New Energy Exploitation and Application
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Impact of Gender and Technological Innovation on Energy Efficiency

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Received: 28 July 2024; **Revised:** 29 July 2024; **Accepted:** 12 December 2024; **Published:** 16 December 2024

Abstract: This study investigates how men and women in MINT countries contribute to enhancing energy efficiency across various sectors through technological innovation. Gender plays a pivotal role in the energy efficiency landscape, and this study examines how promoting gender equality and increasing women's participation in innovation can enhance energy efficiency outcomes. Using data from the World Bank and an annual panel dataset of MINT nations from 1997 to 2020, this study analyzes the relationship between energy efficiency and variables such as per capita consumption of renewable energy, GDP, gender, and urbanization. The study uses the panel autoregressive distributed lag (ARDL) model to examine the variables' long- and short-term relationships. The panel ARDL method has two steps: first, testing for the presence of a long-term relationship between the components, and then, using those results, calculating the long-term coefficients. The study used a causality evaluation which considers the potential causal association between the regressors and the dependent series to determine the presence and direction of causal relationships between the two data sets. If a cointegrating link can be established, it suggests that there may be a causal connection between the indicators, while the direction of causation remains unknown. This research provides empirical evidence of the complex interplay between gender, technological innovation, and energy efficiency in MINT countries. It highlights that gender-sensitive policies and renewable energy sources are crucial to the success of international efforts to promote sustainable development.

Keywords: Renewable Energy; Gender; GDP; Innovation; Urbanization

1. Introduction

Energy efficiency is a leading policy issue for governments worldwide in recent years. This initiative is driven by the imperative to mitigate greenhouse gas emissions in response to the pressing need to address climate change. Efficient energy systems and other technological advances have been instrumental in promoting sustainable practices in many sectors. Inclusion and empowerment of both men and women may drive innovation and enhance energy management, making gender a vital part of the energy efficiency landscape. This article aims to investigate the complex relationship between gender, technical innovation, and energy efficiency in MINT countries, focusing on the roles of both men and women in diverse industries.

Historically, Africa has encountered various obstacles in pursuing energy efficiency and sustainable development. Colonial and postcolonial political structures and a lack of infrastructure and resource access have impeded the continent's capacity to create and deploy novel energy solutions [1]. However, substantial progress has been achieved recently, as African nations have increasingly integrated renewable energy and energy efficiency into their national policies and development programs [2].

Adopting gender-responsive policies has gained support as governments acknowledge the significance of gender equality for sustainable development. The African Union (AU) introduced the African Gender and Development Index (AGDI) in 2005. This framework is used to evaluate gender equality and women's empowerment throughout the continent, as stated by [3]. According to [4], several African countries, including Kenya, South Africa, and Tanzania, have incorporated gender mainstreaming into their national energy policies. These policies aim to tackle gender disparities in areas such as access and control over resources, decision-making, and the benefits of clean energy technology.

Oyedepo [5] emphasizes that energy plays a critical role in accomplishing the Millennium Development Goals. These goals encompass eradicating extreme poverty and hunger, providing universal primary education, promoting gender equality and empowering women, reducing infant mortality, improving maternal health, combating diseases, and ensuring environmental sustainability.

A nation's economy is primarily influenced by energy, which affects international relations, such as politics and military objectives. Besides, energy is a fundamental element for social development. The utilization of renewable energy sources is imperative due to the finite nature of fossil fuel reserves and the significant environmental damage associated with their use, underscoring the essential role of renewables in shaping the sustainable future of nations [6].

Halkos& Aslanidis [7] stated that public authorities focus more on renewable energy sources (RES) than conventional ones due to their environmental benefits. Greenhouse gas emissions can be reduced using renewable energy technologies instead of conventional methods for electricity generation.

The energy sector in Africa has historically had a low representation of women. Still, recent initiatives to promote gender equality have increased women's engagement in pushing technological innovation for energy efficiency. The Women Energy Entrepreneurs Framework (AWEEF) initiative aims to empower women entrepreneurs in the renewable energy sector and promote women-led clean energy businesses [3]. AWEEF supports women entrepreneurs with training, mentorship, and financial assistance, allowing them to develop new solutions for energy efficiency and access in their communities.

Men are crucial in driving technological innovation in Africa for energy efficiency. Recognizing the need for inclusive and diverse perspectives in the energy sector, several initiatives have sought to involve both men and women in creating and implementing innovative solutions. For instance, the African Network for Solar Energy (ANSOLE) aggressively encourages gender parity in its membership, research activities, and capacity-building programs, establishing a collaborative and inclusive atmosphere for innovation [8].

