	3.649	0.130***	1.549
LnHUC	0.895	3.141	0.540	1.130	2.484	−0.508***	2.145
LnTNI	7.273	7.580	3.583	10.184	2.215	0.279***	1.165
LnGEF	3.657	10.461	1.752	4.330	4.366	−0.213***	2.495
LnURB	16.602	4.151	14.496	19.047	1.631	0.751***	2.639

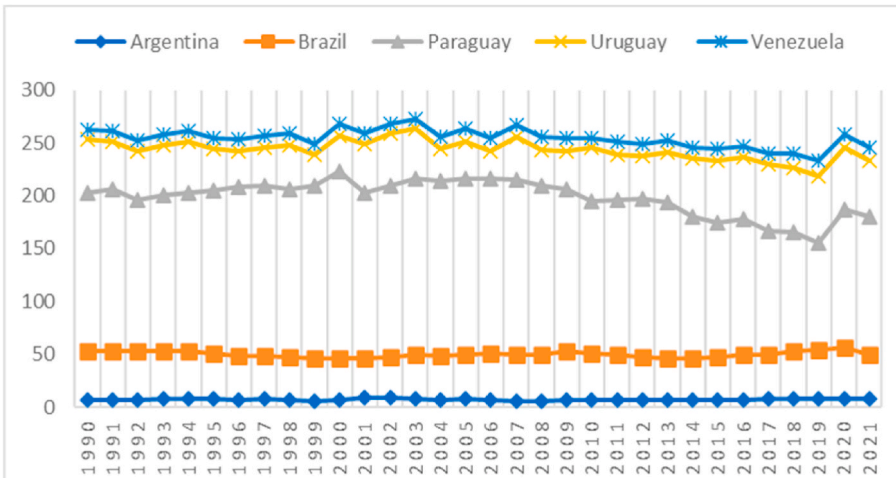

Fig. 1. Evaluation of REC trends for the Mercosur region.

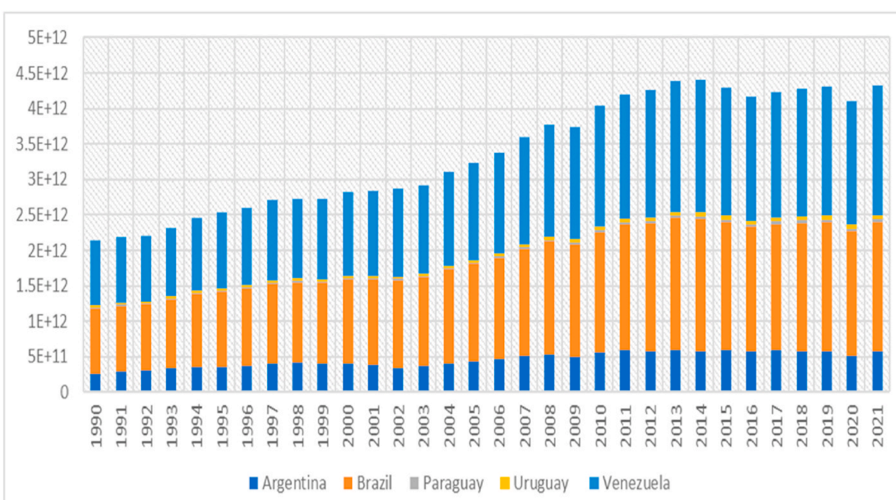

Fig. 2. Evaluation of EXP trends for the Mercosur region.

$$P_\tau = \frac{\widehat{\eta_i}}{S.E(\widehat{\eta_i})} \quad (11)$$

$$P_a = T\eta_i \quad (12)$$

Here, the mean for the group statistics is depicted by t $(G_t - G_a)$ and the co-integration is donated by $(P_t - P_a)$.

3.4.4. Estimation approach

This paper used the CS-ARDL framework to attain the study's objectives [38]. The CS-ARDL strategy has been recognized as more satisfactory to offset cross-sectional issues than traditional approaches, including the ordinarily least square and pooled mean group [46,82]. Moreover, studies have established that this approach can generate accurate and credible panel data estimates [83,84]. This estimate approach's key uniqueness is its ability to find any errors that may arise from the interactions among the indicators understudied in this paper [23]. Moreover, the CS-ARDL model marks a significant advancement over previous methodologies, such as pooled mean and liner regression, particularly in the context of renewable energy studies. The CS-ARDL is superiority lies in its ability to handle heterogeneity and cross-sectional dependence, which is a common issue in panel data analysis. This innovative method ensures more robust and accurate long-run and short-run elasticity estimates, addressing issues of endogeneity and

