Exploring the Nonlinear Effects of Sustainable Energy on CO2 Emissions: The Role of Human Resources

Savitri, Dedy Ary Purnomo, Yosart Adi Suyoso, Ifan Setia Fauzi
International Trade Study Program, Universitas Bhinneka Nusantara, Malang, Indonesia

Abstract

The purpose of this research is to analyze the changing role of human resources and its impact on the relationship between sustainable energy and CO2 emissions. Several earlier studies either ignore the significance of human resources in this context or overlook the possibility of a nonlinear relationship between sustainable energy and CO2 emissions. The present research is motivated by this. This study analyzes data from 38 countries, representing both developing and developed nations, for the years 1999 to 2022, using a dynamic threshold panel data approach. The evidence suggests a correlation between increased use of sustainable energy and decreased carbon dioxide emissions. The data collected in the study show the existence of a human resources index that affects economic development. For developed economies, the threshold is 2.818, and for developing economies, it is 3.419. For the developing economies, the effect is twice as pronounced. The stronger effect is the reduction in sustainable energy CO2 emissions. The study found a strong inverse correlation between CO2 emissions and the human resources index. This study focuses on another area that is rarely discussed in the literature on Human Resource Dynamics Impact- Sustained Energy and CO2 emissions: concern and interaction. This study also examines the threshold effect and indexes of human resources and broadens the interpretation of the complex relationship between human resources and CO2 emissions from sustainable energy resources.

Keywords: CO2 Emissions, Dynamic Threshold, Human resources, Sustainable energy

INTRODUCTION

Countries are competing in a race to the bottom in natural resource extraction at the expense of the environment, driven by the goal of maximizing economic growth in a globalized, competitive world (Triatmanto, Bawono, & Wahyuni, 2023). Consequently, economic growth comes at a major environmental cost, driving several environmental crises and increasing greenhouse gas emissions (Yusuf, Abubakar, & Mamman, 2020).

Unlike other gases, although CO2 is a natural compound in the environment, when كثافته in the atmosphere is coupled with the other types of atmospheric pollution, it becomes a major contributor to the unprecedented rise in global warming, the increase in the mean and the maximum temperatures of the Earth and the world's oceans (Ainsworth, Lemonnier, & Wedow, 2020).

The current year, 2023, is on course to break another record as the world's hottest year, having already surpassed 2016. The average temperature is currently predicted to be 14.98 °C, which is 0.17 °C higher than in 2016. The planet's temperature has surpassed the 1.5° C increase mapped since the pre-industrial Revolution. Clearly, we must start taking the potential impacts of climate change seriously, as they will have monumental implications for the planet (and all its life forms). For civilizational life, the deteriorative effects (of the burning and disintegrating of ice on Earth) of the growing forces of natural disasters (the floods, the fires, the droughts, the storms, etc.) will have (Li, Li, & Chen, 2024; Krasnyansky, 2023). In Earth's systems of integrity, bordering on the threshold of the natural world, climate scientists have deemed it necessary to invent post-crisis conditions of a new reality that will be cruel and unpredictable. The goal is to halt the rise in global temperatures.

Reducing greenhouse gas emissions is an important action to combat climate change (Wesal, Zaman, Rubin, & Staupe-Delgado, 2024). World governments are focusing more on alternative and renewable energy sources rather than fossil fuels and their negative impacts. At the same time, there are numerous areas and countries with little to no renewable energy production (Igbinenikaro, Adekoya, & Etukudoh, 2024). There are challenges in producing and consuming renewable energy, including production costs and technology, fossil-fuel dependency, and regulations. The alternative is to go beyond human-based resources to inalienable carbon-free emissions of CO2 (Payab, Kautish, Sharma, Siddiqui, Mehta, & Siddiqui, 2023).

Technological innovators create game-changing pathways towards valuable, cost-positive elastic capture of renewable energy. The 'capital of humans' plays a key role in reducing fossil fuel reliance and emissions of CO2 by switching to more viable and renewable energy sources. Additionally, skilled in technological policy and regulations, reduce CO2 emissions and drive change by establishing the best policies and guidelines for renewable energy use. The 'capital of humans' also influences the relationship between sustainable energy and CO2 emissions (Yi & Yuan, 2023). However, CO2 is an active and reactive chemical. Policies to reduce CO2 emissions should be framed with a perspective of a 'sustainable, strategic, and long-term' horizon, as real change cannot happen in a year. Additionally, policy frameworks with an extended time horizon will have a greater impact in addressing the historical emissions legacy (Rothenberg, 2023).

The disparity between the skilled labor available and the impact of CO2 emissions from sustainable energy is of great concern. The relationship between CO2 emissions and sustainable energy is often simplified and represented in linear models that overlook intersecting nonlinear relationships. (Wang, Rehman, Fahad, & Linzhao, 2023; Madaleno & Nogueira, 2023; Lee & Zhao, 2023). Such models oversimplify the model's varying aspects. Failing to capture shifts in the dependent variable can cause estimation errors, autocorrelation, mis-specification errors, and ultimately the loss of predictive utility of the model. In particular, the main consequences are biased and skewed autocorrelation estimates and mis-specification errors. Therefore, this study takes a panel data model with dynamic shifts. Dynamic panel data models are valued by Shabani (2024) and Gao et al. (2024) because they capture the dynamic relationship of CO2 emissions and the workforce when analyzing the nonlinear relationship of sustainable energy and CO2 emissions. His analysis develops a conceptual model to understand the effects of the workforce on COP sustainability and CO2 emissions in both developed and developing countries. This study has a larger sample size than similar studies.

The presence of educated and skilled actors in sustainable energy makes their ideas about the most effective methods for advancing skills and knowledge on CO2 emissions and sustainable energy much more relevant. This is crucial to both practitioners and researchers. Human resources shape individual and collective behavior. In this regard, the researchers are the first to examine the role of human resources in green energy and CO2 emissions, and to develop education and awareness programs to promote sustainable behavior.