Technological advancements in Africa's energy sector have enabled various industries to achieve significant improvements in energy efficiency. In the agricultural sector, for instance, solar-powered irrigation systems have replaced old diesel-powered pumps, cutting greenhouse gas emissions and lowering farmers' energy expenses. The construction industry has adopted energy-efficient building materials and designs to reduce energy consumption and promote sustainability [9]. The significant role played in stimulating technological innovation for energy efficiency is thanks to public-private partnerships. The African Development Bank's Sustainable Energy Fund (AfDB) for Africa is noteworthy. It supports small and medium-sized renewable energy projects by offering technical assistance, grants, and equity investments [8]. With such programs, governments and private sector entities collaborate to create and scale up novel energy solutions, highlighting the continent's potential for significant advancements in energy efficiency.

For Africa's energy sector to achieve its sustainable development and energy efficiency goals, it must incorporate gender-sensitive policies and technological innovation. Energy access, cost, and environmental sustainability could significantly improve if more African men and women were involved in developing and implementing innovative energy solutions.

Understanding the importance of education and training in fostering an environment conducive to technological innovation and energy efficiency in Africa is crucial. Education has been shown to be essential in promoting gender parity and attracting more women to careers in the energy industry [10]. Technical training and education equip women to develop and implement innovative energy solutions.

For instance, the United Nations Development Programme (UNDP) is helping to promote gender-sensitive policies and aid the growth of women-led energy businesses in Ethiopia through its Energy and Gender for Sustainable Development (EGSD).

Women's involvement in energy policy and planning decision-making processes should be encouraged as it is crucial. When it comes to creating policies and programs, involving women in decision-making has been shown by research to lead to outcomes that are more sensitive toward gender and better tailored toward meeting the requirements of women [11].

Kenya has established a regulating agency called The Energy and Petroleum Regulatory Authority (EPRA) to oversee its energy industry. Energy planning and execution are areas where the authority promotes gender balance. The EPRA is tasked with ensuring that all steps are taken with a focus on achieving gender equality in energy development, from initial planning to final implementation.

Recognizing and correcting gender imbalances in the energy sector is crucial for social fairness and economic productivity. Promoting gender equality in the energy sector has improved energy access, decreased energy costs, and boosted economic growth [12].

One study in Tanzania indicated that if women were more involved in the energy sector, it might cut down on family energy costs and boost economic growth [7]. Promoting gender equality in the energy sector was also found to promote economic growth and improve access to energy for rural populations in a study conducted in Nigeria [9].

The term "MINT" refers to Mexico, Indonesia, Nigeria, and Turkey. This acronym was coined by "Jim O'Neil, ex-chief economist of Goldman Sachs" to describe new emerging economies with the most substantial development outlook in the future global economy. Recent IMF data imply that some "MINT" nations have a higher GDP growth rate than Germany, France, Italy, and the United Kingdom. The "MINTs" are anticipated to develop rapidly due to the following characteristics:

•Very significant populations that provide a sufficient labor force at affordable prices until 2050
•Strategic geographic locations facilitate market entry.
•Raw materials accessibility, including metals, hydrocarbons, and natural gas.
•Capability to entice international investment.
•Governments favor economic development.

Recently, the significance of addressing gender differences and the role of technological innovation in shaping energy efficiency outcomes has been emphasized, particularly in MINT countries, where rapid urbanization and economic growth are driving heightened energy demand. Prior research has highlighted the significance of government policy, market structures, and consumer behavior in driving energy efficiency. Still, gender dynamics and technological change have received less attention.

We chose MINT countries as our focus due to their unique position as emerging economies with rapidly growing energy demands, yet also facing significant energy access, affordability, and sustainability challenges. By examining the intersection of gender and technological innovation in these contexts, we hope to shed new light on how gender and technology interact to shape energy consumption patterns in MINT countries by examining the intersection of gender and technology in the context of energy efficiency. We investigate how gender-based differences in energy use and decision-making are influenced by technological innovation and how these patterns affect overall energy efficiency outcomes. We contribute to a better understanding of energy consumption's complex social and technological determinants as well as offering insights that will contribute to more effective energy policies and practices in MINT countries and beyond.

2. Literature Review

The relationship between GDP and renewable energy has been extensively studied in recent years as countries try to achieve sustainable economic growth while lowering their carbon impact. Because of its environmental benefits and ability to reduce greenhouse gas emissions, renewable energy sources are increasingly considered a critical alternative to traditional fossil fuels. At the same time, GDP is a key indicator of economic growth and development. Understanding the relationship between GDP and renewable energy is essential for policymakers, energy planners, and researchers developing successful sustainable development plans.