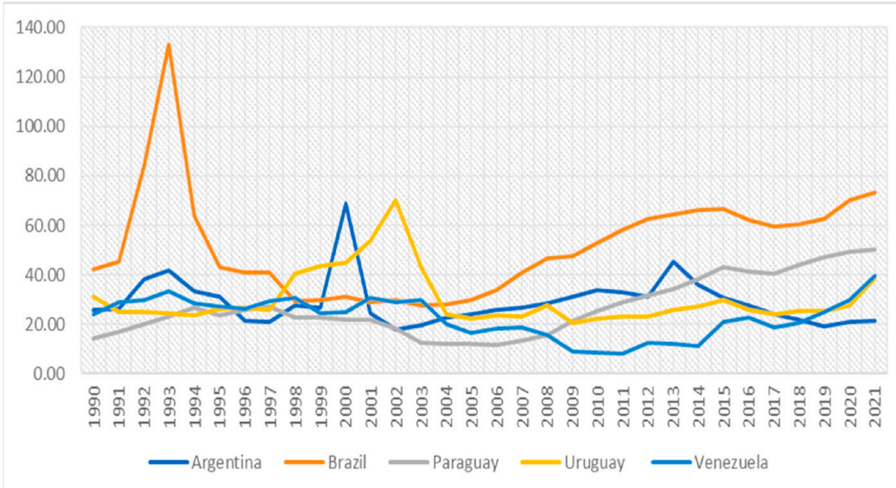

Fig. 3. Evaluation of GFN trends for the Mercosur region.

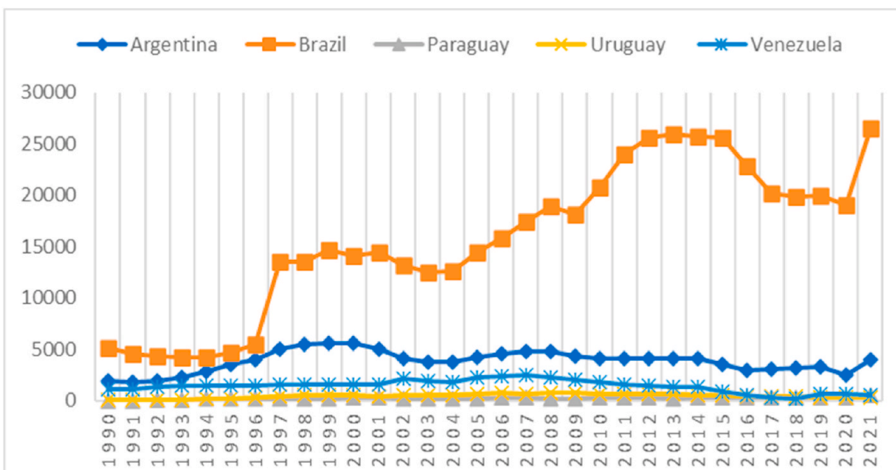

Fig. 4. Evaluation of TNI trends for the Mercosur region.

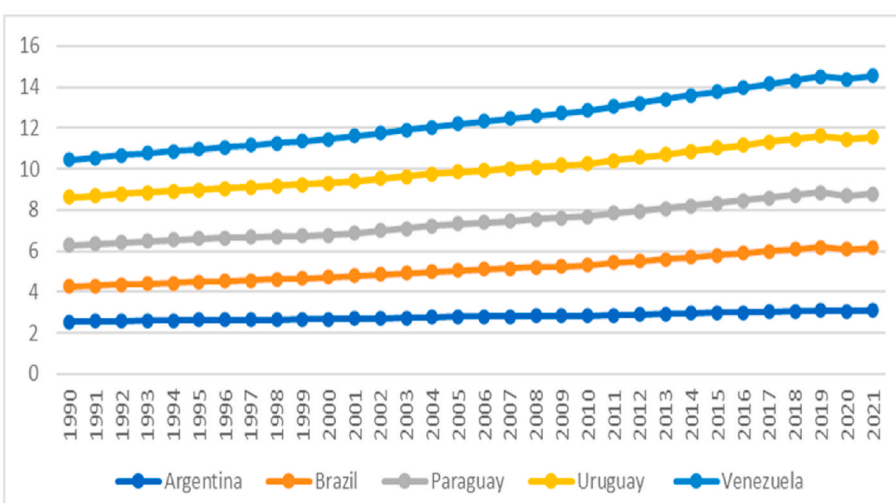

Fig. 5. Evaluation of HUC trends for the Mercosur region.

