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ROLE OF TECHNOLOGY AND HUMAN CAPITAL IN THE DEVELOPMENT OF RENEWABLE ENERGY

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Abstract

The main aim of this study is to explore the role of technology and human capital in the development of renewable energy. The study used time series data from Pakistan spanning from 2005 to 2022 and employs Ordinary Least Squares (OLS) and Granger Causality tests for estimations. The estimation results of OLS reveal that human capital and technology innovation have a positive and significant impact on renewable energy development in Pakistan. Based on these findings, we suggest that the government should prioritize investments in education and training programs to build a skilled workforce in renewable energy and related technologies, offering incentives for students to pursue relevant studies and supporting for research and development in renewable energy technologies and encouraging collaboration among academia, industry, government and global organizations.

Keywords: Human Capital; Technology; Renewable Energy; Sustainability.

Type of study: Original research Article

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1.Introduction

Renewable energy production is of paramount importance in addressing the global challenges of climate change and environmental degradation. Unlike fossil fuels, which contribute significantly to greenhouse gas emissions and air pollution, renewable energy sources such as solar, wind, hydro, and geothermal power offer a cleaner and more sustainable alternative. The reduction of carbon dioxide emissions from burning fossil fuels is crucial for mitigating the adverse effects of climate change, such as rising temperatures, extreme weather events, and disruptions to ecosystems (Asghar et al., 2022). Another key aspect of renewable energy lies in its potential to enhance energy security. Unlike finite fossil fuel reserves, renewable resources are essentially inexhaustible and can be harnessed locally, reducing dependence on foreign energy sources. This decentralization of energy production contributes to a more resilient and reliable energy infrastructure, mitigating the risks associated with geopolitical tensions and fluctuations in fossil fuel prices (Lee et al., 2022). Furthermore, the development of renewable energy technologies fosters economic growth and job creation. The renewable energy sector has witnessed substantial advancements, leading to increased investments and the establishment of new industries. The transition to renewable energy creates a demand for skilled workers, ranging from engineers and technicians to researchers and project developers. This not only stimulates economic activity but also positions countries at the forefront of a rapidly evolving global industry (Jahanger et al., 2023). In addition to economic benefits, the deployment of renewable energy systems helps diversify the energy mix, reducing the environmental impact associated with resource extraction and combustion of fossil fuels. By harnessing energy from sources like sunlight, wind, and water, societies can minimize their ecological footprint, preserve biodiversity, and protect natural habitats. This shift towards cleaner energy aligns with the principles of sustainable development, ensuring that present and future generations have access to the resources they need without compromising the health of the planet (Ostergaard et al., 2022). In short, the importance of renewable energy production cannot be overstated especially the developing country like Pakistan. It is a critical component of a sustainable and resilient energy future, addressing the urgent need to mitigate climate change, enhance energy security, stimulate economic development, and protect the environment. As technology continues to advance and economies transition towards cleaner energy sources, the global community can look forward to a more sustainable and harmonious relationship with the planet (Dinçer et al., 2023).

1.2 Types of Renewable Energy Recourses:

There are four types of resources that are renewable, non-renewable energy, extrinsic and continuous resources

- Solar Energy
- Wind Energy
- Thermal Energy
- Geothermal Energy
- Ocean Energy
- Bio Energy

2. Literature Review

The literature review encompasses several studies that contribute valuable insights into the dynamics of renewable energy, energy consumption, human capital, and technological innovation within the context of Pakistan. Zaigham and Nayyar (2005) underscore the reliance on imports due to the deficit and the lack of electrification in rural areas. The study highlights the untapped potential of diverse renewable energy sources and the need for technology advancement to address the deficit and promote a cleaner environment. Sharif's (2005) study focuses on diminishing conventional energy reservoirs and escalating prices, advocating for a shift to renewable energy. Asif (2009) discusses technology's role in efficient renewable energy management, job creation, and global partnerships. Amer and Daim's (2011) AHP model prioritizes renewable energy technologies, offering insights for long-term energy policies. Awan and Khan (2014) stress the vital role of energy in economic development and propose harnessing renewable sources to address the energy crisis. Doytch and Narayan (2016) analyze the relationship between Foreign Direct Investment and renewable energy, revealing nuanced effects on consumption. Wang et al. (2018) link human development, income levels, and renewable energy adoption, contributing valuable insights to sustainable development discourse. Fatima et al. (2019) explores the bidirectional causal relationship between human capital, renewable energy generation, and economic performance, emphasizing the interconnectedness of these factors in shaping government strategies. Li et al. (2019) focus on dynamic interactions among renewable energy production, energy consumption, and human capital, revealing bidirectional causal relationships. Bamati and Raoofi (2020) examine factors influencing renewable energy production, emphasizing differences between developed and developing countries. Khan et al. (2020) explores innovation and human capital's impact on renewable energy consumption, advocating for investment in human capital and regulatory policies. Mubarik and Naghavi (2020) investigate the role of human capital in promoting energy efficiency and green energy adoption in the manufacturing sector. Raza et al. (2020) discusses renewable energy technology, emphasizing the need for governmental intervention in rural areas. Khan et al. (2021) analyzes short and long-term effects of technological innovation, finance, and FDI on renewable energy, recommending a focus on R&D investments. Chien et al. (2021) highlights technological innovation's positive correlation with renewable energy and its negative correlation with environmental degradation. Ali et al. (2021) emphasizes the role of green technology strategies in the sustainable development of solar power projects in Pakistan. Hashemizadeh et al. (2021) explore the inverse correlation between public debt and renewable energy consumption. Kang et al. (2021) reveal an adverse nexus between FDI and renewable energy in South Asian countries. Esquivias et al. (2022) discuss the impact of technological innovation, human capital, and renewable energy on environmental quality in Asian emerging economies. Ahmad et al. (2022) stresses the economic advantages and job creation potential of integrating renewable energy sources in Pakistan. Zhou and Li (2022) explore the role of human capital in the relationship between trade liberalization and renewable energy. Jianhua (2022) assesses the impact of public debt on renewable energy consumption across Asian economies. . Hussain et al. (2023) argue for robust investment in human capital as a key factor in enhancing renewable energy production in Pakistan, emphasizing the synergy between human capital development and sustainable energy initiatives.