Several studies have investigated the relationship between GDP and renewable energy, employing methodologies such as econometric modeling, time-series analysis, panel data analysis, and case studies, with a focus on various countries and regions. Ref. [12] conducted a study examining the impact of renewable energy usage on economic growth in a group of emerging countries. Their findings revealed a positive association between renewable energy usage and GDP, indicating the potential role of renewable energy to foster sustainable economic development in underdeveloped countries. Similarly, Cui et al. [13] investigated the relationship between renewable energy investment and economic development in a group of OECD countries. Their findings demonstrated a positive and statistically significant association between renewable energy investment and GDP, implying that increasing investment in renewable energy can promote economic growth.

Several scholars have focused on regional analyses in addition to country-level investigations. For example, Halkos& Aslanidis [7] investigated the relationship between renewable energy use and regional economic growth in the European Union. Their findings revealed a positive and statistically significant association, showing that incorporating renewable energy sources can aid regional economic development. Furthermore, the research underlines the significance of renewable energy policies and their effect on the GDP-renewable energy nexus. Chen et al. [6] investigated the effects of renewable energy assistance programs on Chinese economic growth. Their findings demonstrated a positive link between renewable energy support policies and GDP, demonstrating that policy interventions are important in encouraging renewable energy adoption and enabling economic growth.

Recent studies have investigated on the economic impacts of renewable energy. For example, Cui et al. [13] investigated the cross-country spillover effects of renewable energy use on economic development in a panel of nations. Their findings suggested that increasing renewable energy consumption in one nation can boost the economic growth of surrounding countries via technological diffusion and knowledge transfer.

In addition, the literature has investigated the effect of various forms of renewable energy sources in fostering economic growth. For example, He [14] evaluated the association between GDP and specific renewable energy sources in South Korea, such as solar and wind energy. Their findings demonstrated that solar energy had a greater beneficial influence on economic growth than wind energy, highlighting the necessity of understanding the individual contributions of various renewable energy technologies.

As cities aim for sustainable development with a decreased environmental effect, the relationship between urbanization and renewable energy has become important. Urbanization is a worldwide phenomenon, with an increasing number of people living in cities. Rapid urbanization presents significant challenges about energy consumption, environmental sustainability, and climate change. Renewable energy has emerged as a critical solution to these concerns, potentially cutting greenhouse gas emissions while improving energy security. Recent empirical research has examined the relationship between urbanization and renewable energy, covering many elements and dimensions. One area of study is the effect of urbanization on renewable energy uptake. For example, Chen et al. [15] investigated the impact of urbanization on renewable energy usage in China. Their findings found a positive association, demonstrating that demand for renewable energy increases as cities strive for sustainable growth and lower carbon emissions.

In addition, the research highlights renewable energy's potential benefits in addressing urban energy challenges and enhancing measurable aspects of city life, such as public health, economic growth, and reduced air pollution. Chen et al. [15] research examined the relationship between renewable energy use and urban energy efficiency in Chinese cities. Their findings revealed a positive relationship, implying that incorporating renewable energy technology can improve energy efficiency and contribute to sustainable urban development. Researchers have also investigated the spatial elements of the urbanization-renewable energy nexus. For example, Chen et al. [6] evaluated the geographical patterns of renewable energy generation in metropolitan regions and their association with degrees of urbanization. Their research found that urbanization has a considerable impact on the spatial distribution of renewable energy generation, with higher levels of urbanization associated with greater renewable energy capacity.

In their study of the energy consumption and supply-side decisions made by Northerners, Clancy& Roehr [16], for example, did not consider the role of gender. The evidence on gender variations in preferences for primary energy sources as a supply source is equivocal. However, nuclear energy and both men and women have a definite favorable association. However, atomic energy and both sexes have a profitable solid association. A person's energy consumption in the North is influenced by factors such as geographic location, which determines access to energy infrastructure, and socioeconomic status, which affects affordability and energy usage patterns. Despite Sweden's justifiable reputation as a progressive and egalitarian culture, studies conducted there indicate significant gender differences in the places men and women like to visit. To create laws that more appropriately reflect people's lives and determine who is responsible for their energy use, it is crucial to comprehend the variables that drive consumption patterns and the consequences of those patterns.

Evidence suggests that women's implementation of energy-saving practices has limited impact on the energy efficiency of consumer items. Studies suggest that women are already inclined toward eco-friendly behaviors like switching to gas stoves or stopping the use of tumble dryers because they already have these tendencies. The stereotype that women are less concerned about environmental issues than men is thus also contradicted. However, there is no indication in these suggestions as to whether households can implement such possibilities (such as whether or not a given apartment has the square footage for a drying room or whether or not gas supplies to a habitation are even a possibility).

Obtaining gender-disaggregated data on energy supply could provide valuable insights regarding energy released on a gender-disaggregated basis if you are interested in learning whether or not there are gender inequalities in the supply side of the equation. It is not difficult to provide information separated into male and female categories, at least in Europe. EU citizens are polled by the European Commission every other year on energy and environmental protection policies. There is currently no information available that tailors its presentation to specific genders. Adjusting the framing or phrasing of survey questions could provide deeper insights into how men and women in the EU perceive energy policies and potential solutions, highlighting differences in priorities, values, or levels of awareness.

