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Article

Brown vs green energy sources and resource productivity: The role of human capital and technology transfer in developing economies

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Abstract: This study determined the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside human capital and technology transfer roles for 40 selected developing economies. The study relied on a dataset sourced between 1991 and 2021. The study applied the method of moments quantile regression (MMQREG) procedure for the analyses while ensuring inferential robustness through the fully modified ordinary least squares (FMOLS), dynamic OLS (DOLS), and Driscoll-Kraay (D-K) methods. Empirically, the study revealed that an increase in brown energy consumption exhausted resource productivity from the lower to the upper quantiles. In contrast, green energy utilisation enhanced resource productivity from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy means, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, inferences from the DOLS, FMOLS, and D-K techniques revealed similar findings. However, despite non-renewable energy being the dominant means of energy in these developing economies, the size of its adverse impact on resource productivity falls short of the increasing effect of renewable energy across all quantiles. Also, the magnitude of the negative impact of human capital on resource productivity is marginally more substantial with non-renewable energy. In contrast, the robustness of the enhancing impact of technology transfer is slightly more with renewable energy.

Keywords: non-renewable energy; renewable energy; economic growth; human capital; technology; developing economies
JEL Classification: O47; Q2; Q32

1. Introduction

At no particular point has climate change been a critical threat to life's existence as now. Globally, its impact is significantly revealed in changing atmospheric conditions, rising sea levels and distortion of landscapes. Climate change is associated with the enormous utilisation of fossil/brown energy sources such as oil, natural gas, and coal. These energy sources are pivotal in nations' economic prosperity, as energy consumption is critical for economic growth. Consequently, economies desiring to expand their productivity and output require more energy consumption. However, the quest for more energy to accelerate economic output continues to grow the quantum of world greenhouse gas (GHG) emissions [1–7]. Carbon dioxide (CO_2) emissions constitute the lead contributor to GHG emissions and aid the rise in global warming [8–11].

Energy utilisation is a foremost requirement for advancing economic development since it contributes significantly to producing jobs, transportation, commerce, and agriculture [12]. Thus, energy is needed for poverty eradication and, by extension, sustainable human development [13,14]. For a lengthy time, brown energy sources served as triggers of economic prosperity. Hence, their demand remains swift even in the last decades for guaranteeing economic and social developments. For instance, the world's energy demand rose from 107 to 595 exajoules between 1991 and 2021 [15]. Although the proportion of conventional energy sources in total energy demand declined marginally from 86.5% to 82.3% between 1991 and 2021, renewable sources grew from 7.3% in 1991 to 13.5% in 2021 [16]. Nevertheless, brown energy sources still account for over 80% of global energy requirements in 2021.

Furthermore, the world's reliance on traditional energy sources has produced various worldwide challenges, the most prominent being the environmental harm of oil, coal, and natural gas, energy price shocks, energy depletion rate, supply security and independence [12]. These issues force economies to transit their reliance from non-renewable sources to renewable/green energy sources [17]. Thus, in the growing energy demand in economies, developed and developing countries are gravitating towards exploring green energy sources [18,19]. These green energy sources responsible for nominal ecological degeneration include solar, wind, hydrothermal, waves, geothermal heat, bio-fuel, hydrogen, etc.

Aside from the consequential impact of energy consumption on economic productivity, human capital and technological development are needed. Hence, developing nations have been trying to advance on these front to boost their industrialisation process for better production of goods and services [20–22]. However, many developing economies still struggle with the needed human capital and technology for efficient resource utilisation [23]. Thus, the crucial challenges of high unemployment, poverty, inflation, weak per capita, and sluggish industrialisation persist. Surviving with these challenges means the more the efforts to promote production and income growth, the more the intensity of natural resource use, which can accelerate resource depletion than their natural regeneration rate. Also, the phenomenon aggravates environmental debasement, which triggers global warming.

Several extant literatures provide evidence of the significance of energy, technology, and human capital for economic growth [23,24]. However, few studies have considered these factors on resource productivity, particularly for developing economies. Thus, this study expands the literature on this front. Higher production in developing countries demands more natural resource intensity, and the nature of energy adopted, combined with the available human and technological resources, can either exacerbate or mitigate the depletion rate of natural resources for output growth.

Hence, the primary objective of this study is to compare the effects of non-renewable and renewable energy consumption on natural resource productivity, alongside the roles of human capital and technology transfer for 40 selected developing economies. Aside from the fact that this study chose these countries due to data availability and completeness, they comprise over two-thirds of the world's population and economy. For instance, the world's gross domestic product (GDP) in 2022 is $101.6 trillion, and 67.5% ($68.6 trillion) of this sum belongs to developing economies [25]. This category's five largest developing economy include China, India, Russia, Iran, and Brazil, with $18.3 trillion, $3.5 trillion, $2.1 trillion, $2 trillion, and $1.9 trillion, respectively [25]. Furthermore, developing nations consume over half of the world's energy but have significantly weak per capita incomes [22,26]. Energy demand in developing countries has doubled in almost two decades and is estimated to rise by another 30% in the next two decades [27]. Their energy utilisation increasingly influences the global energy landscape, including trade and investment flows and climate change dynamics. Consequently, the intense resource utilisation for economic growth in developing economies, the applied energy source, the level of technological advancement, and human capital development are crucial for the sustainable use of natural resources for development.

