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How ICT Investment and Human Development Accelerate Renewable Energy and Environmental Progress?

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ABSTRACT

Addressing environmental challenges relies on fostering pro-environmental behavior within society. Human development and ICT investment are crucial to comprehend their roles in promoting environmentally conscious actions. In this context, the present research investigates the relationship between human development, ICT investment, and pro-environmental behavior in the context of China for the period of 1996-2020. Employing a classy nonlinear NARDL model, the study explores the asymmetric impact of human development and ICT investment on pro-environmental behavior indicators. The results show that positive changes in human development and ICT investment promote renewable energy consumption and reduce CO_2 emissions. In contrast, the negative change in the human development index does not significantly impact Renewable energy consumption, while it increases CO_2 emissions. On the other hand, the negative change in ICT investment reduces renewable energy consumption and increases CO_2 emissions. Policymakers should prioritize enhancing human development and encouraging sustainable ICT investment in China.

Keywords: Renewable Energy, Environment, ICT Investment, Human Development
JEL Classifications: O15, Q43, Q56

1. INTRODUCTION

The growing environmental apprehensions have directed firms to implement environmentally friendly activities and practices at an increasing rate, enabling those firms to become more competitive (Afsar and Umrani, 2020). Various scholars have highlighted the significant role of human development in environmental sustainability (Chams and García-Blandón, 2019). Moreover, the growing environmental issues have driven the need for human development. Human development mainly refers to such practices that enhance environmental sustainability (Mousa and Othman, 2020). Various studies have highlighted the importance of human development (e.g. Yong et al., 2020). Literature suggests a positive impact of human development on the financial performance of the organization, supply chain management, and environmental performance (Longoni et al., 2018).

Human development wields a dual influence on environmental quality, yielding both positive and negative outcomes through a network of transmission channels (Rahman and Sultana, 2024). These channels represent the intricate pathways through which human activities, policies, and practices impact the natural world. Understanding these transmission channels is pivotal in unraveling the complex relationship between human development and environmental quality. One of the most direct and potent transmission channels is resource consumption, accentuating the heightened demand for natural resources like fossil fuels, minerals, water, and land, which accompanies the imperatives of economic growth and human development (Ul-Durar et al., 2023). The extraction and utilization of these resources resonate across the environment, resulting in habitat destruction, resource depletion, and upheaval within ecosystems. Industrialization, emblematic of human progress, emerges as another significant transmission channel, serving as a source of pollution (Ullah et al., 2020). Factories and manufacturing facilities release pollutants into the air, water, and soil, culminating in environmental repercussions such as air and water quality deterioration, soil contamination, and damage to ecosystems. Urbanization and land use change materialize as key channels in the context of human development. Fueled by population growth and economic incentives, urban expansion drives the transformation of natural landscapes into urban environments (Sakketa, 2023). While this transition fuels progress, it also leads to habitat loss, deforestation, and the fragmentation of ecosystems, with far-reaching implications for both biodiversity and the quality of life in burgeoning urban areas. Climate change takes Center stage as a central transmission channel, precipitated by human activities encompassing energy production, transportation, and land use. Greenhouse gas emissions cause climate change, the foremost environmental challenge of our time, leading to rising global temperatures, frequent severe weather, higher sea levels, and significant ecological shifts (Brooke, 2014).

The realm of technological advancements and innovation embodies a dual-edged channel, capable of both exacerbating and alleviating environmental challenges (Li et al., 2013). Innovations in renewable energy, energy efficiency, and conservation technologies offer the potential to reduce the environmental footprint of human activities (Suki et al. 2022). Nevertheless, unchecked technological progress can give rise to increased resource consumption and pollution unless meticulously managed to ensure sustainability (Alok et al., 2022). Conversely, as societies develop, they tend to establish more robust regulatory frameworks and environmental policies. These policies can lead to improved waste management, emissions control, and sustainable resource management, contributing positively to environmental quality. Moreover, human development often accompanies improved education and heightened environmental awareness (Zsóka et al. 2013). Informed and engaged citizens are more likely to advocate for sustainable practices and policies, thus catalyzing positive change at both local and global levels (Laiphrakpam et al., 2019).