Based on the crucial data presented here, decision-makers should consider our argument that women and men must have equal access to energy use and participation in energy decision-making. This must occur both in terms of policy and in their personal lives. Clancy& Roehr [16] suggests that there is a significant lack of representation for women within the energy business. Is the underrepresentation of women in the energy industry statistically significant compared to men? Human resources experts in the energy industry agree that including more women in leadership roles would be helpful for business. From a social equity standpoint, the answer may be "probably not" if women can find employment in other sectors of the economy where they have an equal say in policymaking and implementation and earn wages at or above those of men. This is the case if women can enter different fields of work.

In contrast, a responsive political strategy would consider the reality that males and females are socialized differently and have distinct norms and expectations. Sectors of the economy dominated by one gender tend to develop laws and cultural norms that align with prevalent gender attitudes. This can cause those sectors to have insufficient diversity and inclusivity. Several strategies exist to transform the energy industry, among them recruiting more women to participate in this field. It is plausible for transformation to transpire by utilizing male individuals who endorse "feminine" principles. Clancy& Roehr [16] surveyed women scientists in the European Union. They discovered that some of the older women respondents perceived a difference in the attitudes and actions of younger males and older males working in the energy business. Specifically, these older women noticed a difference in how young males and older guys approached their jobs. Older women were the ones who saw this distinction more than their younger counterparts. Recent research indicates that younger men are more aware of social and environmental issues compared to previous generations. They are less likely to adopt traditional male-dominated workplace norms without critical evaluation.

In their report published in 2016, Empowering Women in Africa through Access to Sustainable Energy [17] emphasizes the significance of accessing energy sources that are both affordable and dependable while also being kinder to the environment. The term 'energy justice' also encompasses the broader societal shift towards equitable access to energy resources, fair distribution of energy benefits and burdens, and the inclusion of marginalized communities in energy decision-making processes. The social, economic, and environmental consequences of limited access to electricity affect women more acutely, as per the "Subprogramme 6 of the economic commission for Africa: the African gender and development index" report [3]. Ensuring universal access to electricity requires increased efforts. According to a report by UN Women (2020), women residing in several impoverished nations must allocate a considerable portion of their time to collecting and processing fuel. This responsibility restricts opportunities for education, income generation, and political participation. The restricted entry of women into economic sectors that have conventionally been male-dominated poses a substantial obstacle to the economic enfranchisement of women. The execution of these duties is significantly hindered by the lack of dependability in energy supply and the substantial expenses involved. The region of Sub-Saharan Africa harbors a population exceeding six hundred million individuals who lack access to electricity. With approximately eighty percent depending on conventional heating and food preparation sources, this contributes to considerable gender inequality. The limited availability of contemporary energy sources disproportionately affects women in sub-Saharan Africa, who are typically the primary caregivers for their families. Negative consequences on their health, education, and economic opportunities are directly linked to these conditions. The Women's Entrepreneurship Report: Education and Finance for Successful Entrepreneurship in Africa [1] revealed that conventional fuels are responsible for causing indoor air pollution. This contributes to respiratory and other problems, negatively impacting women's health.

Encouraging gender equality and women's empowerment via policies and programs could potentially increase the participation of women in the energy sector. According to UN Women guidelines on this subject matter, acceptable policies include gender quotas within decision-making entities focusing on energy generation and distribution issues. Moreover, exclusive training opportunities should be designated solely for female employees of such organizations. Lastly, financial rewards should be given to businesses that are led by females [1].

The significance of gender diversity within the energy sector is critical, particularly in light of Africa's ongoing shift towards sustainable energy. Throughout history, the energy sector has demonstrated a significant absence of female participation, particularly in upper management positions. The renewable energy transition in Africa report [2] showed that women remain inadequately represented in the renewable energy industry compared to the fossil fuel and nuclear sectors despite notable advancements. Notwithstanding significant progress, this observation remains valid.

The recognition and subsequent closure of the gender gap in the energy sector is imperative for Africa to attain an energy transition that is both equitable and inclusive. Societies can optimize their utilization of the diverse talent pool within their nations by cultivating an inclusive environment that values and respects individuals of all genders and sexual orientations. According to Räty& Carlsson-Kanyama [18] research has demonstrated that African women play significant roles in regulating household energy usage. Furthermore, women are disproportionately impacted by energy availability and use, making this a matter of the utmost relevance because of its significance.