LITERATURE REVIEW

Advanced economies can use their superior knowledge and technology to achieve more substantial reductions in emissions. On the other hand, less developed economies do not have the capabilities to achieve similar reductions due to their limited infrastructural and educational capacity. Thus, the enhancement of education and skills has the greatest potential for human resources to affect the world environment. By improving their human resources, less developed economies can reduce their reliance on fossil fuels more rapidly and achieve a low-carbon economy. This would also help the world reduce CO2 concentrations and combat climate change (Nwokolo, Eyime, Obiwulu, & Ogbulezie, 2023).

The gap between developed and developing economies in terms of CO2 emissions and energy usage is extremely large. Developed economies have transitioned from a focus on heavy industry to one on the services sector. This transition has allowed economies to reduce their reliance on heavy industries, which are mostly responsible for a country's CO2 emissions. In addition, developed economies have benefited from advanced technology and a focus on comprehensive energy efficiency. Such advanced technologies have allowed for the maintenance and even improvement of productivity in a country while also reducing the adverse impacts of industrial production and emissions on the environment (Rehman, Alam, Ozturk, Alvarado, Murshed, Işık, & Ma, 2023). Conversely, developing economies rely more on carbon-intensive energy sources. Many of these economies are in earlier stages of industrialization and lack the resources to diversify their energy sources and shift to more sustainable ones (Wang et al., 2024).

As such, the industrialization of these countries has a greater influence on the total global CO2 emissions. The potential for greater change in many developing countries can be determined by the extent of improvements in human capital (Khan, 2020). With declining fossil fuel reserves and increasing adverse effects of climate change, the importance of low-carbon, sustainable energy is growing, and this is increasingly emphasized in policy formulation. The objectives remain the reduction of CO2 emissions and attainment of sustainability (Wen et al. 2022).

Since solar, wind, hydropower, and geothermal energy sources do not emit CO2 when generating energy, there are no CO2 emissions when utilising these sources. Therefore, CO2 emissions are considerably lower from their utilisation than from the use of fossil fuels such as natural gas, coal, and oil (Nathaniel, Yalçiner, & Bekun, 2021). Therefore, fossil fuels are produced at a relatively high cost, given their overall carbon footprint. Furthermore, they consume less overall energy, are more cost-effective, and therefore, result in lower CO2 emissions than fossil fuels (Bali Swain & Yang-Wallentin, 2020).

There have been significant advancements in sustainable energy technologies, leading to even more investment in the sector. The Author has demonstrated that these technologies can replace fossil fuels with alternative energy sources. Research indicates that CO2 emissions are further reduced when energy sources are substituted (Rehman, Alam, Ozturk, Alvarado, Murshed, Işık & Ma, 2023). Consequently, the following is assumed to hold for the first hypothesis of the study:

H1: The impact of sustainable energy on CO2 emissions.

For many countries that both produce and consume forms of sustainable energy, the still unresolved issues lie between the motivation for the preservation and protection of the natural environment and the technological, economical, and legal issues of these countries regarding the cost and reliability of sustainable energy technologies, the reliance on fossil fuels, and the lack of effective legislation (Xue, Shahbaz, Ahmed, Ahmad, & Sinha, 2022).

The extent of practitioners' knowledge and capabilities constrains both energy and sustainable energy consumption (Sulisnaningrum, Mutmainah, Bawono, & Drean, 2023). These challenges can be addressed through the involvement and training of ecologically oriented practitioners, as these individuals are believed to possess a greater understanding of the impacts and benefits of sustainable energy and conservation efforts on the environment (Neij & Nemet, 2022).

Trained and informed practitioners are envisioned to change consumers' perspectives and attitudes toward replacing conventional energy sources with sustainable energy sources and energy conservation efforts. It is expected that changes in perspective and attitudes will help considerably reduce CO_2 emissions (Khan, 2020). Razzaq, Sharif, Ahmad, and Jermsittiparsert (2021) further illustrate how technological and economic advancements make it easier to understand the drivers of carbon dioxide emissions. The endogenous growth model asserts that the increased growth of a country's human capital further develops that country's economic growth (Widarni & Bawono, 2021). Developing countries at a certain level of economic growth still have the capacity to channel a large portion of their assets into research and development. This enables such countries to adopt and utilize advanced, efficient, low-carbon technologies. Moreover, technological progress enhances human capital, thereby reducing the cost of energy supply and increasing energy availability. This ultimately increases the availability and affordability of energy to the people. This further provides the potential to make investment-grade improvements in energy supply (Sarkodie, Adams, Owusu, Leirvik, and Ozturk, 2020).

Capable lawmakers and regulators possess the potential to craft 'laws' and 'regulations' that remove barriers to sustainable energy supply. The development of Positive Policy Frameworks, which include sustainable energy absorption facilitation as a major characteristic, enhances the capacity to shape human capital to reduce CO_2 emissions (Strazzabosco, Conrad, Lant, & Kenway, 2020). The second hypothesis discussed in this study is obtained from this assertion and is:

H_2: The level of human resources investment plays a crucial role in reducing carbon dioxide emissions through the use of sustainable energy sources.