On the other hand, China has experienced a swift growth in internet usage. By March 2020, internet dissemination had reached 64.5% of the population, totaling 904 million users, a rate substantially higher than the global average of 9.5%. This surge in internet access, especially through mobile devices, has significantly transformed people's lifestyles in China (Cui et al. 2024). Simultaneously, China grapples with persistent environmental challenges. Acknowledging the gravity of the situation, the Chinese government, through initiatives like the 13th Five-year Plan for Eco-Environmental Protection, prioritized building an ecologically friendly society (Wan et al. 2022). Active citizen participation has been deemed crucial in addressing environmental concerns (Dong and Ullah, 2023). In this context, the intersection of ICT investment and environmental issues has emerged as a critical focus in China. Due to limited data, the link between ICT investment and pro-environmental behavior is still unclear. Given the ICT's profound impact on information acquisition, individual attitudes, social connections, and civic engagement, it is essential to explore how ICT investment influences individuals' pro-environmental behavior.

In light of the aforementioned discussion, it is evident that both human development and ICT investment play pivotal roles in shaping environmental outcomes. Despite their crucial significance, there exists a conspicuous research gap in this area. While the existing body of literature extensively explores the impact of human development on organizational progress, its influence on pro-environmental behavior remains inadequately investigated. Similarly, the current research primarily centers on the relationship between ICT development and environmental performance, neglecting a comprehensive empirical analysis of ICT investment's role in fostering pro-environmental behavior. Moreover, a notable gap persists in the simultaneous examination of human development and ICT investment joint influence on pro-environmental behavior within the context of China. Another critical limitation of existing studies lies in their reliance on outdated estimation techniques, raising questions about the accuracy and relevance of their findings. To address these gaps, our study endeavors to bridge this knowledge void. We aim to meticulously investigate the nexus between human development, ICT investment, and pro-environmental behavior in China, spanning the years from 1996 to 2020.

This study makes significant contributions on multiple fronts. Firstly, it stands as a pioneering exploration into the asymmetric effects of human development and ICT investment on pro-environmental behavior in China, representing a novel contribution to the existing body of knowledge. Secondly, our research employs two key proxy variables, renewable energy consumption (REC) and CO_2 emissions. It will establish a connection between human development, ICT investment, and environmental outcomes. Thirdly, the study utilizes an advanced estimation method, the NARDL approach, which offers a more updated and precise analysis. By employing this methodology, the research can effectively capture both positive and negative shocks in human development and ICT investment, providing a more complex perspective on their influence on pro-environmental behavior. Lastly, the findings of this study hold practical significance. By offering valuable insights into the relationship between human development, ICT investment, and pro-environmental behavior, this research provides actionable implications for both the human development and ICT sectors. These implications can inform strategies aimed at enhancing pro-environmental behavior not only in China but also in other developing economies, contributing to a more sustainable future.

2. MODEL AND METHODOLOGY

In line with the environmental literature (Zaid et al., 2018; Usman et al., 2021), to examine the relationship between pro-environmental behaviour, human development, ICT investment, financial development, and trade openness, we have the following functional form of both models:

$$REC_t = \pi_0 + \pi_1 HD_t + \pi_2 ICT_t + \pi_3 FD_t + \pi_4 Trade_t + \varepsilon_t \quad (1)$$

$$CO_{2t} = \pi_0 + \pi_1 HD_t + \pi_2 ICT_t + \pi_3 FD_t + \pi_4 Trade_t + \varepsilon_t \quad (2)$$

Eq. (1 and 2) are renewable energy consumption (REC) and CO_2 emissions (CO_2) models that depend on human development (HD), ICT investment (ICT), financial development (FD), and trade openness (Trade). Human development has the capacity to encourage the transition to a low-carbon economy, an estimate of ψ_1 should be positive in model 1 and negative in model 2. Similarly, ICT investment and financial development improve the environment by increasing REC and reducing CO_2. Finally, trade openness is a key source of carbon emissions. The basic equation offers only long-run estimates. Pesaran et al.'s (2001) ARDL method is considered to capture the short-run (SR) and long-run (LR) effects in a single step. The modified error-correction model is as follows:

$$\begin{aligned}\Delta REC_t &= \pi_0 + \sum\nolimits_{k=1}^{q} \beta_{1k} \Delta REC_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{2k} \Delta HD_{t-k} \\ &+ \sum\nolimits_{k=1}^{n} \beta_{3k} \Delta ICT_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{4k} \Delta FD_{t-k} + \\ &\sum\nolimits_{k=0}^{n} \beta_{5k} \Delta Trade_{t-k} + +\pi_1 REC_{t-1} + \pi_2 HD_{t-1} \\ &+ \pi_3 ICT_{t-1} + \pi_4 FD_{t-1} + \pi_5 Trade_{t-1} + \lambda.ECM_{t-1} + \varepsilon_t\end{aligned} \quad (3)$$

$$\begin{aligned}\Delta CO2_t &= \pi_0 + \sum\nolimits_{k=1}^{q} \beta_{1k} \Delta CO2_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{2k} \Delta HD_{t-k} \\ &+ \sum\nolimits_{k=1}^{n} \beta_{3k} \Delta ICT_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{4k} \Delta FD_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \beta_{5k} \Delta Trade_{t-k} + +\pi_1 CO2_{t-1} \\ &+ \pi_2 HD_{t-1} + \pi_3 ICT_{t-1} + \pi_4 FD_{t-1} + \\ &\pi_5 Trade_{t-1} + \lambda.ECM_{t-1} + \varepsilon_t\end{aligned} \quad (4)$$

While in Eq. (3 and 4), the LR effects are signified by ψ_1 to ψ_5. The short-run impacts are reported by the "Δ" Variables. Pesaran et al. (2001) advise two valuable tests for cointegration of concern variables' LR relationship, such as F-test and t-test. Under this method, model variables could be a blend of I(1) and I(0). This method works well in the case of small samples. This method uses a single reduced-form equation for SR and LR estimates. The key assumption behind Eq. (2) is that human resource has symmetric effects on REC and CO_2. So, Shin et al. (2014) changed the model so that we can also assess the nonlinear effects of the concern variable, that is, HD.

$$HD^+_t = \sum_{n=1}^{t} \Delta HD^+_t = \sum_{n=1}^{t} max(HD^+_t, 0) \quad (5a)$$

$$HD^-_t = \sum_{n=1}^{t} \Delta HD^-_t = \sum_{n=1}^{t} min(\Delta HD^-_t, 0) \quad (5b)$$

$$ICT^+_t = \sum_{n=1}^{t} \Delta ICT^+_t = \sum_{n=1}^{t} max(ICT^+_t, 0) \quad (5c)$$

$$ICT^-_t = \sum_{n=1}^{t} \Delta ICT^-_t = \sum_{n=1}^{t} min(\Delta ICT^-_t, 0) \quad (5d)$$

Where $HD^+_t(ICT^+_t)$ reveals the positive change in human development (ICT investment) and $HD^-_t(ICT^-_t)$ reflects the positive change in human development (ICT investment). The resulting error-correction model that accounts for nonlinear ARDL is represented as:

$$\begin{aligned}\Delta REC_t &= \pi_0 + \sum\nolimits_{k=1}^{q} \beta_{1k} \Delta REC_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{2k} \Delta HD^+_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \delta_{3k} \Delta HD^-_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{4k} \Delta ICT^+_{t-k} + \\ &\sum\nolimits_{k=0}^{n} \delta_{5k} \Delta ICT^-_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{6k} FD_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \beta_{7k} Trade_{t-k} + \pi_1 REC_{t-1} + \\ &\pi_2 HD^+_{t-1} + \pi_3 HD^-_{t-1} + \pi_4 ICT^+_{t-1} + \pi_5 ICT^-_{t-1} \\ &+ \pi_6 FD_{t-1} + \pi_7 Trade_{t-1} + \lambda.ECM_{t-1} + \varepsilon_t\end{aligned} \quad (6)$$