Therefore, they concluded that exploring the impact of technology on energy efficiency through factors like usage, consumption, and intensity is essential for advancing energy efficiency research. Kemausuor et al. [19] conducted a study to examine the impact of the rate of technological advancement (measured by total factor productivity) on savings in electricity consumption. They surveyed how the advancement of technology impacts energy consumption by following a three-stage procedure. They concluded that the widely held notion of sustainable development, which suggests that the progression of technology leads to a reduction in energy utilization, does not always hold true based on their findings. Furthermore, they advocated for modifying the existing laws to give more importance to technological advancements that improve energy efficiency.

Tandon& Ahmed [20] utilized three distinct innovation indicators to evaluate the influence of three technical innovation measures on Indonesia's energy intensity (also known as Indonesia's energy inefficiency). They came to this conclusion after using ARDL to various proxies for technological innovation and discovering that each had a negative impact on the nation's energy intensity. Due to its substantial pool of technical experts, significant investment in research and development, and large population base, Indonesia has the potential to advance its energy efficiency initiatives.

Consecutive studies, including one performed by Cui et al. [13], backed up earlier findings and confirmed and extended the earlier findings. Chinese cities were discovered to have varied energy efficiency levels. According to their findings, the critical factor in technology translation and distribution is increased resource allocation resulting from technological innovation. This brings about better energy efficiency.

The interrelation of gender equality, technological innovation, and sustainable development has been listed among the priority focus areas in energy efficiency research. Previous research underlined that workforce gender diversity leads toward innovation and consequently promotes inclusive energy solutions together with improved efficiency outcomes [4]. Evidence from the African Women Energy Entrepreneurs Framework (AWEEF) initiative demonstrates that empowering women entrepreneurs in clean energy enterprises significantly raises access to energy and efficiency locally [1]. Similarly, Clancy& Roehr [16] argue that the gender-specific perspectives determine energy consumption patterns and call for policies touching on energy that are gender-sensitive. Technological innovation is yet another significant determinant of energy efficiency. As noted, the development of energy-efficient technologies, like solar-powered irrigation systems, has increased productivity while lowering energy consumption in rural farms [21]. Furthermore, the change that Industry 4.0 embodies seems to increase energy efficiency in developing economies, along with the moderation of developing economies [6]. Focusing on the combined role of gender, innovation, and sustainable development, Tandon& Ahmed [20] argue for policies that bring all these dimensions into a plan that ensures equal access to energy resources, lower costs of energy, and general efficiency in the use of energy. Alignment of these three factors shows the critical role that gender-sensitive, technology-driven, and sustainability-focused approaches play in energy efficiency, mostly in emerging economies like the MINT countries.

3. Data and Methodology

An annual panel dataset of MINT countries for 1997-2020 is utilized. To achieve the aims of this paper, we used renewable energy consumption per capita, GDP per capita, Innovation, gender, and urbanization, which were taken from the "World Bank" records.

However, we also included how renewable energy might be affected by gender, urbanization, and GDP per capita. This can be written as:

lnRE = f(lnGDP, lnU, lnGEN).

The natural logarithm form of the variables was taken. Table 1 below presents an explanation of the data in detail:

Table 1. Justification of the variables.

Variables	**Formula**	**Units**	**Source**
Dependent Variable: Energy efficiency (lnEEF)	% of energy use	Percentage	World Bank
Independent Variable G.D.P. per capita (InGDP)	G.D.P. shared by population	US $ (2010 constant)	World Bank
Urbanization (InU)	The % of the urban population in the total population	Percentage	World Bank
Gender Equality (lnGEN)	No of women in the sit of Parliament	Value	World Bank

MINT Countries are as follows: Mexico, Indonesia, Nigeria and Turkiye.

Following the implementation of the unit root test of [22] and ADF to verify the presence of stationarity that among the variables, the cointegration methods derived by [23, 24] were applied, which is an extension of the EG technique in a panel framework due to its first generation cointegration test residuals. Fisher developed the pooled (panel) test, group-mean test, and heterogeneity in the form of cointegration vectors. It has the null hypothesis of no cointegration, which can be rejected if at least three out of the four statistical tests from four are significant at the 5% level.

The investigation uses the panel ARDL model by [25] to analyze the long-term and short-term linkage between the study's variables. The model performs better compared to others, particularly when the variables are stationary at I(0), I(1), or a combination of both, demonstrating greater accuracy or reliability in such contexts. There are two processes in the panel ARDL technique used to determine long-term cointegration. Investigating whether there exists a long-term linkage between the factors is the first stage. The next step involves estimating the long-term coefficients using the panel ARDL model to assess the existence of a long-term relationship among the parameters. It is argued that to apply this method to panel data with cross-equation relationships, constraints on the long-term variables, such as fixed coefficients or equilibrium conditions, should be introduced. The equation of the ARDL based on the Equation (1) is shown as follows:

$$\begin{aligned} \Delta lnEEF_{it} &= Q_0 + \sum_{i=1}^{q} \rho_1 \Delta lnEEF_{t-j} + \sum_{i=1}^{j} \rho_2 \Delta lnGDP_{t-j} \\ &+ \sum_{i=1}^{f} \rho_3 \Delta lnU_{t-j} + \sum_{i=1}^{f} \rho_4 \Delta lnGEN_{t-j} + \sum_{i=1}^{f} \rho_5 \Delta lnINN_{t-j} + wECT_{t-1} + \epsilon_{it} \ldots\ldots\ldots\ldots \end{aligned} \tag{1}$$