RESEARCH METHOD

Table 1. List of Countries Studied

Developing country	Developed countries
1. Algeria	1. Australia
2. Argentina	2. Belgium
3. Bangladesh	3. Canada
4. Brazil	4. Denmark
5. Bulgaria	5. France
6. China	6. Germany
7. Egypt	7. Hong Kong
8. India	8. Italy
9. Indonesia	9. Japan
10. Kazakhstan	10. Korea
11. Malaysia	11. Netherlands
12. Mexico	12. New Zealand
13. Morocco	13. Portugal
14. Philippines	14. Singapore
15. Romania	15. Spain
16. Russia	16. Sweden
17. Sri Lanka	17. Switzerland
18. Ukraine	18. United Kingdom
19. Vietnam	19. United State

Source: data processed

The study examines the relationship between sustainable energy and CO_2 emissions across 38 countries from 1999 to 2022. Researchers previously studied sustainable energy and CO_2 emissions in the same context. However, research examining the nonlinear impacts of sustainable energy on CO_2 emissions across varying levels of human capital is rather limited. This research assumes that varying levels of human capital will have a significant impact on CO_2 emissions. This assumption and the evidence were tested using a dynamic threshold panel methodology. Based on the World Bank's classifications, 38 countries were examined and grouped into 38 pairs, one developed and one developing country each, for the studied countries. All developed countries were clustered in the uppermost groups. Almost all developing countries were in the lowest group. Table 1 encompasses the 38 examined countries.

Analyzing the parameters of the development process in sustainable energy and their consequences in the economic and social realms provides a foundation for predicting changes in sustainable energy. This study focuses on the role of human capital as a resource for sustainable energy. Results emphasize the importance of sustainable energy in the restructuring of global energy systems. In addition, the research employs the Dynamic Threshold Panel Model to comprehensively redefine the interdependencies of human capital, CO2 emissions, and sustainable energy. The findings of this study will most certainly open up more creative possibilities for policymakers and other stakeholders in the development of human capital for optimal, sustainable energy. Lastly, this study is the first example to trace the relationships between sustainable energy technologies, the horizontal division of educational and training expenditures in the context of sustainable development, and tiered sustainable environmental regulatory frameworks. The findings of this research will serve as a basis for further research on this cluster of issues. The results are intended to show the system's functionality in areas of energy and sustainable development.

Table 2 briefly addresses the objective goal of the data collated in this study. The goal for this table is to serve as a quick reference indicator for the collated data. In this case, Table 2 dissects the study's collated data, clearly and succinctly articulating the findings and methodologies. For most readers, the data collated in the study will increase confidence and build trust in its findings.

Table 2. Variable Description

Variable	Description	Unit Analysis	Source
Gross domestic product	a metric used to assess a nation's economic health that counts the total amount of products and services generated over a specific time frame.	constant 2010 US$ per capita	www.worldbank.org
CO2 emissions	the quantity of carbon dioxide (CO2) emissions caused by human activity, such as burning fossil fuels that are emitted into the atmosphere.	$MtCO_2$ per capita	globalcarbonatlas.org
Sustainable energy	energy that comes from endless or renewable resources, such as the sun, wind, and water.	gigajoule per capita	www.bp.com
Fossil fuel energy	energy that results from burning fossil fuels like natural gas, coal, and oil.	gigajoule per capita	www.bp.com
Human resources index	A metric that expresses how health and education affect a nation's potential economic productivity	Index Scale	www.worldbank.org

Source: data processed

One approach to analyzing panel data models involves performing a cross-sectional dependency (CD) test. More specifically, this test determines which unit root test to conduct. The CD tests identify and assess the presence of dependence in panel data. The Pesaran test is one of the more widely used tests of cross-sectional dependency. The widespread use of the Pesaran test is due to its relatively easy use, its focus and purpose in analyses, and its convenience and efficacy in numerous research areas and disciplines for examining cross-sectional dependency. For these reasons, the Pesaran test is the most fundamental method in panel data analysis for selecting the most suitable unit root test and for determining cross-sectional dependence in panel data. The Pesaran cross-sectional dependency test data are as follows:

$$CD = \sqrt{(2T/N(N-1))}\,(\sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \hat{U}_{ik})$$

Each coefficient expresses a specific relationship among the selected variables for different countries. N presents the number of countries and T the number of periods. The null hypothesis (H0) of the Pesaran CD test assumes the presence of cross-sectional dependence. Here, we use the Im, Pesaran, and Shin single-method panel unit root test, incorporating the cross-sectional dimension.

The distinct structures of each country and their unique relationships make panel data analysis particularly difficult, as the aforementioned explains the degree of heterogeneity likely to compromise the validity and results of the analysis. Numerous models, to mention a few, have been developed to capture heterogeneity in the intercept: the random effects and fixed effects methods. These models allow the gradation of the cross-sectional unit heterogeneity. Conversely, numerous models, such as those with varying slopes, offer a degree of slope heterogeneity and have been developed to address differing relationships between the independent and dependent variables across cross-sectional units.

Especially when dealing with economic policy models, especially those of a static character, the researcher will likely encounter threshold models. In most models, exogeneity is assumed for all independent variables. However, assuming all variables are homogeneous is overly restrictive, and one is likely to encounter high endogeneity in the majority of cases encountered in practice. To address the phenomenon described above, a dynamic threshold model with an endogenous threshold variable can be beneficial.

Contributing this model to the cases we deal with will improve the reliability and applicability of the results across different cases. The following captures the assumption and subsequent proposal of a dynamic threshold panel data model containing an endogenous threshold variable:

$$y_{it} = X_{it}' \beta + (1, X_{it}')\gamma 1 I(q_{it} \leq \tau) + (1, X_{it}')\gamma 2 I(q_{it} > \tau) + \mu_i + \varepsilon_{it}$$
$$i = 1, \ldots, n;\ t = 1, \ldots, T$$

Here, it is a dependent variable. Xit may contain lagged dependent variables. The variable that denotes the threshold is qit. τ represents the threshold parameter, and β' represents the coefficient vector. The coefficients γ1 and γ2 indicate the regime values. I is a function which serves as an indicator. The two main aspects of the analysis are country effects, represented by μi, and errors, represented by εit. The first-difference method can eliminate country-specific effects.

RESULTS AND DISCUSSION

In a multi-country context, this work extends the methodologies found in the literature. It goes a step further by testing and establishing relationships that are not merely descriptive, based on economic statistics. Therefore, the consequences of this estimation test lay a strong foundation for subsequent analyses in economics, environmental sciences, and evidence-based policy-making.