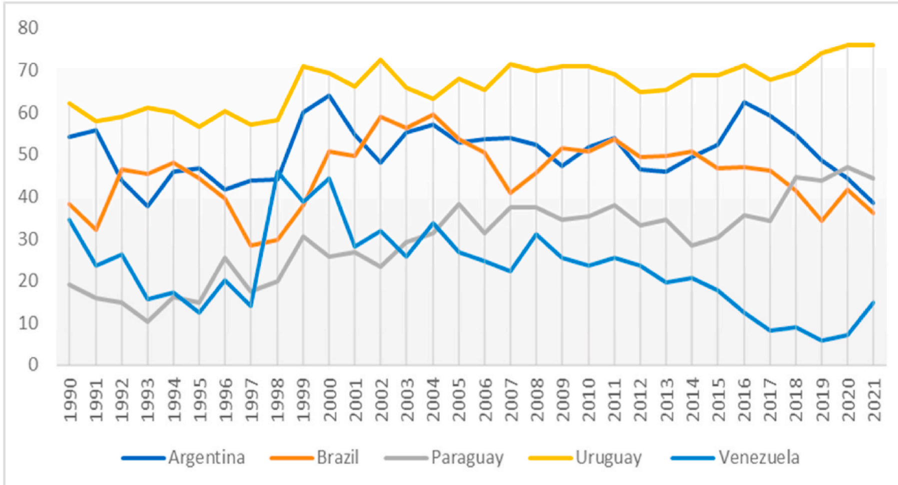

Fig. 6. Evaluation of GEF trends for the Mercosur region.

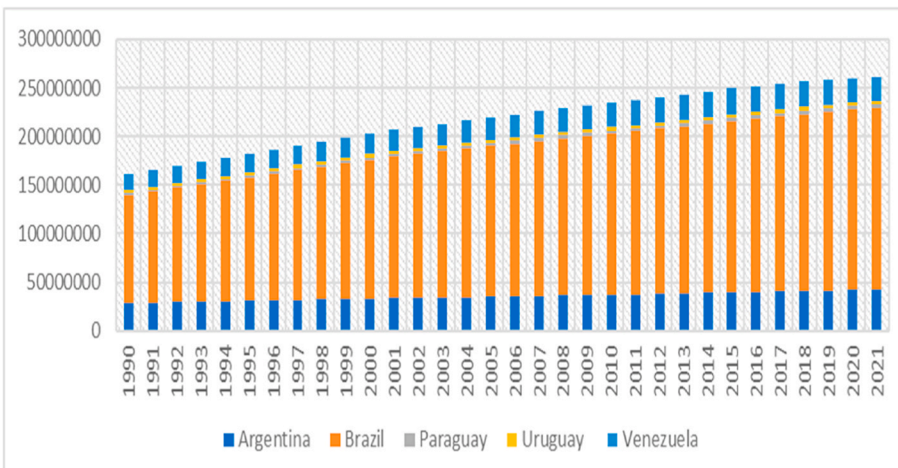

Fig. 7. Evaluation of URB trends for the Mercosur region.

serial correlation more effectively than its predecessors. By employing the CS-ARDL model, this study positions itself at the cutting edge of methodology applied to the analysis of renewable energy deployment. The use of this advanced model allows for the understanding of the dynamic relationships between human capital, technological innovation, green finance, and renewable energy deployment, setting a new standard for empirical analysis in this domain. The econometric process of this estimation approach, depending on the ECT of the CS-ARDL models, is described in Equation (13).

$$\Delta REC_{i,t} = \delta_i + \sum_{j=1}^{m} \delta_{it} REC_{i,t-j} + \sum_{j=0}^{m} \acute{\delta}_{it}\, X_{i,t-j} + \sum_{j=0}^{1} \acute{\delta}_{it}\, \overline{Z}_{i,t-j} + \mu_{it} \tag{13}$$

Such that, $\overline{Z}_t = (\Delta REC_{i,t}, \overline{X}_t)^{'}$ denotes the CST averages and X_{it} identifies the independent series in the study model, which includes EXP, GFN, TNI, HUC, GEF, and URB.

3.4.5. Robustness assessment

To ascertain the robustness and sturdiness of the CS-ARDL technique, the augmented mean group (AMG)-Eberhardt & Bond [85] and commonly correlated effect mean group (CCE-MG)- Chudik & Hashem Pesaran (2013) were incorporated in the analysis. Similar to the main model (CS-ARDL), these approaches address the challenges of SHT, CST, non-stationarity issues and consistent correlation among the indicators. Additionally, these estimation models tend to provide consistent and accurate predictions. These methods also address multicollinearity, autocorrelation, and endogeneity issues with panel data [86,87].