The causality test of the regressors and dependent variable was checked using the DH causality test proposed by Dumitrescu and Hurlin in 2012. Identification of cointegrating relationships among the variables shows that there might be a causal relationship between the indicators, though the direction of causality is not determined. The establishment of these causal relationships gives further validation and robustness to the empirical results.

The Granger causality simple regression with M and T variables is represented in Equations (2) and (3):

$$Mt = a1 + \sum \beta 1iNt - i + n1 \sum \beta 2iMt - i + u1tn1 \tag{2}$$

$$Nt = a2 + \sum \beta 3iNt - i + n1 \sum \beta 4iMt - i + u2tn1 \tag{3}$$

Where n is the number of lags, a1, a2, 1, 2, 3, and 4 are parameters to be estimated, and u1t and u2t are error terms. If M series does not cause N variable, thus the parameters of N over the lagged M together null.

Dumitrescu and Hurlin in 2012 introduced the "Granger causality" approach for panel simulations by including cross-sectional units. For z and h variables which are stationary over the T period and N individuals, where e is the error term for the Equation (4).

$$zi,t = vt + \sum \mu(c)zi,t - c + Cc = 1 \sum \beta(c)hi,t - c + eitCc = 1 \tag{4}$$

4. Results

The "ADF unit root test" outcomes in Table 2 shows that the variables have unit roots at I(0) and are non-stationary. However, at the first difference, they are stationary; hence, the assumption of a unit root is rejected (lnEEF, lnGDP, lnI, lnU, and lnROA are all significant at 1%).

Table 2. ADF unit root test.

Variables	Level (Intercept & Trend)		First Difference	
	(T-Statistics)	(P Values)	(T-Statistics)	(P Values)
InEEF	0.40147	0.6560	−5.98650	0.0000***
InGDP	0.98915	0.8369	−2,29233	0.0109**
InGEN	−1.08010	0.1400	−7.47171	0.0000***
InUB	39.4225	1.0000	−4.16136	0.0000***
InINN	0.88777	0.8127	−5.45437	0.0000***

Note: InEEF= Energy Efficiency, InGDP=GDP Per Capita, InI=Gender Equality, InU= Urbanization and InROA=Innovation.
*** represents 1% and ** represents 5% significance level

The results of Fisher panel cointegration test provide strong evidence of cointegration among the variables in Table 3. The p-values are considerably less than the conventional 0.05 significance level and, therefore, confirm the long-run relationship among the variables. This justifies a structural equation model using these variables and their common underlying factors.

Table 3. Fisher panel cointegration.

Hypothesized	Fisher Stat.*	Fisher Stat.*		
No. of CE(s)	(From Trace Test)	Prob.	(From Max-Eigen Test)	Prob.
None	114.7	0.0000***	98.45	0.0000***
At most 1	71.00	0.0000***	52.43	0.0000***
At most 2	37.00	0.0000***	30.78	0.0002***
At most 3	14.19	0.0770*	14.78	0.0635*
At most 4	7.656	0.4678**	7.656	0.4678**

*** represents 1%, ** represents 5% and * represents 10% significance level

Probabilities are calculated by utilizing the asymptotic Chi-square distribution.

Cointegration tests are run in Tables 4 and 5 to assess whether the series in question demonstrate the long-standing constant link hypothesized. These tests are run in order to comply with the recommendations made by [22–24].

Table 4 highlights the results of the Kao Panel Test for Cointegration, showing a statistically significant t-statistic at the 1% level (p-value = 0.0022). This provides strong evidence to reject the null hypothesis of no cointegration and thus confirms a long-run relationship between the variables in the model. The residual variance and HAC variance values further define the distribution of residuals for the purpose of robustness checks.

Table 4. Kao panel test for cointegration.

	T-Statistic	Prob.
ADF	−2.849734	0.0022***
Residual variance	0.561403	
HAC variance	0.486646	

Note: *** represents 1% significance level of rejecting the null hypothesis of no cointegration, respectively.