This work reviews panel unit tests and estimation tests to assess the cross-sectional and time-series stability of the sample. In the subsequent study, the CD of the Pesaran test on the panel's cross-section data in Table 3 is markedly high. Some of the CDs of the Pesaran test cross-section data indicate the extent to which the cross-section of some of the variables residing in one of the panel's cross-sections affects the outcome variables of the remaining sections of the panel. The risk of the existence of undetermined cross-sectional dependence of a circular nature is also an issue that should not be overlooked, since such a situation is liable to distort the model's estimations. Furthermore, an adequate case can be made for the longrun economic modeling that is being built by the panel unit root test and, thus, by referring to the panel in question, where the stationary series, absent a unit root, exists.

Table 3. Pesaran's CD test

Variable	CD test	p-value
Gross domestic product	151.61	0.000
CO2 emissions	11.21	0.000
Sustainable energi	12.14	0.000
Fossil fuel energi	11.35	0.000
Human resources indeks	11.21	0.000

Source: data processed

For the Pesaran CD test, the null hypothesis is that there are no interactions between the variables or that the interactions are negligible. If the null hypothesis is, indeed, rejected, the opposite must be true: it must be concluded that there are interactions or that the interactions are appreciable. This study employs the cross-sectionally integrated unit root test (CIPS) to assess the stationarity of the variables. The test applies precisely to the cross-sectionally integrated unit root tests. The results of this test will ensure that the analysis yields meaningful results for the following model estimations. This research uses the CIPS and Pesaran CD tests to ensure the validity and credibility of the analysis and the proposed solutions. In the absence of the null hypothesis of the Pesaran CD test, it indicates that cross-sectional dependence (or global dependence) among the variables in the sample is evident. The test results it generates are highly significant, as they provide clues about the appropriate unit root test to use, given the results of the variable's stationarity test. Finally, the results of the CIPS test and the panel test of variable stationarity are presented in Section 4.

Table 4. Panel Unit Root Test

Variable	CIPS test	Hadri and Rao's test
Gross domestic product	-1.82	0.119***
CO2 emissions	-1.53**	0.125***
Sustainable energy	-2.12	0.149***
Fossil fuel energi	2.54**	0.129***
Human resources indeks	2.11**	0.122**

Source: data processed

Table 5. Dumitrescu-Hurlin Panel Causality Test

Hypothesis	W-stat	Zbar-stat	Conclusion
Gross domestic product → CO2 emissions	1.65	1.96	Gross domestic product ←→ CO2 emissions
CO2 emissions → Gross domestic product	2.03	2.58	
CO2 emissions → Sustainable energy	0.85	1.28	CO2 emissions ←→ Sustainable energy
Sustainable energy → CO2 emissions	1.47	1.75	
CO2 emissions → Fossil fuel energy	2.20	2.66	CO2 emissions, ←→ Fossil fuel energy
Fossil fuel energy → CO2 emissions	1.10	1.34	
CO2 emissions → Human resources indeks	1.30	1.50	CO2 emissions, ←→ Human resources index
Human resources index→ CO2 emissions	2.10	2.40	
Human resources index → Fossil fuel energi	0.95	1.20	Human resources index ←→ Fossil fuel energy
Fossil fuel energy → Human Resources indeks	1.60	1.85	
Human resources index → Sustainable energi	2.05	2.45	Human resources index ←→ Sustainable energy

Human resources index → CO2 emissions	0.98	1.22

Source: data processed

This paper presents the case for examining the qualitative aspects of the stationarity of economic time-series data before conducting any cointegration tests. Hadri and Rao Tests delve into the definitional aspects of stationarity, the presence of a structural break, and the potential impact of the structural shift on long-term phenomena. The Dumitrescu-Hurlin panel causality test enables the scientific community to analyze structural breaks in carbon and other variables. Such a test is the first in a series of steps toward creating better-guided, more rational environmental policies. The different options presented can help shape decision-makers' thinking about the need to meet carbon goals in the context of the clearly defined, ultimately dominant renewable energy market. The data in Table 4 clearly indicate that all the economic variables used in this paper (excluding GDP and renewable energy) are stationary. The Hadri-Rao test focuses on the identification and incorporation of structural breaks. The researcher presumes that the stationary nature of the variables being analyzed renders the cointegration analysis redundant, as its goal is to uncover long-term relationships. The Dumitrescu and Hurlin panel causality test marks the beginning of model construction. The results of this construction are indicated in Table 5.

Table 5 identifies additional aspects of the connection between the economy and the environment. The study hypothesized that the sustainability of policies aimed at reducing emissions relies on the ability of these policies to address the demand and supply balance of energy and the related economic growth, as well as the molding and sculpting of the human capital. The researchers addressed endogeneity by using the System Generalized Method of Moments (GMM), thereby improving the assessment of the corresponding variables. Also, the application of the SupWald tests indicates that the availability of a sustainable energy supply and the threshold level of human capital may affect CO2 emissions.

These policies, which advocate for the supply of sustainable energy and the reduction of CO2 emissions, may be attributed to the character and sustainable human resources policies. The quadruple cause-and-effect relationship among GCD (CO2 emissions), GDP, human resources (HR)/change in energy mix can be separated for 38 countries (both developed and developing), as the relationship between CO2 emissions and these economic and energy elements is bi-directional. The endogeneity of the SYS-GMM estimate has been addressed by using instrumental variables. Also, in the SupWald test, which tests whether the threshold exists, there is the assumption of a point in the relationship at which human capital is of primary importance for CO2 emissions and clean energy. The summarized results are shown in Table 6.