3.4.6. Panel causality test

The Dumitrescu & Hurlin [88]-D-H causality test was applied in the study to assess how the parameters' causal relationships interacted. This strategy is innovative, and prior research has used this procedure to investigate causality connections among the understudied series [16, 89]. Equation 14 mathematically represents this D-H strategy: 12:

$$Y_{it} = \alpha_i + \sum_{m=1}^{M} \delta_i^m, Y_{i(m-t)} + \sum_{m=1}^{M} \lambda_i^m, Z_{i(m-t)} \tag{12}$$

Here m depicts the lag component of the model and δ_i^m indicates the autoregressive structure of the regressors.

4. Findings and discussion

4.1. CST and SHT outcome

Table 3 provides the results for the CST and SHT for all the series. The outcome from the three CST tests validated the presence of CST among the series at a 1% significance level. The inference is that any exogenous

Table 3
Synopsis of the CST and SHT outcome.

Series	Corrected scaled coefficient	Scaled LM coefficient	Pagan LM coefficient
LnREC	8.251***	8.332***	47.262***
LnEXP	23.093***	23.173***	113.635***
LnGFN	12.286***	12.206***	54.699***
LnHUC	66.016***	66.935***	305.232***
LnTNI	23.173***	23.093***	113.635***
LnGEF	9.657***	9.577***	39.778***
LnURB	67.255***	67.175***	310.777***
Test of SHT			
*Delta tilde*Δ	18.034***		
*Delta tilde adjusted*Δ	18.648***		

Note: *** implies a 1% significance level; SHT represents a homogenous slope coefficient.

Table 4
Finding of unit root test.

Variables	CADF I (0)	I (1)	CIPS I (0)	I (1)	Order of Integration
LnREC	−2.334	−8.666***	−1.064	−7.842***	I (1)
LnEXP	−1.463	−6.863***	0.868	−6.492***	I (1)
LnGFN	−0.793	−5.357***	1.714	−5.651***	I (1)
LnHUC	−1.126	−5.548***	0.719	−6.802***	I (1)
LnTNI	−1.605	−9.327***	−1.774	−8.383***	I (1)
LnGEF	−1.856	−8.698***	−1.622	−8.249***	I (1)
LnURB	−2.334	−8.198***	−1.489	−6.452***	I (1)

Note: *** represents a 1% significance level.

impact, which includes global financial challenges, modernization, and globalization that affects one nation, will affect the other economies in the Mercosur block. The findings from the SHT reject the null hypothesis that the slope coefficient of the model is homogenous (see Table 4).

4.2. Stationarity test outcome

In order to perform valid and trustworthy regression analysis and ultimately provide more accurate and robust results in econometric studies, the data used in panel models must be stationary. This may be achieved with the use of the CADF and CIPS [7,90]. The results of the stationarity tests confirm that the indicators are stationary at the transition from level I (0) to first difference I (1).

4.3. Findings from the co-integration test

Before evaluating the long-run influence of EXP, GFN, TNI, HUC, GEF, and URB on REC, it is imperative to assess the possibility of co-integration in the research model. This paper applied the Westerlund [80] co-integration approach; the OUTCOME IS presented in Table 5. The outcome confirmed the occurrence of long-term co-integration among the series. This finding means the null hypothesis of "no co-integration" should be rejected at a 1% significance level. This test verified that both categories—($G_t - G_a$) for group statistics and ($P_t - P_a$ f for panel analysis. Hence, the study can conclude that the series been investigated are interlinked in the long term.

Table 5
Result of the co-integration test.

	Value	*Z − value*	*P − value*
G_τ	−2.425	3.526	0.042
G_α	−7.604***	4.754	0.000
P_τ	−2.278	2.532	0.265
P_α	−6.852***	4.851	0.000

Note: *** represents a 1% significance level.

4.4. Finding from estimation

After addressing the issues of CST and detecting the stationarity, the next phase of the econometric approach is assessing the estimates. Table 6 summarizes the CS-ARDL strategy approximations for the study. In addition, the diagnostic evaluation has been presented.