Based on the above reviewed literature and objectives of study the following, hypotheses of study have been developed:

H_0: There is no significant impact of human capital on the development of renewable energy in Pakistan.

H_1: There is a significant positive impact of human capital on the development of renewable energy in Pakistan.

H_0: There is no significant impact of technology advancement on the development of renewable energy in Pakistan.

H_1: There is a significant positive impact of technology advancement on the development of renewable energy in Pakistan.

These hypotheses set the stage for empirical research to either accept or reject the null hypothesis based on the data collected and analyzed. If evidence supports the alternative hypothesis, it suggests a meaningful relationship between the variables in question.

3. Data and methodology:

Research study is based on the impact of renewable energy on economic growth in Pakistan for a period of 2005 to 2022. Renewable energy is taken as dependent variable and the explanatory variables are as follows Foreign Direct Investment, Human Capital, Technology, Public Debt, Population Growth as a proxy for renewable energy. All the economic variable are taken as annual growth percentage. A time series data of all economic variables is taken from the economic survey of Pakistan, State bank of Pakistan and World Bank of Pakistan. Table 1 shows the detail of variables.

Table 1:

Description of dependent and independent variables.

Variables	**Description of the Variables**	**Measurement**
Dependent Variable		Annual Growth (%)
Re	Renewable Energy	Annual Growth (%)
Independent variable		Annual Growth (%)
FDI	Foreign Direct Investment	Annual Growth (%)
HCAP	Human Capital	Annual Growth (%)
TECH	Technology	Annual Growth (%)
POP	Population Growth	Annual Growth (%)
DEBT	Public Debt	Annual Growth (%)

3.1 Selected Variables:

The description of dependent and independent variables is given below: -

3.1.1 Renewable Energy:

Renewable energy is the dependent variable. Renewable energy is energy obtained from resources that refill themselves instinctively on a human timescale and are virtually limitless in the long run. Sunlight, wind, rain, waves, geothermal heat, and biomass are common examples of these sources. Renewable energy is regarded more sustainable than non-renewable energy sources such as fossil fuels (coal, oil, and natural gas) since its use does not exhaust the Earth's finite resources and has a lesser environmental impact in terms of greenhouse gas emissions. Renewable energy is critical to worldwide efforts to combat climate change, reduce reliance on fossil fuels, and establish a more environmentally sustainable energy future.

3.1.2 Human Capital:

Human capital is defined as an individual's stock of knowledge, skills, abilities, experience, and other characters that contribute to their productivity and economic value. It refers to the intangible assets embedded in people as a result of education, training, and job experience, which improve their ability to perform tasks and contribute to economic activity. Human capital is an important aspect in economic development and progress, as well as in societal improvement. It highlights the notion that investing in education, training, and healthcare may lead to improved productivity and innovation, benefiting both individuals and the economy as a whole.

3.1.3 Technology:

It refers to "high-technology exports," which are products with a high level of R&D intensity. These products often use innovative technologies and innovation in their design, manufacture, and functionality. Aerospace products (such as aircraft and spacecraft), computers and related equipment, pharmaceuticals, scientific instruments, and electrical machinery are all examples of high-technology exports. The data presented are in current US dollars, meaning that the figures indicate the monetary worth of these high-technology exports at the time of measurement without adjusting for inflation. Monitoring high-technology exports is sometimes critical for analyzing a country's technological capabilities, competitiveness in the global market, and position in the high-tech industry, providing significant insights on the country's economic development and innovation ability.

3.1.4 Foreign Direct Investment:

FDI and economic development of renewable energy may also depend on the variety of factors, counting the specific type of investment and economic policy. FDI play an important role in economic growth as it can bring in new capital, technology and expertise. Some studies have found that investment in renewable energy can encourage economic growth by creating jobs and innovations.

3.1.5 Population Growth:

Population growth is the increase in the number of people in a population over time. It is usually given as a percentage or a rate, and it represents the change in population size over a specific time period, usually a year. Birth and death rates, as well as immigration and emigration, all have an impact on population growth. A population grows when the birth rate exceeds the death rate and the net migration is positive. In contrast, if the mortality rate exceeds the birth rate or if there is a net outflow of individuals, the population may contract. Population increase is an important demographic indicator that influences the social, economic, and environmental dynamics of regions and countries.

3.1.6 Public Debt:

Debt service is a financial measure used to analyze a country's capacity to satisfy debt commitments in relation to export revenues. Total debt service is the sum of multiple components, including principal and interest payments on long-term debt, interest payments on short-term debt, and repayments to the International Monetary Fund (IMF). This ratio is derived by dividing total debt service by total products, services, and primary income exported by the country. In essence, the ratio indicates how much of a country's export revenues are dedicated to debt servicing, demonstrating the sustainability of its debt burden. Renewable energy sector is the sample of study. The study has been collected data spanning from 2005 to 2022. The selected variables include

3.3 Conceptual framework

Renewable Energy, Human Capital, Technology, FDI, Population Growth rate per Anum and Public Debt. In the light of these variable a conceptual model has been sketched and is shown in Figure 1.