This research relied on a dataset sourced between 1991 and 2021. For inferential robustness, this study applied the fully modified ordinary least squares (FMOLS), dynamic OLS (DOLS), Driscoll-Kraay (D-K), and the method of moments quantile regression (MMQREG) techniques for the analyses. Since the economic development of the selected countries is not the same despite their classification as developing economies, the MMQREG approach is appropriate because it captures the distributional heterogeneity of the subject matter by integrating fixed effects (FE). Thus, the method allows for heterogeneous nexus between the dependent and regressor variables at distinct conditional quantile distributions, which conventional mean regressions might ignore. Empirically, the study demonstrated that increasing brown energy utilisation diminishes resource productivity from the lower to the upper quantiles. In contrast, by accelerating green energy utilisation, resource productivity is improved and is evident from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy sources, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, estimates from the DOLS, FMOLS, and D-K methods echoed these findings.

The rest of the research reveals Section 2 as the literature section; Section 3 as the research's data and method; Section 4 as the study outcomes and discussion; Section 5 as the concluding remarks.

2. Literature review

2.1. Theoretical review

This study's brief theoretical exposition is grounded in the endogenous growth theory, which infers that human capital, innovations, and knowledge are the fundamental propellers of economic growth as against physical investments [28,29]. The endogenous growth premise encourages the convergence of economies through the spread of technology [30,31]. It is a phenomenon where developing nations gradually catch up to developed economies regarding technology. One endogenous component that connects to technology is energy. Today's equipment mostly thrives on the availability of usable energy to function. Hence, the more energy employed alongside well-equipped human capital, the better the economy's productivity. This assertion of the endogenous model validates the law of energy conversion that "no production process can be driven without energy conversion". However, energy is not the only form of technology application used in the production process. There are other forms in hard and software which are also vital components to ensure the application of technology at whatever level of the production process. The energy transformation from an unusable state into a usable one is enormously technology-driven. Also, the more efficient the energy source, the greater the capital required for production. Thus, significant expenditures in the energy sector are needed for any economy to achieve efficiency in energy production.

2.2. Empirical review

The scarcity of studies on the role of energy sources, human capital, and technological advancement on resource productivity led this study to review other related literature.

2.2.1. Economic output-energy sources relationship

By applying the DOLS and FMOLS techniques, Rahman and Velayutham [32] found that using renewable and non-renewable energy positively impacted the economic growth of South Asian nations. In contrast, Maji and Suleiman [33] used panel DOLS for 15 West African countries and revealed a deflating effect of renewable energy on economic growth. Similarly, in a selected African study for oil-producing economies, Awodumi and Adewuyi [34] demonstrated with the use of a panel non-linear autoregressive distributed lag (NARDL) model and submitted that after exceeding a particular threshold, developing nations experience a positive impact of renewable energy consumption on economic growth; but before then, it is adverse. Taskim et al. [35] employed the FMOLS and DOLS approaches and found that renewable energy positively affected green economic growth for OECD countries. Likewise, Shabbaz et al. [36] used the FMOLS and DOLS methods. They reported that although renewable and non-renewable fuels affected economic prosperity, renewable energy had the most influence across the 38 energy-consuming economies considered by the study. Similarly, Saidi and Omri [37] used FMOLS and VECM and reported that renewable energy promoted economic output in the 15 world's largest consumers of renewable energy. Chen et al. [38] used a threshold model for 103 countries and found an increasing effect of renewable energy on economic output in OECD economies but an insignificant impact in developed countries.

Also, Anser et al. [39] demonstrated by using a vector error correction method (VECM) that renewable energy has a blessing effect on the economic expansion of South Asian countries. Similarly, Baz et al. [40] applied NARDL and asymmetric causality techniques and confirmed asymmetric positive feedback from renewable energy to economic growth. However, an adverse positive and negative shock existed from fossil fuels to economic growth. Likewise, Mohsin et al. [41] reported a reducing effect of non-renewable energy on economic growth in 25 developing Asian countries. In a related study, Yikun et al. [42] used the fixed effect (FE) and PVECM tests to conclude that renewable energy enhanced the economy of South Asian Association for Regional Cooperation (SAARC) countries. Also, Abid et al. [23] used the cross-sectional ARDL technique to confirm that renewable energy decelerates material footprint for G-10 economies. Similarly, Li et al. [43] expressed that renewable energy lowers the ecological footprint of South Asian nations.

Summarily, the above studies demonstrated the interaction between economic growth, renewable and non-renewable energy sources. While most of the studies reported an overwhelming benefit of renewable energy for growth, the effect in

African countries were either adverse or insignificant, hence, leaving room for ambiguity in its effect for developing nations.

2.2.2. Association between human capital and economic productivity

Usman and Adeyinka [44] used the FMOLS and showed a positive impact of public spending on education, health, and school enrolment on economic expansion in the ECOWAS nations. Gwale and Wagner [45] used a system-generalised method of moments (SGMM) and submitted that human capital promotes economic progress in China. Later, Ding et al. [46] revealed for 143 countries that human capital has higher production elasticity than physical capital. Furthermore, the study found green GDP is more responsive to human capital than traditional GDP. Rahim et al. [47] also showed for the Next-11 nations that human capital mitigates the impact of a resource curse. Sonmez and Cemaloglu [48] demonstrated that technology and innovations are crucial for 31 emerging and developed nations in promoting economic output. Likewise, Shidong et al. [49] employed continuously updated fully modified (CUP-FM) and continuously updated bias-corrected (CUP-BC) techniques for G-10 economies. The study reported a blessing effect of human capital on economic productivity. Furthermore, using the heterogeneous mean group (MG), augmented MG, and common correlated effects MG procedures, Aladejare [50] revealed that human capital development has an insignificant impact on economic prosperity in 45 resource-reliant countries.