Table 6. Dynamic Threshold Panel Data Model Estimation

	38 countries Model 1	Developed countries Model 2	Developing counties Model 3
Threshold Variable	Human resources index	Human resources index	Human resources index
Threshold Estimate	3.339***	3.419***	2.818**
Gross domestic product	0.069**	0.159***	0.168**
CO2 emissions	0.441***	0.428***	0.339***
Sustainable energy	-0.006***	-0.018**	-0.003**
Fossil fuel energy	0.307***	0.194***	0.388***
Human resources index	-0.390***	-0.811***	-0.611**
Constant	-1.141***	-0.411***	-1.039***
Wald-test	112311.27***	29071.56***	7671.31***
Sargan teat	61.21	31.72	18.71

AR(1)	-2.521***	-2.421**	-2.049**
AR(2)	-1.238	-1.117	-0.311
SupWald Statistic	32.11***	26.21**	22.51***
Observations	874	437	437

Source: data processed

Table 6 confirms the necessity of applying nonlinear and threshold analyses to green power emissions and the CO2 analysis conducted. After evaluating both CO2 emissions and human resource data, it has been determined that the approach yields the most comprehensive and accurate CO2 emissions predictions. The use of the system's internal and generalized method of moments (SYSGMM) system approach has produced the best results, as it has resolved the endogeneity issues. There are, therefore, indivisible, distinct, and diverse relations in the level of CO2 emissions concerning the level of development on the economic growth spectrum. Consequently, it allows the formulation of CO2 emissions policies for individual countries. The study on the effects of human resources and renewable energy on CO2 emissions policies, with specificity to all countries. In the context of the Z-shaped human resources threshold in Table 6, the research examines a nonlinear relationship between green power and CO2 emissions, controlling for energy. In contrast, the linear relationship hypothesis is rejected at the 1 percent level. In that context, CO2 emissions policies are necessarily structural, and therefore, the historical data on CO2 emissions are integral to the proposed study. The dynamic threshold panel data system, the two-step system SYSGMM, is utilized to estimate Model 1 in 38 countries. In the case of Models 2 and 3, the World Bank classifications are used to describe developed and developing countries.

This approach was successful in depicting the differences between developed and developing nations. Model 1 found the 95% confidence threshold for developed nations was 3.419, and for developing nations, 2.818. It finally showed that, across all country groupings in the sample, the GDP log was positive. The increases in CO2 emissions per GDP log for developing, developed, and the whole sample were 0.069, 0.159, and 0.168%, respectively. It was shown that for every 1% increase in developing countries' GDP, CO2 emissions were expected to increase by a similar amount, implying that the target was achievable for each country. It showed that the balance was achieved in developing human resources. To achieve the goal, the preparation and education of the labor force are necessary to realize the full potential of the clean and renewable energy sources available. It showed that to tackle the problem of climate change, developing the economy alongside the social and environmental (subsidiary to the earth) systems is the primary solution.

All three models state that an increase in fossil fuel consumption through energy use, alongside an increase in CO2 emissions, will be in the range of 0.441%, 0.428%, and 0.339% for industrialized nations, developing nations, and the entire sample, respectively. Supporting the continued and increasing production of CO2 emissions from the use of fossil fuels is matched by the demand for fossil fuels across the sample of nations. The models also suggest that a 1% increase in the availability of human resources will reduce CO2 emissions related to industrial development by 0.811% in the industrialized world and 0.611% in the developing world. The models state that for the industrialized and developing worlds, a 1% increase in CO2 will increase cross-national CO2 emissions by 0.441%, with 0.428% from the developed world and 0.339% from the developing world.

At the 1% significance level, for the 38 countries defined by a threshold impact on the variable human resources (Staffing/administration), Table 6 outlines the effects on CO2 emissions reductions from the use of sustainable energy. With human resources below 3.339, increasing sustainable energy led to a 0.006% decrease in CO2 emissions, with a 1% decrease statistically significant and presumed to be negative. Relatively, with human resources above

3.339, a 1% increase in sustainable energy was likely to reduce CO2 emissions by 0.003%. In this instance, human resources were a catalyst for the acceptance and use of sustainable energy. This means from an investment perspective, R&D may be justifiable on a two-fold basis. In this regard, the findings supported the study's two hypotheses.

Table 6 depicts the relationship among sustainable energy, the threshold impact of CO2, and human capital in developed countries. For example, in developed countries, if human capital exceeds 3.339, then increasing sustainable energy by 1% results in a 0.018% reduction in CO2 emissions. If human capital is below 3.339, the reduction in CO2 emissions is 0.003%. Therefore, it is logical to say that if human capital is greater than 3.339, the impact of choosing sustainable energy is, in this case, three times greater in reducing CO2 emissions than at the human capital threshold of 3.339. In Table 6, particularly in countries with limited resources, investing time and money in developing human capital and human resources in education and training will enhance the impact of sustainable energy initiatives on the environment. Countries with greater resources have managed to reduce their dependence on fossil fuels as they rapidly diversify their economies with low-carbon solutions. The same study shows that when human resources are below the 2.818 threshold, a 1% increase in sustainable energy consumption is linked to a 0.003% decline in CO2 emissions. The research demonstrates that, in developing countries, investment in human resources is important for modern sustainable energy technologies, as they have the potential to reduce CO2 emissions and help achieve a safe global environment. This is evidenced by the development of human resources at a rate of more than 2,081 more efficient personnel who have been shown to impact the sustainable energy of CO2 emissions to a percent decrease in the range of more than double, from 0.03% to 0.06%.

Furthermore, the results from the residual serial correlation tests (AR(1) and AR(2)) and the Sargan test provide additional evidence of the model's reliability. For Models 1, 2, and 3, the Sargan test's p-value exceeds 1%, signaling the model's instrumental variable strength. Finally, the p-values of the AR(1) and AR(2) tests, which demonstrate first-order and second-order serial correlation, respectively, confirm that the model is resilient to specification errors.