4.5. Discussion

The study revealed that EXP positively correlates with REC in the Mercosur regions. Thus, the long-term estimates from the estimation model showed that a 1% exponential uprise in EXP will stimulate the integration of REC by 0.832%. This outcome indicates that a rise in EXP activities in these regions will lead to the development of REC. This finding implies that EXP is an essential driver of the deployment of REC. More specifically, the analysis has confirmed that the transition to REC promotes higher productivity, favouring the bolstering of EXP in these nations. The research conducted by Papież et al. [91] asserted that EXP is a relevant component in enhancing the growth of REC. This result is consistent with numerous investigations that have noted that EXP stimulates growth in REC from different jurisdictions like Eastern and Central European nations [44], 133 emerging economies [42], 107 nations [32,92]- 104 selected countries [47], top ten REC economies and [48] for BRICS.

Furthermore, the outcome of the CS-ARDL strategy highlighted that GFN has a positive influence on REC in the Mercosur economies. The empirical outcome showed that a 1% rise in GFN improved REC's growth by 0.025% in the long term. This outcome confirms that GFN has a favourable and substantial influence on the investment in REC, such as solar, hydro, and wind energy sources. There are several reasons for the positive correlation between GFN and REC. First, since the GFN strategy is still in the initial phase of development in the Mercosur region, a well-structured policy has been developed to support the growth of REC through GFN. Second, REC initiatives are typically funded via capital investment, and before providing funding for such projects, investors typically examine two ideas: investment risk and rewards. If investors find that the returns outweigh the risks, it will influence them to invest in REC projects. Third, as Azhgaliyeva et al. (2020) pos, GFN effectively promotes REC growth. Moreover, He et al. (2019) asserted that a GFN increase could improve investment in REC by decreasing credit issuance through bank credits. This finding supports erstwhile studies that have demonstrated investment in GFN promotes the growth of REC ([93]; M. [94,95]).

Regarding the influence of HUC on REC, the results revealed that a 1% increase in HUC enhanced REC by approximately 0.095 in the long-run. The possible interpretation for this result is that HUC is high among citizens in the Mercosur countries, and the populace has sufficient knowledge about the importance of using REC for industrial and household consumption purposes. In addition, the study's outcome has demonstrated that higher educational levels, good health conditions, and better living conditions benefit the deployment of REC growth. The study by Zhu [25] indicated that in economies where the HUC is high, there is an increase in environmental stability and improvement in sustainable devilment, encouraging the growth of REC. The transition to REC can be achieved through the development of HUC (Acheampong, ErdiawKkwasie et al., 2021). This inquiry supports recent findings that HUC substantially and positively influences REC [27,56,57].

TNI showed an efficacious and notable impact on REC, implying that a 1% rise in TNI stimulates REC by 0.531% in the long term. The forgoing result pointed out that the effect of TNI on REC is substantial, as demonstrated through the CS-ARDL estimates. The possible reason for this outcome is that over the last decades, there has been an improvement in the TNI in the Mercosur nations. Hence, the expansion of TNI might improve the development of REC in these countries. Another possible reason is that the rising usage of cleaner energy involves the extension and transmission systems. Hence, applying TNI strategies

Table 6
Outcome for short and long-term elasticities.

Series	Short-run estimates			Long-run estimates		
	Coff.	Std. Error	Prob	Coff.	Std. Error	Prob
LnEXP	0.607***	0.462	0.000	0.832	0.047	0.003
LnGFN	0.421***	0.233	0.042	0.025	0.085	0.006
LnHUC	0.082***	0.782	0.007	0.095	0.646	0.000
LnTNI	0.497***	0.172	0.050	0.531	0.296	0.004
LnGEF	0.353***	0.057	0.000	0.424	0.104	0.000
LnURB	−0.184***	0.152	0.000	−0.412	0.068	0.000
ECT (−1)	−0.802***	0.112	0.000			
Model Diagnostics Test						
Test type	Diagnostic	Stats.	P-Stats			
Modified Wald test	Heteroskedasticity	326.122	0.006			
Woodridge test	Autocorrelation	218.957	0.574			
Jarque Bera test	Normality	9.369	0.083			
F-statistics	Goodness of fit	80.474	0.002			
	R^2	87.60				
	Adjusted R^2	86.58				

Note: *** represents a 1% significance level.

comprising internet of things and artificial intelligence approaches can expand REC development without jeopardizing energy security. Also, advanced digitalization is essential to optimize the flexibility and utilization of cleaner energy sources. Accordingly, the outcome of this analysis supports the erstwhile analysis that highlighted that REC can be promoted through TNI [48,53,54,96]. In contrast, some investigations have discovered that TNI causes a decline in REC [97,98].