The above reviews have attempted linking human capital development to economic prosperity in different developing countries. Overwhelmingly, the studies showed that human capital has an enhancing effect on the economic growth of most developing nations reviewed, hence, making it a critical ingredient for economic advancement. Nevertheless, there is a vacuum in research on the impact of human capital on resource productivity, extending beyond economic growth in these countries.

2.2.3. Economic growth–technological progress nexus

The study by Gyedu et al. [51] used the panel GMM and VAR estimator and submitted that R&D, trademarks, and patents positively impact the economic growth of the G7 and BRICS countries. Furthermore, Ahmad et al. [52] used a long-run model to determine the link between eco-innovation and economic output in G7 economies. However, Belazreg and Mtar [53] revealed a neutral effect of innovation on economic output for OECD nations. Khan et al. [54] applied the dynamic GMM technique to report a bi-directional relationship between technical innovation and renewable energy and a positive relationship between FDI and GDP growth. A study by Skare and Malgorzata [55] demonstrated that technological advancements at the micro level (business) are more significant for green growth than non-technological advancements. Fang et al. [56] applied a two-step OLS method and expressed that improving R&D helps to promote green economic output in South Asian nations. The study by Kurniawati [57] submitted that information and communications technology (ICT) and internet use enhanced the economic productivity of 25 Asian countries. Likewise, Anakpo and Ayenubi [58] used DOLS regression and showed a significant long-term effect of technological innovation on per capita economic growth in Southern African economies. Similarly, Iqbal et al. [59] proved that technological improvements support economic output in Belt and Road Initiative countries (BRI). Abid et al. [23] further submitted that ICTs diminished the material footprint of G-10 economies.

Although, the above reviews significantly aligned with the beneficial effect of technology for economic growth in developed and developing countries, little is known about this impact on resource productivity, particularly as it pertains to sustainable growth.

2.3. Literature gap

Generally, evidence of scant studies on resource productivity exists from the reviewed literature, particularly for developing economies. Most studies focused on the effect of renewable and non-renewable energies, human capital, and technological advancement on economic growth. However, the pursuit of economic prosperity entails the use of natural resources which may have dire consequences on sustainable growth, depending on the management technique adopted. Hence, this study extends the literature on these fronts. As prior noted, developing nations' energy consumption is accelerating due to the need for output growth; and it is increasingly affecting the global energy landscape, trade and investment flows, and exacerbating climate change challenges. Hence, the intense resource use for output growth, the adopted energy source, technological advancement, and human capital development are critical for the sustainable use of natural resources in every economy.

3. Data and methodology

3.1. Data

This study employed a dataset between 1991 and 2021 for 40 developing economies. Presented in **Table A1** are the selected nations whose choice is by data availability and completeness.

This study expands the purpose of the real GDP (RGDP) and ecological footprint (EF) to derive a reliable measure of resource productivity by deflating the former by the latter to have RGDP per EF indicator. The measure suits well as it demonstrates output efficiency from productive behaviours and natural wealth since it is the ratio between GDP (the output index) and EF (the natural resource utilisation). Apart from the EF serving as an appropriate measure of natural resource consumption, it further defines man's impact on (built-up, arable, grazing, energy, and forest) land and fishing grounds [60]. Also, Rees [61] posited that EF is significantly equivalent to Ehrlich and Holdren's [62] typical submission of man's environmental effect represented as I = PAT; where I denotes impact, P shows population, A is affluence, and T expresses technology. Hence, the EF accommodates the impacts of population and technology on natural resources. Further justification for this indicator is that since the production function seldom captures the ecological resource, their overexploitation without replenishment is mostly inevitable. In other words, as economies expand in GDP size, the availability of resources to aid such growth becomes overly limited (i.e., in EF).

Furthermore, fossil energy per total energy consumed indicates brown energy. Fossil energy includes energy from oil, natural gas, and coal. Similarly, the proxy for green energy is renewable energy per total energy consumed. It is the share of renewable energies, including wind, solar, hydro, geothermal, biomass, etc., in total energy utilisation. Also, human capital development is essential for economic growth and resource productivity. When a country has sufficient quality human capital engaged in its production process, it can serve as a balancing factor between output growth and resource utilisation. Likewise, technology is critical for output growth and resource consumption. While countries can use technology to increase output, it can harm or enhance sustainable resource usage equally. Therefore, this study applied the KOF's information globalisation index to proxy technology transfer. The research variables, their measurement, and sources are in **Table 1**.

Table 1. Variable description.

Variable	Measurement	Source	Symbol
Resource productivity	$\frac{RGDP}{Ecological\ Footprint}$	WDI [63] and GFN [64]	rep
Non-renewable energy	Fossil energy % of total energy consumption	OWD [16]	$nrew$
Renewable energy	Renewable energy % of total energy consumption	WDI [63]	rew
Human capital	Human capital index	Feenstra et al. [65]	hc
Technology transfer	Weight index	Gygli et al. [66]	tgb

Source: Authors' compilation.

