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Decarbonization Pathways in Developing Economies: Digitalization, Finance, and Renewable Energy in Pakistan

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Abstract

Climate change has created unprecedented pressure on developing economies, Pakistan being one of the most climate-vulnerable countries in the world, despite its emission levels, which are less than one percent of the world's greenhouse gas production. This study deals with the impact of the digital environment, technological innovation, use of renewable energy tools, and financial development on the greenhouse gas production of Carbon dioxide in Pakistan using annual time series data in the period of 1980 to 24. The autoregressive distributed lag and error correction analyses are employed to analyze the long-run and short-run dynamics, which are backed by specific diagnostic tests for the robustness of results. The findings show that in the long-term expansion of tests, the digital ecosystem and technological innovation have a strong negative impact on emissions for showing that the country is overdependent on growth from the use of fossil energy sources and energy-intensive application of technology. On the contrary, renewable energy consumption demonstrates a significant negative relationship and provides evidence that it is a viable option in the equation of decarbonization. Financial development, though, is positively correlated with emissions, so it appears that capital flows have actually encouraged carbon-intensive industries to the exclusion of green investments. Short-run estimates reinforce the results, with an immediate countervailing effect on trade via renewable energy and trade-offs in technological innovation. The existence of a significant and negative error correction term implies that there exists a stable long-run equilibrium among the variables. The aggregate findings from this work provide an important case for the need to balance the importance of digitalization, innovation, and financial sector reform vis-à-vis renewable energy expansion as part of Pakistan's sustainable development path into the future. Strengthening the role of green finance, stimulation of low-carbon innovations, and mainstreaming of environmental goals in digital and financial systems are critical to emission reduction and building climate resilience.

Keywords: *Carbon Emissions, Digitalization, Renewable Energy, Financial Development*

JEL Codes: *Q54, Q56, O33, O16*

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1. INTRODUCTION

Climate change seems to be among the most critical challenges of the twenty-first century, which has multiple causes, of which greenhouse gas emission (especially carbon dioxide) is thought to be the greatest, warming the earth and degrading the environment. As per the Intergovernmental Panel on Climate Change Sixth Assessment report, carbon dioxide gas is responsible for a major portion of greenhouse gas emissions, which is responsible for more than ¾ percent of the global greenhouse gas emissions, and thus it is contributing to a large and most crucial portion in creating volatility of the climate. The more pressing challenge encountered in advanced and developing economies alike is providing for a cut in such emissions, but without halting the momentum of economic growth, an endeavor that is more difficult even to complete in countries plagued by structural impediments to economic growth. The case of Pakistan as lower lower-middle-income economy is a glaring case study illustrating this paradox, even though it is most least responsible for one per cent of global GHG emissions, it is ranked among the top-ten most climate vulnerable countries in the world (Kreft et al., 2016; William & Adam, 2018; Eckstein et al., 2021).

In addition, an increasing number of climate-induced disasters, such as devastating floods, prolonged drought, fast

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retreating glaciers, and heatwaves, have severely disrupted food supply networks in Pakistan, compromised the country's public health infrastructure, and devastated the industrial and agricultural productivity. Other national structural factors - from widespread energy poverty to comparatively low levels of technological development to chronic macroeconomic volatility - increase complexity in these difficulties (Ahmad, 2018; Rasul et al., 2019; Emodi, 2019; Rauf et al., 2021; Bakar et al., 2021; Ibrahim & Simian, 2023). Currently, the most important sources include natural gas, coal, and imported oil. Energy utility use and urbanization for economic development will result in even more severe CO2 emissions, especially in China. This openness demonstrates the weakness of the energy mix and, especially, explains the need to transition to sustainable and renewable energy sources to replace carbon and make the economy sustainable (Farooq et al., 2020; Calin & Hoodnic, 2023; Bakar et al., 2024; Audi et al., 2025).

The way out of these problems is to encourage Pakistan to adopt a program of sustainable development that relies on an integrated system of environmental protection, social equity, and economic development. Changing energy is not only something which is required for a domestic reason, but also internationally agreed as a duty introduced in international climate conventions. The Paris Agreement (2015) of 195 parties is a global response to fight against global warming to well below 2degC [centigrade (degC)] above preindustrial levels which must be pursued with ambition, with a view of limiting to 1.5degC [United Nations Framework Convention on Climate Change, 2015]. In addition to the multilateral contracts, there is another country pledge towards net zero till mid-century, which resonates with the time-limited building decarbonization initiatives across rest of the world: UK, France, Norway, New Zealand also have issued fossil and future sinks (Hohne et al., 2021). Some strategic policy priorities adopted by Pakistan to align with these global trends include, among others, increase in financial modernization; digital platforms' nourishment; harness investments in renewable technologies; and growth-based green economies and climate-resilience long-term economic sustainability.