$$\begin{aligned}\Delta CO2_t &= \pi_0 + \sum\nolimits_{k=1}^{q} \beta_{1k} \Delta CO2_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{2k} \Delta HD^+_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \delta_{3k} \Delta HD^-_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{4k} \Delta ICT^+_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \delta_{5k} \Delta ICT^-_{t-k} + \sum\nolimits_{k=0}^{n} \beta_{6k} FD_{t-k} \\ &+ \sum\nolimits_{k=0}^{n} \beta_{7k} Trade_{t-k} + \pi_1 CO2_{t-1} + \pi_2 HD^+_{t-1} \\ &+ \pi_3 HD^-_{t-1} + \pi_4 ICT^+_{t-1} + \pi_5 ICT^-_{t-1} \\ &+ \pi_6 FD_{t-1} + \pi_7 Trade_{t-1} + +\lambda.ECM_{t-1} + \varepsilon_t\end{aligned} \quad (7)$$

Eq. (6 and 7) called it a nonlinear ARDL model, although Eq. (3 and 4) is called a linear ARDL model. Both types of models can be estimated by OLS and all extra tests are equally valid to Eq. (6 and 7), except the Wald test. The Wald test is also employed in the end for SR and LR asymmetries.

3. DATA AND DESCRIPTIVE STATISTICS

We employed two proxy variables to measure pro-environmental behaviour in this analysis, including renewable energy consumption (REC) and CO_2 emissions (CO_2) for the period of 1996-2020 in China. Renewable energy consumption (REC) is proxied by nuclear, renewable and other energy consumption collected from the EIA. On the other hand, the CO_2 emissions are represented by CO_2 emissions in metric tons per capita, and the data is collected from WDI. The major independent variables include the human development index and ICT investment. Human development index data is gathered from the UNDP. ICT investment variable is measured via total ICT investment, % share of GDP and data is collected from the WDI. Lastly, the control variables include R&D intensity, financial development, and trade openness. R&D intensity (RDI) is measured through total number of researchers in R&D per million people. Financial development (FD) is measured by domestic credit to private sector as percent of GDP. Whereas, trade openness (Trade) is measured in terms of total trade as percent of GDP. The data for these control variables are gathered from National Bureau of Statistics. For the convenience of the readers, we have provided the variables along with symbols, descriptive statistics, definitions, and sources in Table 1. The mean scores are reported as: 8.296 for REC, 5.281 for CO_2, 0.664 for HDI, 2.150 for ICT, 6.730 for RDI, 4.824 for FD, and 3.780 for Trade. The S.D scores are reported as: 6.397 for REC, 2.062 for CO_2, 0.071 for HDI, 2.386 for INT, 0.411 for RDI, 0.182 for FD, and 0.219 for Trade.

4. EMPIRICAL RESULTS AND DISCUSSION

The study examines the asymmetric impact of HD and ICT investment on REC and CO_2 using the NARDL estimation technique. For NARDL, the integration order of variables needs to be I(0) or I(1). To detect the stationarity of variables, our study has used ADF and ZA unit root tests and their respective output is presented in Table 2. The important feature of ZA test is that it identifies structural break in data series as well. The ADF test and ZA test report dissimilar outcomes. In the ADF test, REC, CO_2, HD, RDI, FD, and Trade are first difference stationary series and only ICT is level stationary series. In ZA test, REC, CO_2, RDI, FD, and Trade are stationary at the first difference and HD and ICT are stationary at level. Additionally, the ZA test reported that 2007 is a break period in REC, 2017 in CO_2, 2001 in HD, 2006 in ICT, 2009 in RDI, 2007 in FD, and 2008 in Trade. Both unit root tests confirm the feasibility of the application of NARDL approach for exploring the asymmetric nexus. One more preliminary test, i.e. BDS test is applied on data before proceeding toward NARDL estimation process. This test is applied to explore the nonlinearities among our variables. Table 3 reported the estimates of BDS test for HD and ICT variables separately. The test estimates display that the alternative hypothesis is accepted for all variables. It indicates that all the variables are nonlinear, thus confirming the suitability of the NARDL technique for estimation.

Table 4 reported the REC estimates of the NARDL model. In the LR, the results show that positive shock in HD brings a significant and positive upsurge in REC, whereas negative shock in HD produces a significant and negative impact on REC in the LR.