3.2. Methodology

Two relationships are estimated based on this research's objective: to compare the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside the roles of human capital and technology for developing economies. The first determines the effect of non-renewable energy, human capital, and technology transfer on resource productivity.

$$lnrep_{it} = \alpha_0 + \alpha_1 nrew_{it} + \alpha_2 lnhc_{it} + \alpha_3 lntgb_{it} + \mu_{it} \quad (1)$$

The second equation ascertains the impact of renewable energy, human capital, and technology transfer on resource productivity.

$$lnrep_{it} = \beta_0 + \beta_1 rew_{it} + \beta_2 lnhc_{it} + \beta_3 lntgb_{it} + \varepsilon_{it} \quad (2)$$

For inferential robustness, this study employed DOLS, FMOLS and D-K techniques. Pedroni [67] noted that when estimating dynamic cointegrated panels, heterogeneity issues, mean variation between cross-sections and divergence in cross-sectional alignment to the long-run equilibrium are critical. Hence, Pedroni's FMOLS model incorporates individual-specific constants and accommodates heterogeneous serial correlation properties of the stochastic processes across each panel cross-sectional unit, thereby treating these issues accordingly [68]. Later, Kao and Chiang [69] extended the DOLS estimator to panel data analyses based on the outcomes of Monte Carlo simulations. In contrast to the OLS and FMOLS, the DOLS estimator produced unbiased coefficients in finite samples [70]. Also, the DOLS estimator corrects for endogeneity by augmenting lags and leads variations to inhibit the endogenous feedback. Furthermore, Driscoll and Kraay [71] proposed a method that can yield robust results regardless of cross-sectional dependency (CSD), serial and spatial dependence, and heteroscedasticity in panel datasets. Also, the D-K technique is efficient for small and large panels and unbalanced and balanced panels [72].

The constraints of previous estimation approaches motivated the development of a panel quantile regression method for investigating the heterogeneous and distributional impact across quantiles. Essentially, quantile regression determines the dependent variance and conditional mean concerning the values of the regressors' coefficients. Quantile regression outcomes are more robust even when incidences of data outliers are evident. In addition, it suits adequately when the association between the conditional means of two series is weak or non-existent [68].

Consequently, this study applied the Machado and Silva [73] MMQREG with FE. Despite quantile regressions being robust to outliers, it fails to control for potential unobserved heterogeneity across panel cross-sectional units. In contrast, the MMQREG approach enables the identification of the conditional heterogeneous covariance impacts of the independent variables on resource productivity by permitting the specific effects to predict the entire distribution instead of just altering averages. Furthermore, the MMQREG estimation method applies to events where individual effects and endogenous regressor variables constitute the panel data model. Thus, the MMQREG conditional quantiles $Q_Y(\sigma|X)$ estimation for a model of the location-scale variant is:

$$Y_{it} = a_i + X'_{it}\beta + (\pi_i + G'_{it}\aleph)U_{it} \tag{3}$$

given the probability, $P\{\pi_i + G'_{it}\aleph > 0\} = 1(a, \beta', \pi, \aleph')'$ are coefficients to be determined. $(a_i, \pi_i), i = 1, \ldots, n,$ represents the individual i FE, and G denotes a k-vector of identified elements of X which are differentiable transformations with component l described as:

$$G_l = G_l(X), l = 1, \ldots, k \tag{4}$$

X_{it} is uniquely and identically distributed for any fixed i and is unique throughout the period (t). Likewise, U_{it} is uniquely and identically distributed across cross-sections (i) and through the period (t) and is orthogonal to X_{it} and normalised to fulfil the moment conditions in Machado and Silva [73], which do not suggest strict exogeneity; thus, Equation (5):

$$Q_Y(\sigma|X_{it}) = \big(a_i + \pi_i p(\sigma)\big) + X'_{it}\beta + G'_{it}\aleph p(\sigma) \tag{5}$$

From Equation (3), X'_{it} represents a vector of regressors in this research: non-renewable energy, renewable energy, and the natural logarithm of human capital and tech-globalisation. $Q_Y(\sigma|X_{it})$ signifies the quantile distribution of the response variable Y_{it} (natural logarithm of resource productivity) which is a function of the location of explanatory variables X_{it} - $a_i(\sigma) \equiv a_i + \pi_i p(\sigma)$ expresses the scalar parameter related to the quantile $-\sigma$ FE for each i. The individual impact does not represent a constant change, unlike the traditional least-squares FEs. They represent time-invariant coefficients whose independent effects are free to vary through the quantiles of the conditional distribution of the dependent variable. $p(\sigma)$ signifies the σ-th sample quantile, determined by treating the given optimisation challenge;

$$min_p \sum_i \sum_t \varphi_\sigma \left(W_{it} - (\pi_i + (\pi_i + G'_{it}\aleph)p\right. \quad (6)$$

where $\varphi_\sigma(J) = (\sigma - 1)JI\{A \leq 0\} + TAI\{A > 0\}$ represents the check function.

4. Results

4.1. Descriptive statistic test outcome

Table 2 reveals the defining feature of the panel data. It shows that resource productivity (RGDP per EF) has a mean value of $2.08 billion. This value shows the average efficiency of natural wealth in developing countries which is substantial. Also, while the mean non-renewable energy consumption is 83%, the average renewable energy utilisation is 14.3%; thus, non-renewable energy is the dominant energy source in developing countries. Furthermore, the mean human capital index is 144,610.8, while the average technology index is 72,421.5.

Table 2. Aggregate descriptive statistic.