At the 1% level of significance, the findings presented in Table 6 of the ARDL report demonstrate that there is a positive connection between GDP and Gender and renewable energy. When there is a growth of both GDP and Gender by 1%, the selected countries' renewable energy increases by approximately 0.51% to 0.30%. However, there will be a decline in the amount of renewable energy by 0.45 and 2.24 percent due to Innovation and Population, respectively. Enhanced energy efficiency leading to increased energy consumption is supported by the findings of the study of Poumanyvong& Kaneko [26]. Urbanization adversely affects the renewable energy industry. A rise in urbanization concentration by 1% results in a decrease of 0.45% in renewable energy consumption. Urbanization poses challenges to this industry by increasing resource demands and altering market dynamics, compounding existing pressures. The findings match those of Zhao& Zhang [27].

At the 5% significance level, the ARDL for short-run estimates presented in Table 5 reveals that the negative and statistically significant associations between GDP and Gender (−0.50, −0.102) continue to hold. This provides more evidence that there was a decrease in the use of renewable energy (−0.50 and −0.102, respectively) for every 1% change in GDP and Gender. At the 1% significance level, there is a correlation between renewable energy and both innovation and population growth in a favorable direction. The relationship between innovation and renewable energy is such that an increase of one percent results in an increment of 1.13 percent. Additionally, when population growth rises by just one percent, renewable energy output drops by 12.35 percent. Renewable energy sources are positively correlated (0.45) with urbanization.

Table 5. ARDL test.

Variable	Coefficient	Std. Error	T-Statistic	Prob.*
		Long Run Equation		
LGDP(−1)	0.512824	0.161147	3.182344	0.0040
LGENDER(−1)	0.303572	0.059886	5.069186	0.0000
LURB(−1)	0.834209	0.518753	1.608104	0.1209
LINNO	−0.453247	0.043319	−10.46299	0.0000
LPOP(−1)	−2.224705	0.332683	−6.687172	0.0000
		Short Run Equation		
COINTEQ01	−0.817908	0.129314	−6.324958	0.0000
D(LGDP(−1))	−0.500730	0.219805	−2.278071	0.0319
D(LGENDER(−1))	−0.102520	0.053109	−1.930384	0.0655
D(LURB(−1))	0.321849	0.427031	0.753692	0.4584
D(LINNO)	0.129880	0.036376	3.570492	0.0015
D(LPOP(−1))	−12.35067	1.170253	−10.55385	0.0000
C	20.03522	3.312332	6.048675	0.0000
Log-likelihood	83.53395			

*Note: p-values and any subsequent tests do not account for model selection.

The cointegration of InREC with InGDP, InGEN, InNNO, and InURB over a long period of time allows for the analysis of the potential causes and effects that may exist between the variables. According to the Dumitrescu and Hurlin Causality Test findings, a link is identified as both causative and reciprocal between energy efficiency, GDP per capita, gender, innovation, and urbanization, as shown in Table 6. Therefore, gender causes renewable energy, that is a one-way or unidirectional relationship moving from gender to renewable energy, but renewable energy does not cause gender as it is not statistically significant. There's a no statistically significant causal relationship between innovation and renewable energy. GDP does not cause renewable energy; therefore, it's not substantial. Renewable energy causes GDP; there's a one-way or unidirectional relationship moving from GDP to renewable energy. Urbanization does not cause renewable energy; and the relationship is not statistically significant. Renewable energy causes Urbanization; indicating a unidirectional relationship from renewable energy to Urbanization to renewable energy.

Table 6. Dumitrescu and Hurlin casualty tests.

Absence of Casualty	Z Bar-Statistic	P-Value
lnGEN ↔ lnREC	2.31753	0.0205
	−0.44500	0.6563
lnGDP ↔ lnREC	−1.04238	0.2972
	−1.04456	0.2962
lnNNO ↔ lnREC	0.50307	0.6149
	1.96023	0.0500
lnURB ↔ lnREC	−1.35423	0.1757
	1.97914	0.0478

Research has shown that gender-inclusive energy policies can lead to a great increase in energy efficiency. Clancy & Roehr [16] emphasize the importance of gender perspectives for sustainable energy development. Also, gender-diverse workforces in the energy sector have been associated with better innovation outcomes, as noted by Pearl-Martinez& Stephens [4]. Another critical factor influencing energy efficiency is related to technological innovation, as documented by the work of Chen et al. [6], in which the authors underline that advancements in Industry 4.0 technologies contribute to energy savings. In addition, urbanization and GDP growth are the factors that influence energy demand and efficiency patterns, as proven by the research of Li et al. and Liu& Fu [28, 29], which shed light on the intricate relationships between economic development, urbanization, and sustainable energy use. Liu& Fu [29] underline the role of urbanization in the formation of energy consumption and economic growth and prove that green finance initiatives may offset the adverse influences and promote energy efficiency. In like manner, Li et al. [28] underlines the synchronized development between urbanization processes and eco-efficiency, pointing to the potential of urban planning strategies in supporting sustainable use of energy. Radulescu et al. [30] underlines the importance of energy efficiency policies and environmental regulations in the process of carbon emissions reduction in fast-urbanizing areas. These results can be used by policymakers to design gender-responsive, technology-driven, and economically viable energy policies with a view to achieving better energy efficiency outcomes in MINT countries and beyond.