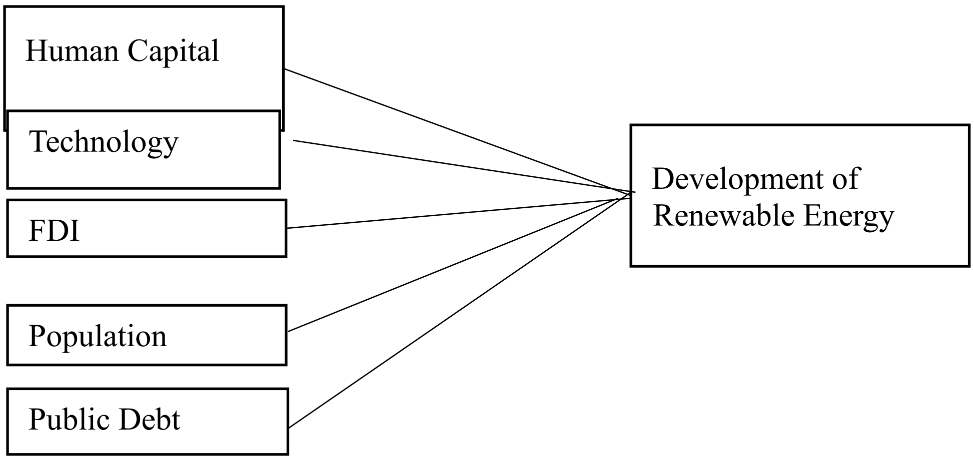

Fig 1: Conceptual Model

The general form of the model is engraved in the following equation.

Renewable Energy = f (Human Capital, Technology, FDI, Population Growth, Public Debt) **(1)**

This model can be transformed into following econometric equation: -

$$\mathbf{RE_t = \beta 0 + \beta 1HCAP_t + \beta 2TECH_t + \beta 3FDI_t + \beta 4POP_t + \beta 5DEBT_t + \epsilon_t} \quad \textbf{(2)}$$

Where:

Renewable energy development = is the dependent variable while Technology, Human capital, FDI, Public debt, Population growth are independent variables.

β_0: This is the intercept term, which represents the dependent variable's value when all of the independent variables are zero. β_1, β_2, β_3, β_4, β_5 are the coefficients for each independent variable. They indicate the change in the dependent variable caused by a one-unit change in the associated independent variable, assuming that all other variables remain constant. Basically, $\beta_1$shows the impact of changes in the Human Capital variable on renewable energy. β_2 shows the effect of changes in the "TECH" (Technology) variable on renewable energy. Where β_3 shows the effect of changes in the "FDI" (Foreign Direct Investment) variable on renewable energy. β_4 shows the effect of changes in the "Population growth" variable on renewable energy. Likewise, β_5 indicates the effect of changes in the "Public debt" variable on renewable energy. $\in$ is the error term, this term represents the error or residuals in the model—unobserved factors that affect the dependent variable but are not explicitly accounted. It captures the difference between the predicted and actual values. The study used ADF test to check stationarity, Ordinary Least Square to determine long run relationship between independent and dependent variables. Granger Causality test is used to check cause and effect. SPSS software was employed to compute the results.

4. Results

4.1 Descriptive Statistics

Descriptive statistics is used to highlight the aspects or qualities of a data-set. It provides a simplified summary or overview of the data features, assisting in understanding its patterns, variability, and distribution. Statistics include measures such as mean, median, mode, range, standard deviation, and percentiles. These statistical metrics provide insights into the form and dispersion of the data, allowing for a better understanding of the broad patterns and trends existing in the collection without requiring complex analysis. The Jarque-Bera test and its associated probability values assess the normality. Overall, these descriptive statistics provide a comprehensive understanding of the data characteristics, which can be used to conduct further analysis and draw meaningful conclusion. Table 2 shows the results of descriptive analysis.

Table 2

Results of Descriptive Statistics

	RE	HCAP	TECH	FDI	POP	DEBT
Mean	98.43568	39.58390	1.879264	0.022793	2.307026	13.23089
Median	98.56953	39.40926	1.887812	0.026529	2.263116	10.68103
Maximum	100.0000	43.75055	2.302693	0.091688	2.837192	28.98407
Minimum	96.28487	36.60081	1.448113	-0.026487	1.779757	6.513967
Std. Dev.	1.289540	2.506943	0.239340	0.030329	0.378609	7.304390
Skewness	-0.277294	0.494103	0.110611	0.485119	0.156548	1.138858
Kurtosis	1.731934	1.947510	2.439663	3.401734	1.607365	3.002905
Jarque-Bera	1.037595	1.128988	0.196580	0.597325	1.103625	2.810165
Probability	0.595236	0.568648	0.906386	0.741810	0.575905	0.245347
Sum	1279.664	514.5908	24.43043	0.296309	29.99133	172.0016
Sum Sq. Dev	19.95497	75.41717	0.687402	0.011038	1.720138	640.2494
Observations	18	18	18	18	18	18

Source: Author’s calculations

The mean represents the average value of each variable. For example, the mean of RE is 98.43568 indicating that the average number of developments of renewable energy approximately 98.45. The median represents the middle value of variables. It gives an idea of the central tendency of the data. For instance, the median of FDI is 0.02. The maximum value represents the highest observed value in the data. For example, the maximum value of Workers 43.75 indicating the highest value observed. The least value represents the lowest observed value in the data. For example, the minimum value of -0.02. The ordinary abnormality dealings the scattering or inconsistency of the data. The highest ordinary deviation indicates the greater variability. For example, RE is 1.289540 suggesting a relatively large variation in the number of RE. The skewness measures the irregularity of the data scattering. The positive value shows the exact skewed distribution, while a negative value indicates a left skewed distribution. For Example, FDI 0.485119 indicating a right skewed distribution. Kurtosis measure the nature of the distribution and indicate the occurrence of outliers or extreme values. Moreover, Kurtosis is a measure of variable shows that renewable energy is platy Kurtics and FDI is Meso Kurtic. While public debt is meso Kurtics population growth and technology platy Kurtic. Kurtosis is a measure of the combined weight of distributions tails relatives to the Centre of distribution. Skewness is measure of lack of symmetry in the data. Renewable energy and FDI are skewed in this case.

4.2 Correlation Analysis:

This section presents the correlation analysis of given study. Correlation analysis is a technique that assesses the strength and direction of the connection, between two numerical variables. It requires computing a correlation coefficient, which measures the extent of association, between these variables. Table 3 shows all conceivable correlation coefficient among a set of variables. The association matrix reveals the interrelationship among the selected variables. We check either there is a positive or negative association between dependent and independent variables or there is weak or strong association between variables.