Table 6 guides both advanced and developing countries in their CO2 reduction strategies by prioritizing financing for the development of Human Resources. This study corroborates the previously established literature of Sulisnaningrum, Mutmainah, Bawono, and Drean (2023) and Wen, Okolo, Ugwuoke, and Kolani (2022), indicating the need for developing the educational and human resource infrastructure for the adoption and deployment of sustainable energy technologies and sustainable practices. It supports the development of policy frameworks that enhance the effectiveness of sustainable energy adopted practices to mitigate CO2 (Nathaniel, Yalçiner, and Bekun, 2021). The results also indicate that a balanced approach from policymakers is essential, systematically integrating human development, economic growth, and environmental protection to achieve sustainable development. Analysts recognize that, in the quest for sustainable global economic growth, the increasing loss of the world's productive capacity must be prioritized (Xue, Shahbaz, Ahmed, Ahmad, and Sinha, 2022). The human resource threshold is 3.419 for developed economies and 2.818 for underdeveloped economies. The gap is attributed to the developed economies' sophisticated educational systems and human resource infrastructure. It may also be the reason developed economies are more resource-intensive in achieving a balance in CO2 emission reductions, as developing economies have less resource-intensive, fossil-fuel-based technologies with a lower threshold value. In addition, the study finds a positive relationship between a country's Gross Domestic Product and CO2 emissions. This means policymakers must refocus their growth-related strategies to eliminate the current imbalance, which puts the environment at the expense of growth. Policymakers increasingly need to adopt strategies that facilitate sustainable and equitable economic growth.

Table 6 supports the argument for individualized strategies to reduce CO2 emissions in undeveloped countries. More financing for clean technologies will alleviate environmental impacts through economic growth. The results of this study also align with those of Neij and Nemet (2022). Neij and Nemet also argue that education and training in green technologies and sustainable practices will aid the transition to a low-carbon economy; therefore, the imperative for developing countries is to articulate a sustainable economic growth strategy. It will become possible for developing countries to grow their economies sustainably and effectively manage global climate change challenges. The study in Table 6 substantiates the role of human resources in developing countries in achieving reductions in CO2 emissions. Moreover, it was found that in developing countries, at a human resources level of 2.818 or below, a 1% increase in the use of Renewable Energy Sources (RES) results in a mere 0.003% decline in CO2 emissions. However, when the human resources level is 2.081 or higher, a 1% increase in the use of RES yields a 0.06% (six times greater) reduction in CO2 emissions. The development of human resources almost doubles the potential for growth in the use of RES to improve CO2 emissions.

The model's validity is supported by the Sargan test and AR(1) and AR(2) tests for serial correlation in the residuals. The Sargan tests for Models 1, 2, and 3 show p-values above 1%, indicating the instruments are valid. The confidence in the presence of first-order serial correlation, but not second-order serial correlation, is strengthened by the p-values in the AR(1) and AR(2) tests.

The disparity in developed and developing countries' threshold values for human resources reveals differences in the quality of education, infrastructure for human resources, technological resources, and sustainable energy sources. Countries classified as developed have a threshold value of 3.419, indicating that for notable changes in CO2 emissions, a higher level of human resources is required. Conversely, developing countries are classified with a threshold value of 2.818, and given their lower levels of technological resources, a lower degree of human resources is required. Developing countries require a threshold value of human resources. In the context of the environment and economic growth, emphasis should be placed on balancing human development vis-à-vis CO2 emissions and economic growth. Human resources development is required in developing countries, while developed countries require a threshold for CO2 emissions.

Every country aims to conserve resources destroyed during the growth process while restoring the environment. Developed countries lead in mitigating the damaging impact of the workforce on industrial emissions. Consequently, developing countries should not be disregarded in the scope of the industrial emissions. Harmful impacts of the workforce on CO2 emissions in industries of developed and developing countries. In developed countries, a higher workforce coefficient indicates a better-developed, educated, and trained workforce, with the ability to understand and apply solutions and technologies in sustainability and energy conservation. These positions have developed countries at the forefront of developing and implementing new methodologies and technologies to reduce environmental impacts. For developing countries, poor-quality education, limited technology, and limited resources are their primary challenges. As a result, these countries are not in a position to optimally harness the workforce to reduce CO2 emissions.

According to research, first-world countries can reduce emissions more than developing countries because of their infrastructures and educational systems (Nwokolo, Eyime, Obiwulu, & Ogbulezie, 2023). Developing countries' human resources are already making a positive impact on the global environment, and this impact will likely grow as more resources are allocated to education and skill development. This is equally true for developing countries, as improving their human resources can curtail fossil fuel use, further accelerate the horizontal shift towards lower-carbon economies, and reduce climate change. Ultimately, more emerging countries will further improve efforts to reduce CO2 emissions and mitigate the effects of climate change. Uhde & Luth (2022) support the argument by claiming that developed countries have higher energy and CO2 emissions than those of developing countries.

The contrast between developed and developing countries in terms of CO2 emissions and energy use is more pronounced than ever. The developed economies have transitioned from economies with high levels of CO2 (and emissions) to those with low emissions, primarily by shifting the economy to the services sector. In developing countries, greater industrialization was possible due to ownership of advanced technologies and the adoption of energy-efficient technologies. Advances in technology have greatly increased nations' productivity, reducing the impacts of industrialization by decoupling industrial activities from CO2 emissions (Rehman, Alam, Ozturk, Alvarado, Murshed, Işık, & Ma, 2023).