Variable		Mean	Std. Dev.	Min	Max	Observations
	Overall		1.330	41.132	1.14×10^{11}	N = 1240
rep	Between	2.08×10^9	1.310	250.651	8.30×10^{10}	N = 40
	Within		3.010	-2.46×10^{10}	3.34×10^{10}	T = 31
	Overall		20.034	11.2	100	N = 1240
$nrew$	Between	82.992	19.970	15.008	99.995	N = 40
	Within		3.494	60.357	101.806	T = 31
	Overall		20.091	0	88.8	N = 1240
rew	Between	14.290	20.083	0.015	84.992	N = 40
	Within		3.174	−4.524	36.925	T = 31
	Overall		3,599,265	1.244	8.97×10^7	N = 1240
hc	Between	144,610.8	914,583.5	1.634	5784336	N = 40
	Within		3,484,035	−5,639,723	8.40×10^7	T = 31
	Overall		2,547,118	12	8.97×10^7	N = 1240
tgb	Between	72,421.53	457,291.9	37.258	2,892,227	N = 40
	Within		2,506,711	−2,819,772	8.68×10^7	T = 31

Source: Authors' estimated output.

4.2. Correlation, slope heterogeneity, and CSD test results

Table 3 contains two test outputs; the upper section is the correlation outcome, and the lower area is the slope heterogeneity test. Deducible evidence from the table shows low multi-collinearity between the covariates, except between renewable and non-renewable energies. However, both energy types do not belong in the same estimated equation, nullifying their high collinearity nexus. Remarkably, the lower section of **Table 3** demonstrates the validity of slope heterogeneity for the study variables.

Captured in **Table 4** are the four CSD tests applied in this research, and the output reveals the none significance of the null hypothesis of cross-sectional freedom. Hence, the acceptance of the alternative hypothesis of significant CSD in the study's panel dataset.

Table 3. Correlation matrix and heterogeneity tests.

	$lnrep$	$nrew$	rew	$lnhc$	$lntgb$
$lnrep$	1				
$nrew$	−0.097	1			
rew	0.122	−0.958	1		
$lnhc$	−0.055	0.017	−0.076	1	
$lntgb$	0.040	0.089	−0.152	0.642	1
Slope heterogeneity test					
	Equation 1		Equation 2		
Test-Statistics	Value	*P*-value	Value	*P*-value	
$\bar{\Delta}$	41.741	0.000***	41.313	0.000***	
$\bar{\Delta}_{adjusted}$	45.446	0.000***	44.979	0.000***	
H_0	Slope coefficients are homogenous.				

Source: Authors' estimated output.

Table 4. CSD test output.

Variable	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CSD
$lnrep$	12,369.06***	293.418***	292.751***	82.594***
$nrew$	5564.997***	121.149***	120.482***	15.750***
rew	5367.725***	116.154***	115.488***	14.951***
$lnhc$	21,175.82***	516.391***	515.725***	143.704***
$lntgb$	21,103.64***	514.564***	513.897***	143.529***

Note: *** indicates statistical significance at 1%. H_0: No cross-section dependence.
Source: Authors' estimated output.

4.3. Unit root and cointegration results

Table 5 presents the output for three different unit root tests capable of incorporating heterogeneity and CSD issues in panel analysis. The results show that all the variables are stationary at the first difference level.

Table 5. Unit root test output.

	First-generation unit root		**Second-generation unit root**				
Variable	**Maddala and Wu (1999)**		**Pesaran's CADF (2003)**		**Pesaran's CIPS (2007)**		
	Without trend	With trend	Without trend	With trend	Without trend	With trend	Decision
$lnrep$	67.388	103.392	−2.269***[a]	−3.183***[b]	−3.372***	−1.088	I (1)
$nrew$	86.207	39.769	−2.610***[b]	−2.936***[b]	2.465	5.435	I (1)
rew	91.790	42.217	−2.782***[b]	−3.004***[b]	3.072	3.959	I (1)
$lnhc$	130.687	49.242	−2.039**[a]	−2.591**[a]	0.500	−0.220	I (1)
$lntgb$	197.342	36.670	−7.311***[b]	−5.035***[b]	−3.820	−0.566	I (1)
H_0	Series is I (1)		Series is non-stationary		Series is I (1)		

Note: a and b represent stationarity at the level and first difference, respectively, while ** and *** indicate statistical significance at 5% and 1%, respectively.
Source: Authors' computation.

Furthermore, the Westerlund cointegration method is applied to ascertain the long-term association between the study covariates. This approach efficiently handles heterogeneity and CSD issues in panel data analysis. Consequently, in **Table 6** are the test results for the two equations, demonstrating the rejection of the null hypothesis of no cointegration association. Instead, the alternative view of the long-term covariate nexus is validated.

Table 6. Westerlund panel CSD cointegration test.

Equation 1		**Equation 2**	
Statistic	**Value**	**Statistic**	**Value**
G_t	−2.272***	G_t	−2.227***
G_a	−8.982***	G_a	−8.484***
P_t	−9.251	P_t	−9.254***
P_a	−6.631***	P_a	−5.835***
H_0:	No cointegration		

Note: *** indicates statistical significance at 1%.
Source: Authors' computation.