Table 3:

Results of Correlation Analysis

Variables	RE	HCAP	TECH	FDI	POP	DEBT
RE	1.000					
HCAP	40.021	1.000				
TECH	70.326	80.412	1.000			
FDI	62.382	60.753	31.070	1.000		
POP	-50.456	-50.309	-30.052	-20.004	1.000	
DEBT	52.666	65.801	24.309	80.042	0.412	1.000

Source: Author's calculations

Table 3 presents the correlation analysis between the dependent Renewable energy (RE) and independent variables human capital, technology, Foreign Direct Investment (FDI), population (POP) and public debt (DEBT). It shows that that there is a strong positive correlation between renewable energy and human capital. Likewise renewable energy also has a strong and positive effect with technology, Foreign Direct Investment (FDI), population, public debt that is controlling variable. Human capital has a strong correlation and positive effect with technology, Foreign Direct Investment (FDI), population, public debt that is controlling variable. There is a weak correlation of technology with Foreign Direct Investment (FDI), population, public debt. Foreign Direct Investment (FDI), and Population progress has a weaker correlation with respect to the development of renewable energy. Likewise, there is a strong association between FDI and Public debt. Furthermore, the weaker association has been existed between public debt and population growth. The unit root test is presented in the below section.

4.3 ADF Unit Root Test:

This section describes the Unit root test that is important for time series data set. Unit root test is a statistical method for determining whether a time series variable has a unit root, implying that the variable is non-stationary or stationary. Stationarity is an important term in time series analysis because it influences the statistical features of the data as well as the validity of specific studies. A unit root denotes a variable with a stochastic (random) trend that does not tend to revert to a stable mean over time. The results of Unit root test are presented in Table 4.

Table 4.

Results of Unit Root Test

Augmented Dickey-Fuller Test

Variables	**Level**			
	Intercept	**Trend & Intercept**	**None**	**Conclusion**
RE	-4.537*	--	--	I(0)
HCAP	-3.558*	--	--	I(0)
TECH	-3.517*	--	--	I(0)
FDI	--	-4.252**	--	I(0)
POP	--	--	-3.346*	I(0)
DEBT	--	-5.732*	--	I(0)

Source: Author's calculations

The results of Augmented Dickey-Fuller test reveal that variables are integrated with order 1(0). As the values of Renewable energy, Human capital, FDI, Debt show that these variables are stationary at level 1(0). However other variables technology and FDI are also stationary at zero level 1(0). Based on these results we can use OLS model for empirical analysis.

4.4 Regression Analysis:

Table 5 shows that the coefficient value of human capital indicates that human capital has a significant positive impact on renewable energy. It can be due to stimulating innovation, nurturing knowledge, and supporting the creation and implementation of long-term solutions. It is expected that skilled researchers and engineers may help to enhance renewable energy technologies, increasing efficiency and affordability. Educated workforces are critical to the success of renewable energy projects in their development, execution, and maintenance. Likewise, policymakers who are informed and possess expertise in energy related fields can play a role, in creating regulations and providing incentives to encourage the widespread adoption of sustainable energy. Furthermore, when individuals with knowledge and skills in energy engage, in activities it leads to the emergence of innovative ventures that introduce cutting edge technologies and business models. Thus, a strong human capital base not only accelerates the transition to renewable energy, but it also helps to job creation, economic development, and worldwide progress toward a cleaner, more sustainable energy future. Our results are same alike the studies Saleem et al. (2017) and Edziah et al. (2021) in which they found a positive association of human capital and renewable energy.

The coefficient value of Technology indicates that it also has a significant positive impact on renewable energy. It is expected that technology has a transformational and overwhelmingly significant impact on renewable energy, transforming the efficiency, accessibility, and scalability of sustainable solutions. Technological progresses have considerably improved the performance of renewable energy, making them more competitive with traditional energy sources. Solar panels, wind turbines, energy storage, and smart grid systems today have improved the reliability and integration of renewable energy sources into existing energy infrastructures. Furthermore, digital technology, data analytics, and artificial intelligence play critical roles in optimizing energy generation, storage, and distribution, hence increasing total system efficiency. Similarly, the continual growth of technology not only accelerates the renewable energy sector towards greater sustainability, but also ensures its flexibility to future difficulties, reinforcing its critical role in the global shift to cleaner and more environmentally friendly energy sources. Study of Lin and Xie (2023) also provides the same association between technological changes and renewable energy with respect to China's economy structure.

Likewise, the coefficient value of Foreign Direct Investment (FDI) reveals that it is positively connected with the renewable energy. It is assumed that Foreign Direct Investment (FDI) has a substantial positive impact but insignificant impact on renewable energy. The weighty financial resources are channeled into renewable energy projects, facilitating their development and supporting the expansion of sustainable infrastructure. Foreign investors may frequently offer sophisticated technologies and best practices, hastening the adoption of breakthrough renewable energy solutions. Though, the inoculation of FDI leads to the expansion of local industries, providing jobs and boosting economic development. Collaborations between domestic and foreign businesses promote knowledge transfer and talent development, improving the overall efficiency and competitiveness of renewable energy programs. In conclusion, FDI serves as a catalyst for the worldwide shift to cleaner, more sustainable energy sources, resulting in favorable economic and environmental benefits. The current study is match with the results of Li et al. (2019) in which they found a positive association of Foreign Direct Investment (FDI) and renewable energy. But the insignificant condition occurs when our industry may not contribute expressively to the growth level in the country. This absence of a significant link could be attributed to a variety of issues, such as inconsistent government policies, regulatory impediments, or market conditions that do not properly incentivize foreign investors to prioritize or heavily participate in renewable energy projects Adjei-Mantey and Adams (2023).