5. Conclusions

This study aims to examine the relationship between gender and technological innovation on energy efficiency from 1997 to 2020 by employing an annual panel dataset of MINT nations. Consumption of renewable energy per capita, gross domestic product per capita, gender, and urbanization were considered independent factors.

According to the findings of the study conducted on energy consumption trends over a time period - Energy Efficiency increases were associated with advancements in technology and urban growth as well as improvements in gender equality however declined during periods of rapid industrialization. According to the study's findings, increasing GDP can help reduce the negative impact of innovation on energy efficiency. MINT country policymakers and others may benefit from the insights provided by this study.

This study indicates that both technological improvements and gender play a vital role in determining energy efficiency. Dutta et al. [31] has reported that promoting gender equality and investment in technological innovation could potentially aid policymakers in fostering a sustainable and energy-efficient future. Although policymakers are aware of the need to balance the benefits of GDP growth with the need for mitigation of its environmental impacts, the quest for increased GDP per capita remains an entrenched hindrance to successful achievement of energy efficiency. Technological innovation and gender equality are two of the critical determinants that outline policies intended to enhance energy efficiency in order to ensure continued progress toward sustainable development.

Policy recommendations

Based on the study's findings, below are some suggested policies for MINT countries and other countries to consider implementing to improve energy efficiency and enhance sustainable development efforts:

Encourage Gender Equality: Policymakers should prioritize gender equality policies and activities in all sectors, including energy. This might involve ensuring equal opportunities for women in education and training in the fields of science, technology, engineering and mathematics, increasing the participation of women within the energy sector, and addressing the gender-based gaps in income and employment opportunities. Encouraging women's participation and ensuring that they have an active voice in decision-making, countries can leverage their entire talent pool towards technical innovation and efficiency improvement in the energy sector.

Invest in Technological Innovation: Policymakers should prioritize investments in green energy research and development. Financial incentives and support for developing and using renewable energy sources, energy-efficient technology, and smart grid systems might be included. Collaboration between academia, industry, and government in the development of innovation could lead to technology adoption in practical applications. Furthermore, authorities should encourage knowledge sharing and international cooperation to accelerate technological advancements in energy efficiency.

Encourage Sustainable Urbanization: It will also be important for the policy makers to emphasize energy efficiency in sustainability within the built environment. This includes encouraging compact, efficiently designed cities that reduce energy consumption related to transportation and infrastructure. Incentives can be created to encourage the use of public transit systems, sustainable urban mobility solutions, and energy-efficient structures. For more environmental protection, they will encourage the installation of solar panels and district heating/cooling systems at the neighborhood level.

Prevent the Negative Impact of Industrialization: Policymakers should enact regulations and guidelines that ensure industrial growth is long-term development objectives. Setting emissions standards and implementing environmental rules can reduce the negative effects of industrial activities on energy efficiency. Furthermore, authorities can encourage using greener manufacturing methods and energy-efficient innovations in industries. Transitioning to circular economy models, where resources are utilized efficiently, and waste is reduced, can significantly enhance industrial energy savings.

GDP per capita and environmental impact should be carefully balanced to ensure sustainability: Policymakers must strike a balance between economic development (as measured by GDP per capita) and the sustainability of the environment. While economic development is critical for raising living standards and decreasing poverty, it must be undertaken to avoid harmful environmental externalities. Green growth policies that promote sustainable consumption and production patterns motivate enterprises to adopt environmentally friendly practices, and support investments in clean technologies can help policymakers attain this balance.

Promote International Cooperation: Policymakers should engage with international initiatives and accords addressing energy efficiency and climate change. Collaboration among countries can expedite progress in energy efficiency by facilitating technology transfer, capacity building, and knowledge exchange. Policymakers should also engage in policy discourse and cooperation to create uniform norms and regulations that encourage global sustainable energy practices.

Policymakers may foster conditions conducive to gender equality, technological innovation, and sustainable development by implementing these policy proposals, resulting in increased energy efficiency and a more environmentally friendly future.

Author Contributions

Conceptualization, R.O.A. and F.T.; methodology, F.T.; software, F.T.; validation, R.O.A. and F.T.; formal analysis, F.T.; resources, R.O.A; data curation, R.O.A; writing—original draft preparation, R.O.A.; writing—review and editing, F.T.; visualization, R.O.A.; supervision, F.T. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data retrieved from the World Bank web page- World Development Indicators.

Conflicts of Interest

The authors declare no conflict of interest.

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