4.4. Panel estimated outcomes

The research presents Equations (1) and (2) outputs from the DOLS, FMOLS, and D-K estimates in **Table 7**. **Table 7** shows that the three assessments' non-renewable energy (Equation (1) result) significantly negatively affects resource productivity. In contrast, the impact of renewable energy (Equation (2) result) on resource productivity is substantial and positive in the three estimates. Human capital in both equations revealed a significant adverse effect on resource productivity, except in the D-K output, where the impact is insignificant. In contrast, technology transfer in both equations demonstrates a substantial benefit for resource productivity in the three estimates.

Table 7. DOLS, FMOLS, and D-K outputs.

	Equation 1			**Equation 2**		
Variable	PDOLS	FMOLS	D-K	PDOLS	FMOLS	D-K
$nrew$	−0.007**	−0.020*	−0.016**			
rew				0.019***	0.021*	0.020***
$lnhc$	−0.122***	−0.105***	−0.599	−1.377***	−0.101***	−0.590
$lntgb$	0.411***	0.386***	0.752***	2.147***	0.380***	0.802**

Note: *, **, and *** indicate statistical significance at 10%, 5% and 1%, respectively.
Source: Authors' Computation.

Presented in **Table 8** are the MMQREG results for Equation 1 estimates. The effect of non-renewable energy is statistically significant and adverse for resource productivity from the lower quantiles through to the 80th quantile. The magnitude impact of non-renewable energy decelerated from the lower to the middle and upper quantiles. However, in the 90th quantile, the effect turned insignificant. Likewise, the impact of human capital is statistically significant and negative from the 10th to the 80th quantiles, declining from the lower to the middle and upper quantiles, and insignificant in the 90th quantile. In contrast, technology transfer positively affects resource productivity from the lower to the 80th quantiles. However, the magnitude of its positive impact waned from the lower to the middle and upper quantiles and turned insignificant in the 90th quantile.

Table 8. Equation 1 MMQREG with FE output.

Dependent variable: $lrep$											
			Lower quantile			**Middle quantile**			**Upper quantile**		
Variable	Location	Scale	10th	20th	30th	40th	50th	60th	70th	80th	90th
$nrew$	−0.016[c]	0.010[b]	−0.026[c]	−0.024[c]	−0.023[c]	−0.022[c]	−0.021[c]	−0.020[c]	−0.019[c]	−0.016[c]	0.002
$lnhc$	−0.599[b]	0.088	−0.683[c]	−0.669[c]	−0.660[c]	−0.650[c]	−0.644[c]	−0.634[c]	−0.621[c]	−0.597[c]	−0.437
$lntgb$	0.752[c]	−0.089	0.837[c]	0.823[c]	0.813[c]	0.803[c]	0.797[c]	0.787[c]	0.774[c]	0.749[c]	0.586
$cons$	7.523[c]	1.072	6.497[c]	6.669[c]	6.789[c]	6.909[c]	6.977[c]	7.100[c]	7.257[c]	7.555[c]	9.512[c]

Note: b and c indicates statistical significance at 5% and 1%, respectively.
Source: Author's Estimated Output.

Table 9 presents the MMQREG for Equation (2) outputs. The impact of renewable energy on resource productivity is significant and positive from the lower quantiles through to the 80th higher quantile. However, its magnitude impact declined from the lower to the upper quantiles and is insignificant at the 90th quantile. In contrast, the effect of human capital is significant and negative from the 10th to the 80th quantile. Nevertheless, human capital's influence diminished from the lower quantiles to the middle and upper quantiles and was not substantial at the 90th quantile. Technology transfer significantly and positively impacts the lower to the 80th quantiles. Nevertheless, it followed a similar trend as other regressors by reducing in magnitude from the lower quantiles to the middle and upper quantiles before its insignificance at the 90th quantile.

Table 9. Equation (2) MMQREG with FE output.

Dependent variable: $lrep$											
			Lower quantile			**Middle quantile**			**Upper quantile**		
Variable	Location	Scale	10th	20th	30th	40th	50th	60th	70th	80th	90th
rew	0.020[c]	−0.011[c]	0.032[c]	0.029[c]	0.028[c]	0.027[c]	0.026[c]	0.023[c]	0.023[c]	0.020[c]	−0.0004
$lnhc$	−0.590[c]	0.066	−0.658[c]	−0.644[c]	−0.635[c]	−0.629[c]	−0.624[c]	−0.605[c]	−0.605[c]	−0.588[b]	−0.464
$lntgb$	0.802[c]	−0.056	0.859[c]	0.847[c]	0.840[c]	0.835[c]	0.830[c]	0.815[c]	0.815[c]	0.801[c]	0.696
$cons$	5.674[c]	1.895[a]	3.746[c]	4.146[c]	4.395[c]	4.556[c]	4.706[c]	5.232[c]	5.232[c]	5.718[c]	9.260[c]

Note: a, b and c indicates statistical significance at 10%, 5%, and 1%, respectively.
Source: Author's Estimated Output.

Also represented in **Figure 1** is the graphic pattern of the regressors' parameters at different quantile levels. The output mirrored the behaviour in the estimated MMQREG in **Tables 8** and **9** for all significant quantiles.