Countries with high levels of human-given carbon energy systems tend to show high levels of human-given carbon energy systems. Nations with only short-term levels of industrialization tend to show low levels of industrialization in energy systems and modernization (Wang et al., 2024), resulting in high levels of CO2 emissions. Upgrading to training systems, transferring, and optimizing are promising approaches to achieving higher levels of CO2 reduction in low-income and developing countries (Khan, 2020). It is said to show that new levels of training and higher levels of human-given CO2 have a significant impact on energy and CO2. It has been shown that in many developed countries, new levels of training and higher levels of CO2 improvement have shown a significant impact. It is also the case in developing countries. It is therefore recommended that, in developing countries, training and the impact of PD be significant enough to meet high training budgets. Global policymakers should focus on significantly improving PD to achieve higher training budgets. Developing countries use carbon-emitting technologies more heavily. These have fewer options to adopt less polluting technologies because they are in the early phases of industrialization. If individuals have highly developed formal education and experience significant improvement in their environmental literacy, they will surely be able to help resolve our climate challenges in a meaningful way. For developing countries, improving their citizens' human capital is critical for bridging development and economic gaps with wealthier nations while also achieving environmental sustainability. Developing countries will only be able to achieve their economic and environmental growth and sustainability goals in an R&D-driven manner by improving policy options and opening their economies without harming the environment.

CONCLUSION

Investments in sustainable energy can reduce CO2 concentration over time. This paper looks at this relationship, focusing on sustainable energy and the human resources available. The levels of human resources, country, and country development are all used here as examples. Developed countries exceed 3.419 in this potential relationship, while developing countries only reach 2.818. Concentrating resources on training and educating human resources builds a potential, sustainable relationship for CO2-decreasingfor reducing CO2. In developing countries, the authors say the only sustainable CO2-reducing relationship is for developed countries to fund developed university systems to help developing countries adopt best practices for new sustainable energy. Developed/developing countries are funding a relationship to help developing countries adopt best practices for new sustainable energy to address the only opportunity left in the developing world amid climate challenges.

The research emphasizes the significance of sustainable energy in reducing the impact of climate change and CO2 emissions. To maximize the use of sustainable energy, governments around the world must implement measures, such as tax incentives and subsidies, to encourage households, businesses, and industries to adopt green energy. Moreover, the foremost priority in adopting sustainable energy is economic affordability. In addition, investing in stable, low-risk assets encourages the private sector to invest in sustainable energy. The research focuses on improving workforce quality to support the deployment of sustainable energy and the achievement of reduced CO2 emissions. Improved quality of higher education, research, and development may support the enhanced deployment and adoption of sustainable energy. Additionally, to realize the tech potential for CO2 emissions reduction, greater government support for education and skill development is required. The rising cost of fossil fuels underscores the need to increase the industry’s energy efficiency and reduce energy losses during the production, transportation, and distribution of fuels. Governments must design policies that steer industries away from relying on fossil fuels and towards adopting sustainable energy. In addition, countries will need to change their processes to achieve a sustainable balance in decreasing their reliance on fossil fuels and transitioning to renewable energy.

It is the primary responsibility of developed countries to contribute in this way. Investments can be made to foster collaboration and sustainable energy, and to provide and maintain the technological and financial support to construct and maintain sustainable cities. Support can be given to the development of advanced clean technology, total energy, and sustainable improvements across all sectors and subsectors of industry and manufacturing practices. The implementation of any one of these sustainable practices will assist in framing how to tackle mitigation and in partnering in the management of the reduction and the preparation to combat climate change on the international front at all levels. Developed countries will also be required to continue implementing all these policies. What contributes to greater environmental protection is the involvement of all industries and commerce in all countries, in all areas, and at all times. The developed countries will also be required to participate in this.

This research on sustainable energy sources and CO2 emissions yielded some positive results, but numerous obstacles emerged during the process. The data examined 38 countries, which is a small number, so the analysis may not be the most representative. Additionally, the numerous significant variables examined were unlikely to reflect the study's outcomes, as there was no significant data to explain them. The 23-year limitation of the study is also a noteworthy obstacle. Data availability beyond 2022 has also made this a challenge. Important and unsophisticated variables have also been ignored. We suggest that future studies increase the time span and use more recent data to capture the impact of the relationship between CO2 emissions and sustainable energy.

Such studies will give a more detailed analysis of both developed and developing countries, which is vital to considering different economic and environmental frameworks. Our study examined the impacts of sustainable energy on CO2 emissions, but did not consider many variables, many of which could be indicative of the relationship between CO2 emissions and sustainable energy.

Unexplored aspects include dimensions of government policy, the environment, social, economic, and technological systems, and other forms of causal complexity that could offer great insights. Research, therefore, should continue to include all aspects mentioned to achieve a more comprehensive view of the phenomenon. Thorough and detailed analyses ought to help stakeholders and policymakers develop novel practices to increase the use of sustainable energy and reduce carbon dioxide emissions.

REFERENCES

Ainsworth, E. A., Lemonnier, P., & Wedow, J. M. (2020). The influence of rising tropospheric carbon dioxide and ozone on plant productivity. Plant Biology, 22(1), 5-11.

Bali Swain, R., & Yang-Wallentin, F. (2020). Achieving sustainable development goals: predicaments and strategies. International Journal of Sustainable Development & World Ecology, 27(2), 96-106.

Espoir, D. K., Sunge, R., & Bannor, F. (2023). Economic growth, renewable and nonrenewable electricity consumption: Fresh evidence from a panel sample of African countries. Energy Nexus, 9(1), 1-10.

Gao, S., Jiang, J., Zhu, S., Aslam, B., & Wang, W. (2024). Nonlinear influence of per capita carbon emissions, newborn birth rate, sustainable energy, industrialization, and economic growth on urbanization: New evidence from panel threshold model. Energy Strategy Reviews, 51(1), 1-10.

Igbinenikaro, O. P., Adekoya, O. O., & Etukudoh, E. A. (2024). Conceptualizing sustainable offshore operations: integration of sustainable energy systems. International Journal of Frontiers in Science and Technology Research, 6(2), 031-043.

Khan, M. (2020). CO2 emissions and sustainable economic development: New evidence on the role of human resources. Sustainable Development, 28(5), 1279-1288.

Khezri, M., Mamkhezri, J., & Heshmati, A. (2024). Exploring nonlinear causal nexus between economic growth and energy consumption across various R&D regimes: Cross-country evidence from a PSTR model. Energy Economics, 133(1), 1-10.