Table 5

Results of Ordinary Least Square (OLS) Model

Dependent variable: Renewable Energy

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
HCAP	0.293	0.114	2.580	0.037
TECH	6.546	3.118	2.100	0.090
FDI	0.155	0.185	0.840	0.439
POP	1.433	0.392	3.658	0.008
DEBT	0.072	0.042	1.707	0.132
C	90.392	4.541	19.908	0.000
R-squared	0.9429	Mean dependent VAR		98.436
Adjusted R-squared	0.9020	S.D. Dependent VAR		1.290
S.E. of Regression	0.4036	Akaike Info Criterion		1.327
Sum squared Resid	1.1402	Schwarz Criterion		1.588
Log Likelihood	-2.6268	Hannan-Quinn Criter.		1.274

F-statistic	23.1020	Durbin-Watson Stat	1.991
Prob (F-statistic)	0.0003		

Source: Author's calculation

The coefficient value of variable population growth is positive and significant with renewable energy. It is assumed that the positive impact of population growth on renewable energy has the potential for increasing demand and support for sustainable energy sources. As the global population grows, so does the demand for energy to power homes, businesses, and industries. This increased demand can spur investment and innovation in renewable energy technologies, making them more economically viable and widespread. A larger population may raise environmental awareness, fostering a collective commitment to mitigating climate change and reducing reliance on fossil fuels. Furthermore, a larger workforce can contribute to the development and implementation of renewable energy projects, hastening the transition to a more sustainable and resilient energy landscape. So, generally, the population growth can act as a catalyst for the advancement and adoption of renewable energy. Our results are in line with the study of Rahman (2020) in which they discussed population and energy are indivisibly intertwined, and their interaction has a significant impact on energy consumption. Population size and its growth have a direct impact on the demand for energy resources. Higher population density frequently correlates with greater energy demand for a variety of uses, including residential, industrial, and transportation requirements.

The coefficient value of another variable public debt is positive but insignificant in our study. The use of public debt to finance the development and extension of clean energy programs can have a positive impact on renewable energy. It is expected that governments can use public debt to make significant expenditures in renewable energy infrastructure, research, and development, promoting innovation and lowering the costs of sustainable technology. This financial assistance can encourage private sector engagement, fostering a favorable atmosphere for renewable energy initiatives. Furthermore, public debt can be used to fund supportive policies such as subsidies and tax breaks that stimulate the use of renewable energy alternatives. Finally, prudent public debt management can help accelerate the transition to a more sustainable and environmentally friendly energy sector. Though, our results are also similar with the study Hashemizadeh et al. (2021) in which they suggest that the level of public debt in the developing countries plays a critical role in shaping policies and investments in the renewable energy sector. But due to when a government incurs weighty public debt, it frequently faces increased pressure to prioritize short-term economic concerns over long-term environmental initiatives especially in developing countries. This could mean less funding and support for renewable energy research and development. Due to limited financial resources, governments may reduce subsidies and incentives for clean energy programs.

The R square value indicates that the independent variables human capital and technology with other control variables explain approximately 94.29% of the variability in the dependent variable renewable energy. At 0.9020, the Adjusted R-squared adjusts for the number of predictors in the model and remains remarkably high, indicating robustness. The F-statistic of 23.1020 indicates that the whole model is statistically significant, with a low associated probability (Prob (F-statistic) = 0.0003). The mean of dependent variable is 98.436, and the standard deviation is 1.290, revealing information about the variable's central tendency and dispersion. The low standard error of regression (0.4036) indicates a close fit of the model to the data. The Akaike Information Criterion (AIC), Schwarz Criterion, and Hannan-Quinn Criterion all support to evaluate the model's goodness of fit. The Durbin-Watson statistic, at 1.991, indicate that there is no autocorrelation issues in the residuals. Generally, our findings point to a well-fitting and statistically significant model for describing the link between human capital, technology, and renewable energy. Now we check the causality test in the below section.

4.6 Causality Test:

This section represents the granger causality test. The ganger causality test is used toward examine the casual association among variables based on their past values. In the result provided, each test assesses whether one variables ganger cause another variable.

Table 6 exhibits the results of Granger causality test. HCAP does not Granger Cause RE shows that the variable HCAP does not have a statistically significant ability to predict or cause changes in the variable RE. The associated F-Value of 2.93354 and P-value of 0.0888 provide statistical information about the Granger causality test. The F-Value is a test statistic, and the P-value is the probability of obtaining the observed result if the null hypothesis (no Granger causality) is true. In this case, the P-value is 0.0888, which is greater than the typical significance level of 0.05. Therefore, based on the common significance threshold, we would not reject the null hypothesis, indicating that HCAP does not Granger cause RE.

Table 6

Ganger Causality Test

Granger Causality Tests

Null Hypothesis:	**Obs**	**F-Statistic**	**Prob.**
HCAP does not Granger Cause RE	18	2.93354	0.0888
RE does not Granger Cause HCAP		1.66808	0.2265
TECH does not Granger Cause RE	18	1.40574	0.2801
RE does not Granger Cause TECH		1.10233	0.3612
FDI does not Granger Cause RE	18	0.71604	0.5070
RE does not Granger Cause FDI		5.84852	0.0154
POP does not Granger Cause RE	18	1.37166	0.2881
RE does not Granger Cause POP		0.11665	0.8908
DEBT does not Granger Cause RE	18	2.02790	0.1712
RE does not Granger Cause DEBT		6.99389	0.0087
TECH does not Granger Cause HCAP	18	1.62093	0.2352
HCAP does not Granger Cause TECH		0.31732	0.7336
FDI does not Granger Cause HCAP	18	1.16029	0.3438
HCAP does not Granger Cause FDI		7.34444	0.0073
POP does not Granger Cause HCAP	18	0.38520	0.6878
HCAP does not Granger Cause POP		0.17028	0.8453
DEBT does not Granger Cause HCAP	18	3.06943	0.0809
HCAP does not Granger Cause DEBT		6.53244	0.0109
FDI does not Granger Cause TECH	18	1.31452	0.3020
TECH does not Granger Cause FDI		2.13333	0.1580
POP does not Granger Cause TECH	18	2.27716	0.1420