Table 1: Variables and results of descriptive statistics

Variable	Symbol	Mean	Median	Max	Min	S.D	Skewness	Kurtosis	Definitions	Sources
Renewable energy consumption	REC	8.296	6.292	21.26	1.802	6.397	0.672	2.048	Nuclear, renewables, and other energy consumption (quad Btu)	EIA
CO_2 emissions	CO_2	5.281	5.435	8.652	2.517	2.062	−0.135	1.503	CO_2 emissions (metric tons per capita)	WDI
Human development index	HD	0.664	0.670	0.764	0.544	0.071	−0.172	1.730	Human development index	UNDP
ICT investment	ICT	2.150	3.118	4.254	0.337	0.038	−0.091	1.208	Total ICT investment, % share of GDP	National Bureau of Statistics of China
Financial development	FD	4.824	4.813	5.209	4.494	0.182	0.350	2.340	Domestic credit to private sector (% of GDP)	WDI
R&D intensity	RDI	6.730	6.818	7.368	5.945	0.411	−0.451	2.082	Researchers in R&D (per million people)	WDI
Trade openness	Trade	3.780	3.755	4.166	3.479	0.219	0.365	1.841	Trade (% of GDP)	WDI

Table 2: Unit root test results

Variable	ADF		ZA			
	I (0)	I (1)	I (0)	Break date	I (1)	Break date
REC	0.564	−2.658*	−3.123	2013	−4.652**	2007
CO_2	0.231	−2.758*	−1.658	2002	−4.321*	2017
HD	−1.256	−2.714*	−6.325***	2001		
ICT	−3.654***		−7.536***	2006		
FD	−0.356	−3.689***	−2.542	2008	−4.325*	2007
RDI	−0.754	−4.325***	−1.689	1999	−5.689***	2009
Trade	−1.425	−4.235***	−2.321	2010	−5.758***	2008

Table 3: BDS test results

Dimension	HD				ICT			
	BDS	S.E	z-Stat	Prob.	BDS	S.E	z-Stat	Prob.
2	0.191***	0.011	17.01	0.000	0.203***	0.009	23.32	0.000
3	0.316***	0.018	17.30	0.000	0.340***	0.014	23.86	0.000
4	0.409***	0.022	18.35	0.000	0.434***	0.018	24.77	0.000
5	0.478***	0.024	20.06	0.000	0.502***	0.019	26.58	0.000
6	0.526***	0.024	22.30	0.000	0.552***	0.019	29.29	0.000

Table 4: REC results of NARDL

Variable	(1)				(2)			
	Coefficient	Std. error	t-Stat	Prob.	Coefficient	Std. error	t-Stat	Prob.
Long-run								
HDI_POS	2.298***	0.474	4.848	0.040				
HDI_NEG	1.183***	0.242	4.896	0.039				
ICT_POS					1.175***	0.282	4.159	0.001
ICT_NEG					0.848	2.806	0.302	0.766
FD	1.405*	0.749	1.876	0.202	1.039***	0.380	2.730	0.112
RDI	0.903	3.215	0.281	0.793	1.664	2.773	0.600	0.562
Trade	2.819	2.900	0.972	0.386	3.486***	0.911	3.825	0.062
Short-run								
HDI_POS	2.713***	0.909	2.986	0.041				
HDI_NEG	0.112	0.169	0.661	0.577				
ICT_POS					0.605***	0.209	2.886	0.028
ICT_POS(−1)					0.314	0.202	1.555	0.171
ICT_NEG					0.593	7.154	0.083	0.938
FD	1.183***	0.242	4.896	0.039	2.160	3.514	0.615	0.546
FD(−1)	1.393	1.322	1.053	0.352				
RDI	2.422	3.486	0.695	0.526	4.745*	2.733	1.737	0.133
RDI(−1)	2.167*	1.136	1.908	0.105	3.727**	1.600	2.330	0.059
Trade	5.890	6.063	0.971	0.386	3.626**	1.789	2.027	0.089
Trade(−1)	3.055	9.712	0.315	0.769	4.161*	2.411	1.726	0.135
C	17.70*	9.365	1.890	0.132	15.84	21.23	0.746	0.484
Diagnostics								
F-test	9.698***				10.32***			
ECM(−1)*	−0.644***	0.167	−3.850	0.003	−0.301***	0.028	−10.76	0.000
LM	0.302				1.023			
RESET	1.032				2.012			
CUSUM	S				S			
CUSUM-sq	S				S			
Wald-LR	12.02				8.652			
Wald-SR	2.218				2.356			