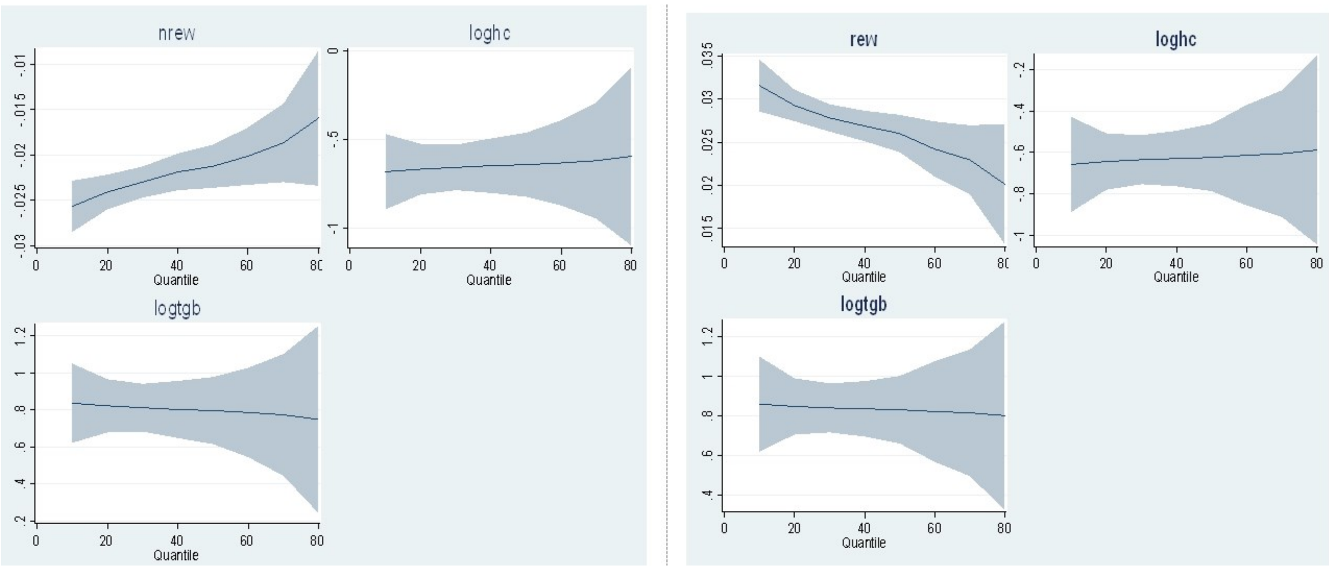

Figure 1. Graphical presentation of regressors' coefficient across quantiles for both equations.

4.5. Discussion of findings

The negative effect of non-renewable energy on resource productivity indicates the excessive depletion of natural resources for economic growth. It suggests that brown energy sources drain more natural resources to produce higher units of economic output. Furthermore, the MMQREG outcome suggest that the negative effect of non-renwable energy is more intense in developing economies with higher natural resources utilisation. For instance, China is the second largest and one of the fastest growing economies in the world. Furthermore, the country's speedy economic rise made it the largest energy consumer in the world and has enabled vast pressure on its natural wealth. A UNEP [74] report noted that China is out-running other countries in its natural resource utilisation. Also, Indonesia, Malaysia, Philippines, Thailand, and Vietnam are countries belonging to the Association of South East Asian Nations (ASEAN) that have an energy depletion rate of over 60% [75]. Their rapidly growing economies fuel the growth in brown energy demand in these ASEAN countries. In aggregate, ASEAN countries contributed about 9% of the global GDP increase between 2012 and 2022 [76]. Specifically, Indonesia, Malaysia, Philippines, Thailand, and Vietnam are at various economic transformation stages, launching them into the middle-income class. However, the reliance on fossil energy for GDP growth in these countries has continued to promote the overexploitation and degeneration of natural resources regarding land usage, water bodies, ecological and biodiversity conservation, and air quality. Ceterisparibus, the long-term effect of this poor resource management is weak resource efficiency which can stunt or retard growth in any economy.

In contrast, the MMQREG result demonstrated that the enhancing impact of renewable energy is more intense in developing economies with higher natural resources utilisation. The positive effect of renewable energy on resource productivity is plausible given that they are considered cleaner and eco-friendly ingredients of growth. Renewable energy reduces the prices of and demand for brown energy through the elevated competition since, unlike fossil energy sources that are dominantly capital and mechanised-intensive, renewable energy is highly labour-intensive. Consequently, green energy sources exert less pressure on natural resources, enabling output expansion through higher resource efficiency. For instance, solar and wind energy are un-exhaustible and require less resource intensity to convert for electricity utilisation in the production process. In the last decade, this reason has encouraged the aggressive global campaign led by the United Nations for world economies to transit to green energy sources. For instance, in its drive to maintain its dominance as a world-leading economy, China embarked on a green economic efficiency transition drive and consolidated its position in 2012 as a critical player in the renewable energy market [74].

In addition, Brazil sources over 80% of its electricity from green energy, as against the world average of 15%–27% [77]. Brazil's significant use of renewable energy gives its economy a competitive edge in producing manufactured and green goods and services in the world market through the rational utilisation of nature's wealth to create jobs and economic prosperity [77]. Also, African economies are joining the trend of exploring the potential of green energy as a sustainable approach to natural wealth conservation. Countries including Ghana, Kenya, and South Africa are some of the African economies to have implemented green energy in rational natural resource consumption in different sectors of their economies. African countries, with international bodies' aid, have been developing a national sustainable energy production and consumption policy to promote green resource efficiency [78].