TECH does not Granger Cause POP		0.17980	0.8375
DEBT does not Granger Cause TECH	18	0.43520	0.6562
TECH does not Granger Cause DEBT		1.08257	0.3674
POP does not Granger Cause FDI	18	1.39071	0.2836
FDI does not Granger Cause POP		0.44746	0.6487
DEBT does not Granger Cause FDI	18	1.60427	0.2384
FDI does not Granger Cause DEBT		0.08362	0.9203
DEBT does not Granger Cause POP	18	0.54266	0.5938
POP does not Granger Cause DEBT		5.28869	0.0209

Source: Author's calculation

HCAP does not Granger Cause RE shows that the variable HCAP does not have a statistically significant ability to predict or cause changes in the variable RE. The associated F-Value of 2.93354 and P-value of 0.0888 provide statistical information about the Granger causality test. The F-Value is a test statistic, and the P-value is the probability of obtaining the observed result if the null hypothesis (no Granger causality) is true. In this case, the P-value is 0.0888, which is greater than the typical significance level of 0.05. Therefore, based on the common significance threshold, we would not reject the null hypothesis, indicating that HCAP does not Granger cause RE. Similarly, RE does not Granger Cause HCAP, indicates that the variable RE does not have ganger causality. RE does not Granger Cause HCAP, on the other hand, suggests that the variable RE has no statistically significant ability to predict or cause changes in the variable HCAP. The corresponding F-value of 1.66808 and P-value of 0.2265 give statistical information for the Granger causality test in the opposite direction. Again, the P-value is greater than 0.05, indicating that we would not reject the null hypothesis that RE does not Granger cause HCAP based on the significance level. Though we will not reject the null hypothesis.

The same link is exhibits in case of TECH to RE and RE to TECH. But FDI to RE and RE to FDI, we reject the null hypothesis. Because, F-value of 0.71604 and a non-significant p-value of 0.5070. This implies that FDI lacks a statistically significant predictive influence on Renewable Energy. Conversely, the analysis suggests that RE Granger causes FDI, supported by a higher F-value of 5.84852 and a significant p-value of 0.0154, indicating a predictive relationship from Renewable Energy to Foreign Direct Investment. POP does not cause RE." The Granger causality test produces F-value of 1.37166 and a p-value of 0.2881 for the variable population with regard to RE (renewable energy). The p-value is bigger than the generally accepted significance level (e.g., 0.05), indicating that insufficient evidence exists to reject the null hypothesis. As a result of these findings, it can be stated that historical population do not Granger induce changes or projections in the variable "RE."RE does not Granger Cause POP: Similarly, the Granger causality test for variable "RE" with regard to variable "POP" yields an F-value of 0.11665 and a p-value of 0.8908. Again, the p-value is large, implying that prior renewable energy ("RE") values are not Granger cause. In this scenario, the null hypothesis is not rejected, demonstrating a minor link between past renewable energy values and population.

Similarly, there is no Granger causation between DEBT (Public Debt) and RE (Renewable Energy), as indicated by an f-value of 2.02790 and a p-value of 0.1712. Similarly, no Granger causality exists between RE and DEBT. Furthermore, with an f-value of 1.62093 and a p-value of 0.2352, TECH does not Granger Cause HCAP. F-value of 0.38520 and a p-value of

0.6878 imply that POP does not Granger Cause HCAP. Additionally, with an f-value of 0.17028 and a p-value of 0.8453, HCAP does not Granger Cause POP. The p-values in each example are above conventional significance standards, indicating that there is no statistically significant causality between the variables in the relevant relationships. Similarly, there is no statistically significant causal association between FDI and Technology (TECH) in both directions. Similarly, neither population nor public debt (DEBT) Granger Cause TECH, nor does TECH Granger Cause POP or DEBT. Furthermore, no substantial Granger causation exists between POP and FDI, nor between DEBT and FDI. Based on the test results and associated F-values and p-values, these findings indicate that there is no evidence to establish the presence of a causal association between the stated economic variables in the examined context. According to a f-value of 1.16029 and a p-value of 0.3438, Foreign Direct Investment (FDI) does not Granger cause Human Capital (HCAP). Similarly, HCAP, with an f-value of 7.34444 and a p-value of 0.0073, does not Granger induce FDI. Furthermore, with f-values of 3.06943 (p-value 0.0809) and 6.53244 (p-value 0.0109), Public Debt (DEBT) does not Granger cause HCAP, and HCAP does not Granger cause DEBT. Furthermore, with f-values of 0.54266 (p-value 0.5938) and 5.28869 (p-value 0.0209), DEBT does not Granger cause POP, and POP does not Granger cause DEBT. Now we test the diagnostic condition in the below section.

4.7 Diagnostic Test:

4.7.1 Heteroskedasticity ARCH Test:

The Heteroskedasticity Test, more specifically the Autoregressive Conditional Heteroskedasticity (ARCH) test, determines the presence of heteroskedasticity in a regression model, which happens when the variance of the errors varies between observations. The F-statistic in the provided data is 0.053049, with a probability value (Prob. F) of 0.8225. This F-statistic examines the null hypothesis of no heteroskedasticity. Table 7 demonstrates results of Heteroskedasticity Test.

Table 7

Results of Heteroskedasticity Test: ARCH

F-statistic	0.053049	Prob. F (1,10)	0.8225
Obs*R-squared	0.063323	Prob. Chi-Square (1)	0.8013

Source: Author's calculation

The F-statistic is 0.053049 in the provided results, with a probability value of 0.8225. Basically, the F-statistic is used to test the null hypothesis of no heteroskedasticity. The high p-value of 0.8225 implies that there is insufficient evidence to reject the null hypothesis, showing that heteroskedasticity in the model is not statistically significant. Furthermore, the Obs*R-squared is 0.063323, with a probability (Prob. Chi-Square) of 0.8013. This statistic is related with a chi-square test for heteroskedasticity and a high p-value confirms the conclusion that there is no significant evidence of heteroskedasticity in the model. Though, it appears that the regression model does not display considerable heteroskedasticity based on these test findings, meaning that the variance of the errors stays relatively low. Now we see the Serial Correlation LM Test in new section.