A 1% upsurge in positive shock of HD reports 2.298% increase in REC in the LR. However, a 1% decline in negative shock of HD reduces REC by 1.183% in the LR. This finding is supported by Sasmaz et al. (2020), who noted that higher levels of education, a key component of human development, have been linked to increased environmental awareness and pro-environmental behaviors, including the adoption of renewable energy sources. Human development enables individuals and communities to invest in renewable energy technologies. Wealthier societies have the financial means to adopt and integrate renewable energy systems. This inference is also supported by Adekoya et al. (2021). Human development also encompasses the development of institutions and governance structures. Countries with well-developed institutions are better equipped to implement policies supporting renewable energy initiatives. A high level of human development fosters innovation in renewable energy technologies, driven by educated and skilled human resources, and has a direct impact on the consumption of renewable energy.

The results also reported that positive shock in ICT brings a significant and positive increase in REC, whereas negative shock in ICT does not produce any significant impact on REC. A 1% upsurge in positive shock of ICT enhances REC by 1.175% in the LR. This result is consistent with Chang et al. (2022), who noted that ICT investment facilitates the development of smart energy technologies. This advancement leads to increased REC. ICT investment increases the demand for renewable energy in each sector of the economy. ICT investment facilitates the development of decentralized energy systems, where localized renewable energy sources. Smart meters and IoT devices enable precise monitoring and billing for energy consumption. This approach encourages the demand for energy consumption. Conversely, FD reports a significantly positive influence on REC in both models. As depicted, 1% intensification in FD enhances REC by 1.405% in model 1 and 1.039% in model 2. RDI is an important control variable in this study, but this variable fails to produce any significant influence on REC in the LR in both models. The trade variable does not report any impact on REC in model 1, but reports a significant positive impact on REC in model 2. The coefficient estimate depicts that 1% escalation in Trade enhances REC by 3.486% in the LR in Model 2.

In the short-run, the findings show that positive shock in HD brings a significant and positive increase in REC, whereas negative shock in HD produces an insignificant impact on REC in the short-run. A 1% rise in positive shock of HD reports 2.713% increase in REC in the short-run. The results also reported that positive shock in ICT brings a significant increase in REC, whereas negative shock in ICT produces an insignificant impact on REC in the short-run. A 1% rise in positive shock of ICT enhances REC by 0.605% in the short-run. Conversely, FD reports a significantly positive influence on REC in model 1. Whereas, RDI and Trade produce a significant positive impact on REC in the short-run in model 2.

Table 5 presents the CO_2 emissions estimates of NARDL model. In the LR, a positive shock in HD brings a significant and negative

Table 5: CO_2 emissions results of NARDL

Variable	(1)				(2)			
	Coefficient	Std. error	t-Stat	Prob.	Coefficient	Std. error	t-Stat	Prob.
Long-run								
HD_POS	−2.853**	1.443	−1.977	0.079				
HD_NEG	−1.499**	0.730	−2.053	0.070				
ICT_POS					−4.645***	0.761	−6.103	0.000
ICT_NEG					−4.938***	0.565	−8.738	0.000
FD	1.813**	0.732	2.476	0.035	2.948***	0.455	6.478	0.000
RDI	−0.730**	0.293	−2.491	0.034	−0.299***	0.075	−3.987	0.002
Trade	3.112***	0.470	6.623	0.000	1.419***	0.328	4.326	0.002
Short-run								
HD_POS	−1.183***	0.242	−4.896	0.039				
HD_POS(−1)	−0.501	0.491	−1.019	0.415				
HD_NEG	−0.563	0.351	−1.605	0.250				
ICT_POS					−2.088**	0.873	−2.392	0.040
ICT_POS(−1)					−0.413	0.333	−1.241	0.246
ICT_NEG					−1.940*	1.037	−1.872	0.094
FD	2.310**	1.001	2.309	0.046	1.916***	0.576	3.326	0.008
FD(−1)					0.278	0.628	0.443	0.667
RDI	0.190	0.588	0.323	0.754	0.029	0.049	0.596	0.565
RDI(−1)	0.708	0.570	1.243	0.245				
Trade	2.244**	0.877	2.558	0.031	1.121***	0.332	3.381	0.007
Trade(−1)	1.721	1.186	1.450	0.181	0.517	0.385	1.341	0.210
C	20.09***	4.910	4.093	0.003	23.64***	3.875	6.102	0.000
Diagnostics								
F-test	8.998***				15.32***			
ECM(−1)*	−0.413**	0.184	−2.241	0.052	−0.701***	0.031	−22.71	0.000
LM	2.021				1.023			
RESET	1.652				2.011			
CUSUM	S				S			
CUSUM-sq	S				S			
Wald-LR	10.32***				9.652***			
Wald-SR	5.325***				1.023			