The paper's outcome indicated that GEF has an advantageous effect on the development of REC in the Mercosur bloc. Thus, the result indicated that a one per cent upsurge in GEF will increase the growth of REC by 0.424% in the long term. GEF emphasizes the integrity of public institutions from partisan interferences and can potentially improve and boost socio-economic activities by delivering improved public services to the citizenry. As a result, the outcome of this study confirmed that GEF encourages the deployment of REC. Mahmood et al. [98] asserted that a fragile government system would be pressed by interest groups, lobbies, corruption, and nepotism, potentially impeding the promotion of REC policies and initiatives. The improvement in GEF will enhance the transition to REC. Wang, Dong et al. [32] believe that a robust democratic context helps ensure ecological conservation policies' sustainability, which ultimately drives the sustainability and growth of REC. A more sustainable political atmosphere also promotes a democratic voice, and citizens effectively articulating their sustainability aspirations can help the government's commitment to encouraging the renewable industry. This study's findings agree with previous research that argued that GEF is an essential driver of REC [99,100].

In addition, the result from the CS-ARDL established that URB exerts an inverse influence on the development of REC in the Mercosur regions. In other words, the results confirmed that a 1% increment in URB reduces REC by about 0.412%. The plausible rationale behind this discovery is that the URB process requires more investment in facilities and infrastructure to sustain and improve the social living standards of urban dwellers. This remodelling and developmental agenda of URB require the use of more energy. Hence, migrants' energy consumption patterns might shift drastically to traditional power sources, comprised of coal and fossil fuel, which might reduce the REC. As the STIRPAT model and the ecological modernization theory revealed, an urban metropolis demands more power than less developed areas [65,101,102]. Concurrently, the increasing demand for energy usage and high infrastructure density may cause traffic jams, leading to the wastage of energy. This circumstance necessitates a distinction between cleaner energy sources and the socio-economic conditions that influence the deployment of REC and URB activities in various ways [36]. Hence, this analysis's finding agrees with articles that revealed that URB has an inverse connection to the development of REC [35,60,103,104]. In contrast, other studies have concluded that changes in the URB positively influence REC ([101]; M [105]).

The error correction term (ECT-1) in the CS-ARDL econometric model represents the long-term equilibrium relationship between variables after accounting for cross-sectional dependencies. It captures the speed of adjustment towards equilibrium following short-term deviations. ECT-1 is crucial for understanding the convergence of variables and the stability of the long-run relationship in panel data econometrics. Therefore, in response to any change in the REC across the Mercosur bloc, it is assumed that a swift increase in an immediate shifting period in designing a long-run stable situation calls for an immediate alteration of 80.2% during a year. Furthermore, the study described several diagnostic tests, including Diagnostic heteroskedasticity, autocorrelation, normality, the goodness of fit, $R^{2,}$ and adjusted R^2. These validity tests demonstrated that the empirical technique is analytically sound, emphasizing that key players and policy-makers may depend on this assessment to carry out the crucial REC implementation activities.

4.6. Robustness analysis

The estimation outcomes from the AMG and CCE-MG outputs are compatible with the empirical results of the main estimation approach, as captured in Table 7 and Fig. 8. Thus, the CCEMG and AMG confirmed a beneficial connection between EXP, GFN, HUC, TNI, GEF and REC. In contrast, URB and rec have an inverse linkage among the Mercosur region.

4.7. Causality analysis

The outcome of the causality evaluation is presented in Table 8. It demonstrates the linkage between the regressors (LnEXP, LnGFN, LnTNI, LnHUC, LnGEF, LnURB) and the explanatory variable (REC). The D-H causality outcome depicted a bidirectional causal interplay between LnHUC, LnURB, and LnREC. This result signifies that slight structural reforms affecting one of these determinants will impact the REC and vice

Table 7
Findings from the robustness test.

Series	CCE-MG		AMG	
	Coff.	*P − value*	*Coeff.*	*P − value*
LnEXP	0.514***	0.004	0.387***	0.001
LnGFN	0.619***	0.000	0.738***	0.000
LnHUC	0.210***	0.001	0.066***	0.000
LnTNI	0.323***	0.002	0.419***	0.046
LnGEF	0.056***	0.000	0.236***	0.012
LnURB	−0.811***	0.001	−0.335***	0.000

Note: *** represents a 1% significance level.