4.7.2 Serial Correlation LM Test:

The Breusch-Godfrey Serial Correlation LM Test is employed to determine the presence of serial correlation in a regression model, revealing whether the residuals follow a systematic pattern over time. The F-statistic is 1.30 in the presented data, with a corresponding probability value of 0.35 (Prob. F), which assesses the combined significance of the lagged dependent variables. The bigger the F-statistic, the stronger the evidence against the null hypothesis of no serial association. Table 8 shows results of multicollinearity test.

Table 8

Results of Multicollinearity test

Breusch-Godfrey Serial Correlation LM Test			
F-statistic	1.2984	**Prob. F (2,5)**	0.3514
Breusch*R-squared	4.4438	**Prob. Chi-Square (2)**	0.1083

Source: Author's calculation

The results in the above table show that, the F-statistic is quite low, and the associated probability is greater than traditional significance thresholds (e.g., 0.05), indicating that there is insufficient evidence to reject the null hypothesis of no serial connection. Furthermore, the Breusch*R-squared is 4.44 with a probability value of 0.11 (Prob. Chi-Square), indicating the overall importance of the lagged dependent variables in the presence of serial correlation. Similarly, the p-value is above usual significance levels, showing a lack of statistical significance in rejecting the null hypothesis of no serial connection. As a result of these findings, one may conclude that there is no strong evidence of serial correlation in the regression model, and the model assumptions relating to serial correlation are not violated significantly.

4.8 Histogram:

Histogram is a chart used to exemplify the incidence circulation of a few data arguments on unique variable. In the histogram, the descriptive statistics for the residuals show that the mean is extremely close to zero (2.08e-14), indicating a balanced distribution, and the median is slightly negative (-0.023772). The range between the minimum (-0.647924) and maximum (0.486436) values is confined, indicating limited variability. The standard deviation is 0.308247, indicating moderate dispersion.

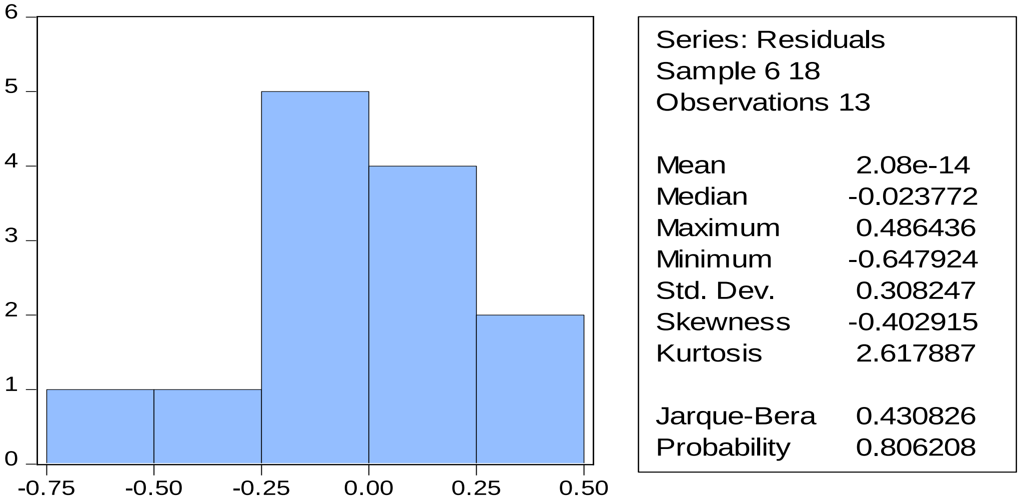

Fig 2 Histogram

The skewness is -0.402915, indicating a minor leftward skewness with a longer tail on the left side. The kurtosis value is 2.617887, which is greater than 3, indicating that the tails are somewhat heavier than in a normal distribution. The Jarque-Bera test statistic is 0.430826, and the associated probability is 0.806208, indicating that there is insufficient evidence to reject the null hypothesis of normality. These findings suggest that, while there are minor deviations from a perfectly normal distribution, indicating that there is insufficient evidence to reject the null hypothesis of normality.

4.9 CUSUM Test:

Current study also computes the Cumulative Sum of Recursive Residuals (CUSUM) that is stable in graph in the context of the study the impact of human capital and technology on renewable energy. Basically, Cumulative Sum of Recursive Residuals (CUSUM) is used to assess the model's stability over time. CUSUM is frequently used in econometrics to discover structural changes or shifts in the parameters of a regression model. The CUSUM plot, which displays the cumulative sum of the model's residuals over time, does not show any major swings or trends

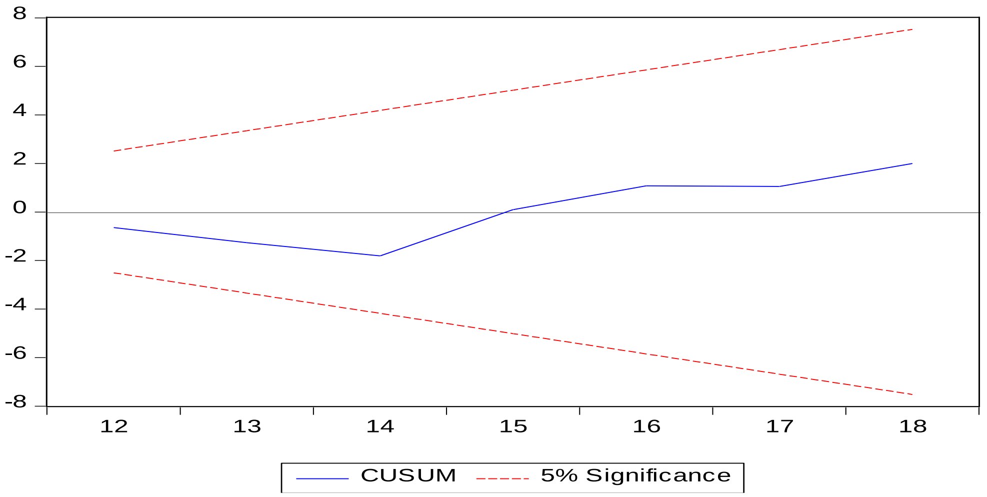

Fig 3: Results of CUSUM Test

The stable CUSUM graph indicates that the model appropriately depicts the interactions between human capital, technology, and renewable energy without substantial structural changes or deviations from the expected model. This analysis contributes to the overall robustness of the study's conclusions by ensuring the reliability and consistency of the estimated parameters.