decline in CO_2, whereas negative shock in HD produces a significant and positive impact on CO_2 in the LR. A 1% escalation in positive shock of HD reports 2.853% decline in CO_2 in the LR. However, a 1% decline in negative shock of HD enhances CO_2 by 1.499% in the LR. This result is also in line with Sezgin et al. (2021), who noted that human development reduces CO_2 emissions by increasing technological advancements and energy efficiency. Human development fosters economic diversification and innovation, contributing to structural transformation (Bedir and Yilmaz 2016). Higher human development is associated with increased investment in renewable energy sources. Developed nations invest in renewable technologies that subsequently lower CO_2 emissions. Furthermore, human development encompasses education and awareness that indirectly lower carbon emissions.

Furthermore, findings show that positive shock in ICT has a significant and negative impact on CO_2, whereas negative shock in ICT produces a significant and positive impact on CO_2. A 1% increase in positive shock of ICT reduces CO_2 by 4.645% in the LR. A 1% increase in negative shock of ICT enhances CO_2 by 4.938% in the LR. This finding is backed by Cui et al. (2023), who noted that ICT investments lead to upsurges energy-efficient technologies. Green ICT practices focus on reducing energy consumption in the information technology sector. These energy-saving initiatives translate into lower overall electricity usage, subsequently reducing CO_2 emissions. ICT infrastructure contributes significantly to environmental quality by reducing fuel consumption (Zhang and Liu 2015). Smart logistics, enabled by ICT, enhance route planning, reduce idle times, and optimize load capacities, leading to more efficient transportation. Moreover, ICT investments in e-government initiatives lead to streamlined administrative processes, reducing the need for physical paperwork. Digital document management systems and online services significantly decrease paper consumption, conserving resources and lowering carbon emissions.

Regarding control variables, FD reports a significantly positive influence on CO_2 in both models. A 1% upsurge in FD enhances CO_2 by 1.813% in model 1 and 2.948% in model 2. RDI reports a significantly negative influence on CO_2 in both models. As shown, 1% intensification in RDI declines CO_2 by 0.730% in model 1 and 0.299% in model 2. Trade also reports a significantly positive impact on CO_2 in both models. A 1% upsurge in Trade escalates CO_2 by 3.112% in model 1 and 1.419% in model 2. In the short run, a positive shock in HD brings a significant and negative reduction in CO_2, whereas a negative shock in HD produces an insignificant impact on CO_2 in the short-run. A 1% rise in positive shock of HD reports 1.183% decline in CO_2 in the short-run. However, positive shock in ICT brings a significant and negative impact on CO_2 in the short-run, whereas negative shock in ICT produces a significant and positive impact on CO_2 in the short-run. A 1% increase in positive shock of ICT reduces CO_2 by 2.088% in the short-run. A 1% increase in negative shock of ICT enhances CO_2 by 1.940% in the short-run. Regarding control variables, FD and Trade report a significantly positive influence on CO_2 in both models. In the lower panels of Tables 4 and 5, the estimates of diagnostics tests are given. The F-stat and ECM estimates (associated with negative sign) are found statistically significant, which confirms the LR cointegration among variables. Moreover, all the models are free from autocorrelation problems as depicted by LM test. The RESET and CUSUM tests confirm the models are well-specified and stable.