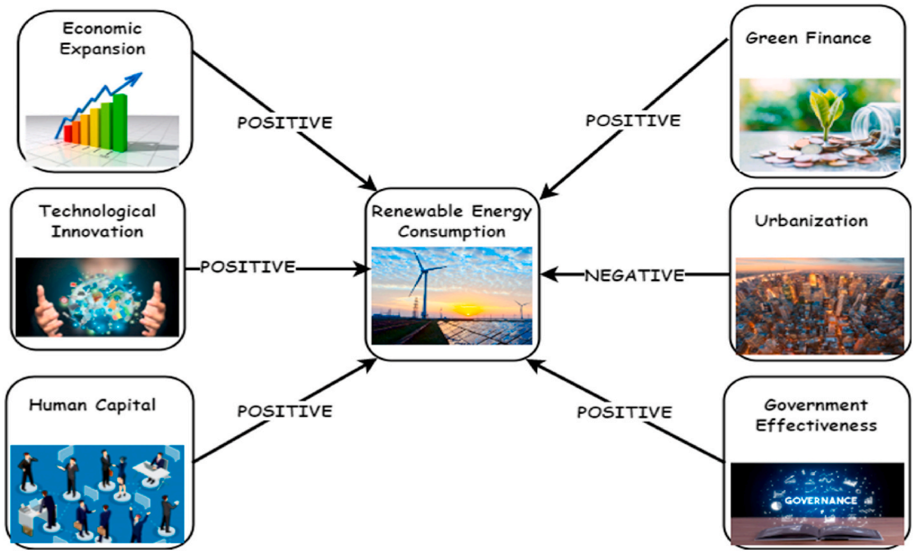

Fig. 8. Graphical illustration from the study findings.

Table 8
Findings from the causality test.

Null Hypothesis	*W − stats.*	*Zbar − Stats.*	*P − Stats.*	Conclusion
LnEXP ⇎ LnREC	7.233***	2.941	0.003	EXP → REC
LnREC ⇎ LnEXP	2.578	1.381	0.703	
LnGFN ⇎ LnREC	6.104***	1.196	0.000	GFN → REC
LnREC ⇎ LnGFN	2.292	0.522	0.895	
LnHUC ⇎ LnREC	8.939***	2.607	0.000	HUC ⟷ REC
LnREC ⇎ LnHUC	7.442***	2.336	0.000	
LnTNI⇎ LnREC	5.650***	3.851	0.004	TNI → REC
LnREC ⇎ LnTNI	2.275	1.573	0.833	
LnGEF ⇎ LnREC	15.136***	12.220	0.000	GEF → REC
LnREC ⇎ LnGEF	3.672	1.412	0.157	
LnURB⇎ LnREC	7.753***	2.259	0.000	URB ⟷ REC
LnREC ⇎ LnURB	5.072***	2.732	0.004	

Note: *** represents a 1% significance level, ⇎ does not granger cause, ⟷ bi-directional and → unidirectional.

versa. In contrast, the results from the causality assessment showed a unidirectional nexus between LnEXP, LnGFN, LnTNI, LnGEF, and LnREC. These findings support the outcomes of prior studies [44,106]. This result demonstrates that governmental decisions and initiatives affecting EXP, GFN, TNI, and GEF will directly impact REC penetration in the Mercosur region.

5. Conclusions and policy direction

5.1. Conclusions

REC has been designated a green power option with fewer adverse repercussions for the ecosystem and the sustainability of people. Therefore, it requires more integration in areas where it is underutilized. In addition, the SGDs outlined by the United Nations (2016) stressed the important role of clean power sources and the eradication of climate change in achieving the 17 SDGs agenda. As part of the efforts to promote ecological stability, the current study evaluated the impact of EXP, GFN, TNI, HUC, GEF, and URB on the development of REC in the Mercosur nations. The research showed that the variables are stationary and cointegrated. The article's findings are as follows: (1) The outcome of the analysis indicated that EXP, HUC, TNI, GFN, and GEF are advantageous and indispensable in the development of REC. (2) The empirical outcome revealed that URB is detrimental to the progress of REC in the Mercosur economies. (3) A unidirectional causality flows from EXP, GFN, TNI, and GEF to REC, where two-way causality exists between HUC, URB, and REC.

The findings of this study illustrate a multifaceted relationship between economic, financial, technological, and governance factors and the consumption of renewable energy within Mercosur economies. Specifically, the positive impact of economic expansion, green finance technological innovation, human capital, and government effectiveness underscores their critical roles in promoting REC. These elements collectively facilitate the development and adoption of renewable energy by improving investment in green technologies, enhancing the efficiency of renewable energy systems, and fostering a supportive regulatory and financial environment. However, the detrimental effect of urbanization on REC progress suggests that the current urban development patterns within these economies may not be sustainable or conducive to the expansion of renewable energy. This indicates a pressing need for urban planning and development policies to be more closely aligned with renewable energy goals.