5. Discussion

Renewable energy has a key importance in addressing the global challenges of climate change and environmental degradation. Unlike fossil fuels, which contribute significantly to greenhouse gas emissions and air pollution, renewable energy sources offer a cleaner and more sustainable alternative. Another key aspect of renewable energy lies in its potential to enhance energy security. Unlike finite fossil fuel reserves, renewable resources are essentially inexhaustible and can be harnessed locally, reducing dependence on foreign energy sources. This decentralization of energy production contributes to a more resilient and reliable energy infrastructure, mitigating the risks associated with geopolitical tensions and fluctuations in fossil fuel prices. In short, the importance of renewable energy production cannot be overstated especially the developing country like Pakistan. The role of human capital and technology in the development of renewable energy shows a key feature in the economic development of Pakistan. Therefore, this study empirically explores the role of human capital and technology innovation in the development of renewable energy in Pakistan. For this purpose, we use the time series data of Pakistan spanning from 2005-2022. To test the objective empirically, we employ the Ordinary Least Square (OLS) and Granger Causality test.

The results indicate that human capital has a significant positive impact on renewable energy. It can be due to stimulating innovation, nurturing knowledge, and supporting the creation and implementation of long-term solutions. It is expected that skilled researchers and engineers may help to enhance renewable energy technologies, increasing efficiency and affordability. Educated workforces are critical to the success of renewable energy projects in their development, execution, and maintenance. Furthermore, when individuals with knowledge and skills in energy engage, in activities it leads to the emergence of innovative ventures that introduce cutting edge technologies and business models. Thus, a strong human capital base not only accelerates the transition to renewable energy, but it also helps to job creation, economic development, and worldwide progress toward a cleaner, more sustainable energy future. Furthermore, the estimation results reveal that the variable technology innovation has a significant positive impact on renewable energy. It is expected that technology has a transformational and overwhelmingly significant impact on renewable energy, transforming the efficiency, accessibility, and scalability of sustainable solutions. Technological progresses have considerably improved the performance of renewable energy, making them more competitive with traditional energy sources. Solar panels, wind turbines, energy storage, and smart grid systems today have improved the reliability and integration of renewable energy sources into existing energy infrastructures. Furthermore, digital technology, data analytics, and artificial intelligence play critical roles in optimizing energy generation, storage, and distribution, hence increasing total system efficiency.

Moreover, the control variables of the study also have a significant impact on the renewable energy. Likewise, the results indicate that FDI is positively connected with the renewable energy. The weighty financial resources are channeled into renewable energy projects, facilitating their development and supporting the expansion of sustainable infrastructure. Foreign investors may frequently offer sophisticated technologies and best practices, hastening the adoption of breakthrough renewable energy solutions. Though, the inoculation of FDI leads to the expansion of local industries, providing jobs and boosting economic development. Collaborations between domestic and foreign businesses promote knowledge transfer and talent development, improving the overall efficiency and competitiveness of renewable energy programs. The variable population growth is positive and significant with renewable energy. It is assumed that the positive impact of population growth on renewable energy has the potential for increasing demand and support for sustainable energy sources. As the global population grows, so does the demand for energy to power homes, businesses, and industries. This increased demand can spur investment and innovation in renewable energy technologies, making them more economically viable and widespread. A larger population may raise environmental awareness, fostering a collective commitment to mitigating climate change and reducing reliance on fossil fuels. Furthermore, the variable public debt is positive but insignificant in our study. The use of public debt to finance the development and extension of clean energy programs can have a positive impact on renewable energy. It is expected that governments can use public debt to make significant expenditures in renewable energy infrastructure, research, and development, promoting innovation and lowering the costs of sustainable technology.

5.1 Policy Implications

Based on the findings that human capital and technology innovation have a positive and significant impact on renewable energy development in Pakistan, here are some policy implications of this study for consideration of the policy makers, researchers and academicians: -

- To promote investment in education and training programs that focus on building human capital in the field of renewable energy and related technologies.

- To offer scholarships to encourage students to pursue studies in renewable energy, engineering, and technology.
- To implement policies that support research and development in renewable energy technologies. This may include providing grants, tax incentives, and other financial support to businesses and research institutions engaged in innovation.
- To foster collaboration between academia, industry, and government to facilitate the transfer of technology and knowledge from research institutions to the market.
- To develop programs to enhance the technical skills and knowledge of workers in the renewable energy sector through workshops, training sessions, and professional development opportunities.
- To encourage partnerships between local and international organizations to facilitate knowledge transfer and skill development.
- To establish a supportive regulatory framework that incentivizes the adoption of renewable energy technologies. This may include feed-in tariffs, tax credits, and other financial incentives for renewable energy projects.
- To launch public awareness campaigns to inform and educate the public about the benefits of renewable energy and its role in sustainable development.
- To encourage community participation and engagement in renewable energy projects through outreach programs and incentives.

5.2 Limitations and suggestions for further research

This study has certain limitations. For example, it focuses on clean energy sector of Pakistan and used data from 2005 to 2022. Other sectors can be included into future sample of study and longer period can be employed to broader the results. Similarly, cross-countries data on renewable energy can be used to compare the pace of adaptation of green energy in different countries and level of investment and technologies as well as people's tendency to renewable energy. This type of study may be more effective and its findings may be more valuable for application.

Data Statement

The data that used in this study and that supports its findings will be made available on strong request.

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Ethical Approval

The formal consent was obtained from participants before using their information for this research. The consent was also obtained from all authors for publishing of this article.

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