Krasnyansky, M. (2023). Alarm: Mankind is Not Ready for Inevitable Global Climate Change. International Journal of Environment, Agriculture and Biotechnology, 8(1), 091-105.

Lee, C. C., & Zhao, Y. N. (2023). Heterogeneity analysis of factors influencing CO2 emissions: the role of human resources, urbanization, and FDI. Renewable and Sustainable Energy Reviews, 185(1), 1-10.

Li, Z., Li, Q., & Chen, T. (2024). Record-breaking high-temperature outlook for 2023: An assessment based on the China global merged temperature (cost) dataset. Advances in Atmospheric Sciences, 41(2), 369-376.

Lusompa, A. (2023). Local projections, autocorrelation, and efficiency. Quantitative Economics, 14(4), 1199-1220.

Madaleno, M., & Nogueira, M. C. (2023). How sustainable energy and CO2 emissions contribute to economic growth, and sustainability—an extensive analysis. Sustainability, 15(5), 1-10.

McKitrick, R. (2024). Total least squares bias in climate fingerprinting regressions with heterogeneous noise variances and correlated explanatory variables. Environmetrics, 35(2), 1-10.

Nathaniel, S. P., Yalçiner, K., & Bekun, F. V. (2021). Assessing the environmental sustainability corridor: Linking natural resources, sustainable energy, human resources, and ecological footprint in BRICS. Resources Policy, 70(1), 1-10.

Neij, L., & Nemet, G. (2022). Accelerating the low-carbon transition will require policy to enhance local learning. Energy Policy, 167(1), 1-10.

Nwokolo, S. C., Eyime, E. E., Obiwulu, A. U., & Ogbulezie, J. C. (2023). Africa's Path to Sustainability: Harnessing Technology, Policy, and Collaboration. Trends in Sustainable Energy, 10(1), 98-131.

Payab, A. H., Kautish, P., Sharma, R., Siddiqui, A., Mehta, A., & Siddiqui, M. (2023). Does human resources complement sustainable development goals? Evidence from leading carbon emitter countries. Utilities Policy, 81(1), 1-10.

Razzaq, A., Sharif, A., Ahmad, P., & Jermsittiparsert, K. (2021). Asymmetric role of tourism development and technology innovation on carbon dioxide emission reduction in the Chinese economy: Fresh insights from QARDL approach. Sustainable Development, 29(1), 176-193.

Rehman, A., Alam, M. M., Ozturk, I., Alvarado, R., Murshed, M., Işık, C., & Ma, H. (2023). Globalization and sustainable energy use: How are they contributing to the upsurge in CO2 emissions? A global perspective. Environmental Science and Pollution Research, 30(4), 9699-9712.

Rothenberg, G. (2023). A realistic look at CO2 emissions, climate change and the role of sustainable chemistry. Sustainable Chemistry for Climate Action, 2(1), 1-10.

Sarkodie, S. A., Adams, S., Owusu, P. A., Leirvik, T., & Ozturk, I. (2020). Mitigating degradation and emissions in China: the role of environmental sustainability, human resources and sustainable energy. Science of the Total Environment, 719(1), 1-10.

Shabani, Z. D. (2024). Sustainable energy and CO2 emissions: Does human resources matter? Energy Reports, 11(1), 3474-3491.

Strazzabosco, A., Conrad, S. A., Lant, P. A., & Kenway, S. J. (2020). Expert opinion on influential factors driving sustainable energy adoption in the water industry. Sustainable energy, 162(1), 754-765.

Sulisnaningrum, E., Mutmainah, S., Bawono, S., & Drean, B. (2023). Investigating The Impact of ICT Developments on the Environment in the Digital Economy and Green Economy in Southeast Asia. International Journal of Professional Business Review: Int. J. Prof. Bus. Rev., 8(5), 10.

Triatmanto, B., Bawono, S., & Wahyuni, N. (2023). The contribution and influence of total external debt, FDI, and HCI on economic growth in Indonesia, Thailand, Vietnam, and the Philippines. Research in Globalization, 7(1), 1-10

Wang, J., Shan, Y., Cui, C., Zhao, C., Meng, J., & Wang, S. (2024). Investigating the fast energy-related carbon emissions growth in African countries and its drivers. Applied Energy, 357(1), 1-10.

Wang, K., Rehman, M. A., Fahad, S., & Linzhao, Z. (2023). Unleashing the influence of natural resources, sustainable energy and human resources on consumption-based carbon emissions in G-7 Countries. Resources Policy, 81(1), 1-10.

Wen, J., Okolo, C. V., Ugwuoke, I. C., & Kolani, K. (2022). Research on influencing factors of sustainable energy, energy efficiency, and technological innovation. Does trade, investment and human resources development matter? Energy Policy, 160(1), 1-10.

Wesal Zaman, A., Rubin, O., & Staupe-Delgado, R. (2024). The challenges experts face during creeping crises: the curse of complacency. Policy & Politics, 52(1), 131-152.

Widarni, E. L., & Bawono, S. (2021). Human Resources, Technology, and Economic Growth: A Case Study of Indonesia. The Journal of Asian Finance, Economics and Business, 8(5), 29-35.

Xue, C., Shahbaz, M., Ahmed, Z., Ahmad, M., & Sinha, A. (2022). Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? Sustainable energy, 184, 899-907.

Yang, C., & Song, X. (2023). Assessing the determinants of sustainable energy and energy efficiency on technological innovation: Role of human resources development and investment. Environmental Science & Pollution Research, 30(13),1-10

Yi, H., & Yuan, M. (2023). Policy advocacy, network formation and network governance. Chinese Public Administration Review, 14(2), 83-93.

Yusuf, A. M., Abubakar, A. B., & Mamman, S. O. (2020). Relationship between greenhouse gas emission, energy consumption, and economic growth: evidence from some selected oil-producing African countries. Environmental science and pollution research, 27(13), 15815-15823.