The study's revelation of unidirectional causality from EXP, GFN, TNI, and GEF to REC and a bidirectional relationship between HUC, URB, and REC further highlights the complex dynamics at play. These findings suggest that while certain factors directly influence the uptake of renewable energy, others, like human capital and urbanization, have a more nuanced relationship, potentially serving both as drivers and outcomes of renewable energy consumption. This underscores the importance of integrated and comprehensive policy approaches that consider the interplay between different factors.

5.2. Policy directions

The estimated discoveries from this analysis have several strategic policy ramifications, which are discussed below. First, the results from the research confirm a beneficial connection between EXP and REC. Hence, this research advocates that policy-makers in the Mercosur nation must pursue investment in cleaner energy by adhering to feasible strategies and frameworks that support green economic growth. Moreover, policy-makers should emphasize developing and using more REC for economic expansion projects. In addition, firms and enterprises incorporating and practising REC should be granted greater subsidies and incentives. Besides, the current investigation advises developing more advanced, practical, and environmentally sustainable REC to guarantee resource efficiency while expanding on Mercosur EXP initiatives.

Second, the paper's outcome confirmed a positive interplay between

GFN and REC. As a result, this study suggests that these economies' governments should galvanize financial assistance from commercial banks, insurance enterprises, and investment banks for soft-interest loans, which involve long-term payment options and low interest to finance REC projects. The use of crowdfunding and energy cooperatives can effectively bridge the financing gap in the deployment of REC sources. Moreover, in practical terms, policy-makers, enterprises, and lending firms must work together to strengthen the stimulation influence of GFN on the efficiency of REC investment in the Mercosur nations.

Third, the findings on the influence of HUC on REC highlighted that key investments in individuals or citizenry help improve energy efficiency. Accordingly, this analysis proposed that policy-advisors in these emerging nations should pay close attention to investment and concentration on the educational sector to acquire higher environmental initiatives and benefits through HUC development. Moreover, governments in each country should provide their citizenry with a high-quality education to encourage energy efficiency and REC.

Fourth, the investigation findings pointed out that URB worsens REC's development. Hence, the current study recommends that urban authorities focus on expanding the use of electronic vehicles, energy-efficient public transportation systems, and alternative fossil-fuel for automobiles in the cities. Urban planners and the government must implement proper awareness measures to educate urban dwellers on the urgency of using cleaner energy supplies and maintaining a healthy environment.

Fifth, as indicated in this study, TNI helps stimulate the growth of REC; it is suggested that the Mercosur nations emphasize their efforts to develop more renewable and environmentally friendly technologies. Policy-makers should underscore the importance of investing in these cleaner technologies and increased spending on research and development in the REC industry due to the increased digitalization, the fourth industrial revolution, and artificial intelligence in contemporary times. Moreover, since TNI in cleaner power sources is capital intensive and needs enormous financial support, the study advocates that Mercosur nations should create the required governance channels and conducive atmosphere to capture other relevant stakeholders in investing in REC. The enabling environment includes inviting academic institutions to contribute to developing smart energy networks for current and future needs and risk consultants to evaluate the threat of such investment opportunities in REC technologies. Lastly, the empirical results from that study revealed that GEF is an essential enabler of REC. Therefore, it is strongly recommended that Mercosur nations continue strengthening the governance system to encourage REC. In addition, law enforcement agencies should prioritize enforcing regulations to manage non-REC energy in the region. These collaborative initiatives would assist in reducing the usage of non-REC energy and improving the environment.

5.3. Limitations and future research perspective

There is no disputing that REC is crucial for attaining the SDGs and dissipating ecological pollution. Extensive studies like this analysis can assist in laying the groundwork for more productive debates on the subject, which can help transform the Mercosur nations' energy industry. Nevertheless, because of the lack of data, the current study mainly explored five Mercosur nations and employed a short time frame. However, further investigation into the subject may strengthen the scope of the analysis by collecting more data. Additionally, a future study might emphasize integrating country-specifics and explore the influence of other factors, such as globalization, carbon emission, and natural resources, on the development of REC from other jurisdictions, such as West Africa, BRICS, and other emerging economies.

CRediT authorship contribution statement

Agyemang Kwasi Sampene: Conceptualization, Methodology, Formal analysis. **Cai Li:** Conceptualization, Methodology. **Takyi Kwabena Nsiah:** Investigation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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