Interestingly, while human capital negatively impacted resource efficiency in both equations, the MMQREG outcome further expressed that the adverse effect of human capital is more intense in developing economies with higher natural resources utilisation. Hence, this result indicates that the investments in the health and education sectors are inadequate to promote resource productivity. For instance, individuals expended an estimated annual $500 billion (i.e., $80 per person) in developing countries to access health services which is not encouraging due to poor income levels in these economies [79]. Also, a learning crisis in developing economies varies from country to country. Thus, the knowledge, experience and skill sets of labour in these developing economies are inadequate for sustainable utilisation of natural resources and are inducing a weak resource productivity level. Practices including bush burning for farming and hunting, indiscriminate falling of trees for fire-woods and charcoal, use of hazardous chemicals for fishing, etc., are still applicable in many of these countries despite their adverse effect on human health [80]. Moreover, they accelerate the challenges of resource depletion through deforestation, soil and land degradation, and pollution of water bodies and air quality. Consequently, the inadequate investment in quality healthcare and productivity driven educational curricula cannot promote efficient resource utilisation—allow rapid economic growth in these developing economies. When there is an expansion in the access to quality human capital in the areas of education, science, health, and management, there is bound to be increases in innovation, productivity, and social well-being, necessary for enhancing economic growth.

However, technology transfer shows that these developing economies have been leveraging resource-friendly production techniques to enhance resource efficiency. In addition, the MMQREG outcome revealed that the beneficial impact of technology transfer is more intense in developing countries with higher natural resources utilisation. Technology adaption by developing countries has a significant positive role in ensuring a rational consumption of natural wealth through production cost reduction, creating standards for quality, and enabling global interaction. Also, the swift pervasiveness of technology in developing countries induced by the internet increases positive cultural alterations that can promote resource efficiency for sustainable growth. Adapting resource or eco-friendly technology provides highly efficient means for saving resource utilisation by lowering reliance on fossil energy sources and enhancing sustainable business models [23].

5. Concluding remarks

This study determined the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside human capital and technology transfer roles for 40 selected developing economies. This study relied on a dataset sourced between 1991 and 2021. For inferential robustness, the FMOLS, DOLS, D-K, and MMQREG are procedures applied in the analyses. Empirically, the study revealed that an increase in brown energy consumption exhausted resource productivity from the lower to the upper quantiles. In contrast, green energy utilisation enhanced resource productivity from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy means, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, inferences from the DOLS, FMOLS, and D-K techniques revealed similar findings.

From the empirical outcomes, it is evident that although brown and green energy, human capital, and technology transfer significantly impacted resource efficiency, the size of their effects are most potent in developing economies with more intense natural resource utilisation. Furthermore, despite non-renewable energy consumption being the dominant means of energy in these developing economies, interestingly, its significant adverse impact on resource productivity falls short of the significantly increasing effect of renewable energy utilisation across all quantiles. Also, the magnitude of the negative impact of human capital on resource productivity is marginally more substantial with non-renewable energy. In contrast, the robustness of the enhancing impact of technology transfer on resource efficiency is slightly more with renewable energy.

Hence, the study recommends that since green energy is an excellent alternative to slow the over-consumption of scarce natural wealth and improve resource productivity, developing economies must concentrate more on generating renewable energy. Also, it is pertinent for energy stakeholders to advocate an increase share of green energy in output enhancement to protect the long-term resource sustainability concerns and to ensure conformity with the sustainable development goals demand. The gains of renewable energy consumption for resource productivity should spur policymakers to implement clean energy portfolios that dissuade brown energy consumption by initiating a carbon tax or emission permits and rewarding businesses adopting green energy. Furthermore, stakeholders in different countries must develop a national energy policy outlining the transition path from brown to green energy and target a low-emission energy system for conservative use of natural resources.

Governments must consolidate the blessing effect of technology and reverse the adverse impact of human capital development. First, the overly rapid preference for quantity over quality in educated graduates must change to have efficient human capital capable of reversing the negative impact on and improving resource efficiency. Furthermore, educational infrastructure needs to be enhanced, and the appropriate authorities should augment the academic curricula in line with current realities that support the sustainable use of resources for economic output. Secondly, more involvement in technology can diminish the reliance on natural wealth and promote energy efficiency in production since it is evident it enhances resource efficiency regardless of the energy type. Thus, more investment in the technological drive is encouraged to innovate new ideas instead of just adapting existing ones. Although the cost may be huge in the short run, the long-term benefits will be more overwhelming. Also, countries should pursue measures that encourage the efficient utilisation of technology at different production stages.

A constraint of this study is the inability to access a complete dataset on technological innovation for all countries used in the study. The KOF's information globalisation index adopted by the study is limited since it measures foreign technology inflows, as well as conditions that aid such transfers to the country. However, data on domestic technological innovations and patents would have been more appropriate to assess how home-grown technologies are aiding resource productivity in these developing economies. The availability of these data would have further enriched testing the findings by using alternative indicators. Nevertheless, the absence of this information does not suggest a vacuum in technological innovation in the researched nations. Consequently, future studies can explore these options.

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Appendix

Table A1. List of 40 study countries.

Algeria	Ghana	Nigeria	Slovenia
Argentina	India	Pakistan	South Africa
Bangladesh	Indonesia	Peru	South Korea
Brazil	Iran	Philippines	Thailand
Bulgaria	Iraq	Poland	Trinidad and Tobago
Chile	Kazakhstan	Qatar	Turkey
China	Kenya	Romania	Ukraine
Colombia	Malaysia	Russia	United Arab Emirate
Ecuador	Mexico	Saudi Arabia	Venezuela
Egypt	Morocco	Slovakia	Vietnam

Source: Authors' computation.