5. CONCLUSION AND POLICY RECOMMENDATIONS

The Industrial Revolution proved to be a turning point in transforming human society. This transformation has greatly increased the prosperity of the countries due to the sharp rise in anthropogenic activities occurring around the globe. However, the sharp increase in anthropogenic activities also turned out to be a key element in the huge carbon injection into the environment. Thus, the problem of climate change has arisen, endangering the continuation of life on Earth. Several options have been put forward to address the problem of global warming, with renewable energy development receiving widespread recognition as a key element in reducing carbon emissions and resulting global warming. Thus, empirics have put their interest in finding the factors that promote renewable energy consumption. Highly skilled and active human resources are deemed to be the nation's most vital tool in dealing with the issues of environmental degradation because such resources may encourage the use of renewable energy, which would help the countries fight the threat of environmental deterioration. Consequently, the fundamental objective of this study is to analyze the interaction between human development, ICT investment, and pro-environmental behavior in China. In addition, this analysis is based on the asymmetry assumption, which enables us to determine the effect of positive and negative fluctuations in human development and ICT investment on CO_2 and REC.

The data utilized in the investigation is a time series; accordingly, the ADF, PP, and DF-GLS tests were used to determine the stationarity of the data. These tests demonstrate that the variables selected for study are I(0) and I(1). Then, we employed the BDS test, which confirms that the series included in the analysis are non-linear. Consequently, we have employed the NARDL model, which is optimal while dealing with non-linear series as well as a mixture of I(0) and I(1) variables. The key findings of the study are as follows: (i) the positive changes in HD and ICT promote REC; (ii) the negative change in HD does not show any significant impact on REC, while the negative change in ICT reduces REC; (iii) the positive changes in HD and ICT reduce CO_2; (iv) the negative changes in HD and ICT increase CO_2; (v) the FD and Trade increase CO_2 and REC, while RDI reduces CO_2 and show no impact on REC; (vi) in the short-run results are mixed; (vii) long-run asymmetric impact is confirmed for HD and ICT in CO_2 model only.

These findings are vital in terms of policy implications. The policymakers should focus on the investment in human development by providing them with better education and health facilities that would help to develop highly efficient human resources, which are crucial for achieving sustainable development goals. Further, investing in research and development activities would help develop renewable energy technologies, which are crucial in decoupling economic growth and CO_2 emissions. Encourage ICT service providers to invest in renewable energy sources for powering data centers. Implement incentives, subsidies, or tax breaks to promote the use of solar, wind, or other green energy solutions within the ICT sector. Allocate funds for research and development in green ICT technologies. Support innovative projects focused on reducing the energy footprint of ICT infrastructure and electronic devices. Foster collaborations between public and private sectors to accelerate the development and implementation of eco-friendly solutions. Introduce a certification system for green data Centers. Companies adhering to eco-friendly practices, such as using renewable energy, energy-efficient cooling systems, and responsible e-waste disposal, could be certified. Publicize these certifications to inform consumers and businesses about environmentally responsible service providers. Invest in education and training programs for professionals in the ICT sector. Develop courses and workshops focused on green technologies, sustainable practices, and energy-efficient programming. Encourage universities and training institutes to integrate environmental consciousness into ICT-related curricula. Finally, skilled and educated human resources are crucial in promoting environmental consciousness that would reduce CO_2 emissions and increase renewable energy consumption. By implementing these policy suggestions, governments and organizations can harness the positive potential of human development and ICT for renewable energy while effectively managing and reducing their carbon footprint, thereby contributing significantly to environmental sustainability.

Though this study offers valuable insights, it has some limitations. Firstly, the study focuses on specific indicators of pro-environmental behavior such as renewable energy and CO_2 emissions, and may not encompass the entirety of environmentally conscious activities. Broader aspects of pro-environmental behavior, such as sustainable consumption patterns or waste management practices, are not explored in depth. Secondly, the findings are specific to China and may not be directly applicable to other countries or regions due to unique socio-economic, cultural, and political contexts. Future studies should expand this research to other countries or regions.

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