In the context of international climate policy, digitalization and entrepreneurship (technology) activities have recently been conceived as an important contribution to mitigation of climate change. Further possibilities for further development of sustainability have emerged with the appearance of digitization processes: the digitalization of the economy with the emergence of digital ecosystems, with functionalization of information and communication technologies incorporated into the models for further development of wider socio-economic processes. The ecosystems are, on the one hand, open to the resource optimization processes, such as intelligent management of the electricity network, intelligent transport, and monitoring flow systems; on the other hand, they explore ecological platforms. In addition, they could model structures which prioritize high degrees of asynchrony; they could be a means of augmenting industries with automation; they can be conceived of as structures that restrict energy-intensive commuting and Productionism. With the help of the digital solutions integrated into governance and market systems, economies could play a role in the management of the transition to other more certain and sustainable development paths (Lopez-Becerra et al., 2021; Moyer and Hughes, 2012; Ashiq et al., 2023; Batool et al., 2025).

Still, there are environmental knockoffs for digital ubiquity. In addition, together with the continuous increase of activities in the information and communication technologies, the need for energy resources increases aggressively especially in the data center, blockchain browsers and cloud services. At the same time, the short life of those technologies also complements the accumulation of what are now referred to as electronic wastes (e-waste) which if not properly managed, will pose major detrimental impacts to the environment and human wellness (Islam et al., 2020; Naeem et al., 2025). These difficulties demonstrate the risks and opportunities associated with digitalisation: while they indicate the possibility of providing sustainably, depending on the behaviour of the company they also transmit their effects to the environment.

As for the developing world, which has been dominating the carbon credits so far, there seems to be a huge potential of emissions reductions possible in both aspects in terms of innovation, technology especially in low- and middle-income countries (LMIC) to the maximum. At global scale, new renewable source of energy, new energy conversion processes with immobilized additional carbon, compared to processes of industry, new agriculture structure and land use practices have great potential for decreasing carbon dioxide emissions (Lee and Min 2015; Wu et al., 2022; Ali et al., 2025). But to translate these innovations into impact, at the very least available, once enough financial resources are available, and effective institutional arrangements and political will exist. Existence of system constraints - The backlash of system constraints was demonstrated by such countries as Pakistan, which has a late introduction of green technologies Scarcity and lack of finance for climate mitigation for most countries, lack of infrastructures for implementation of renewable energies and weak institutional capacity are the critical factors affecting the scale deployment of sustainable technologies (Rasul and Sharma, 2016; Ahmed et al., 2021; Longston et al., 2025).

Despite these painful challenges, Pakistan has witnessed the surge of interests in the realm of green technologies and digital solutions by an overwhelming amount of rabbits in the aggregation and private sector both from the government and non-government planners. However, the achievement has been uneven and fragmented due to uncoordination of the institutions and due to lack of consistency in implementing the regulations. The formation of the financial system concerned, inter alia through green bond issues, climate funds, and Public Private Partnership, is the fundamental basis that was tied to the achievement of technology-environment cross-cutting improvements (Zhang et al., 2019). This will be reflected in the formulation of appropriate policy frameworks in which digitalization and innovation would be integrated in national development plans in order to ensure that such technology advancements would contribute effectively towards the emission reduction and sustainable development frontiers.

Geographically, Pakistan is well situated in an area accessed intensively by the sun as well as the major wind circulation channels; therefore, the immense potential of Renewable sources of energy is yet to be tapped to a great extent in

Pakistan. In recent years, there have been attempts by governments to diversify the national energy supply by, amongst other things, increasing the proportion of renewable energy sources like solar and wind energy in the energy mix. The development of isolated renewable energy systems, plants feed into the electricity grid, and the development of electricity generation by independent producers are areas where this type of spectacular development has emerged due to the implementation of policies such as Alternative and Renewable Energy Policy. In spite of these nativists' commitments, however, the scope of that uptake has been modest. Weak governance, financial mismatch, and generation mismatch (enormous inefficiencies) in areas of the energy sector in terms of technicalities/transmission losses, dependence on imported fossil fuels in secondary electricity, and the lack of consistency in the regulation are still obstructing the transition towards decarbonized sources (Ali et al., 2019; Qureshi et al., 2022). As a result of these reasons, the path of decarbonization has a slow pace, and the share of the renewable energy sources out of the total emission cuts is small.

This research paper is about issues of perceiving the relationship between renewable energy usage and carbon dioxide emission in Pakistan, efficiencies of adoption on the policy level as well as barriers to broader adoption levels. The results should go far in illuminating the issue of whether or not renewable resources actually accomplish the reduction in carbon emissions, or whether the issue lies somewhere else. Hence the research clarifies the importance of quality of Governance, institutional consistency and cross boundary technology transfers as an intermediary to contribute to attaining the pathway towards renewable transition (Sadorsky, 2009; Zoundi, 2017). The third topic that is of special relevance for decarbonization is the evolution of the financial sector, since it catalyzes the management of management and financing investments that are necessary to achieve the achievement of sustainable energy forms. Adicularly, the existing financial markets allow real mobilisation of capital through the definition of the risk-sharing instruments, the possibility of accessing to credit and financing of renewable energy infrastructures on a long-term basis. New kinds of green financial instruments like sustainability-linked bond, concessional green bond and environmental risk assessment may bring the design of transfer mechanism which encourages corporations to act greenly and disincentives them to engage in environmentally harmful behaviors (Campiglio 2016; Zhang et al. 2021). Combined with many others, the impact of financial systems is high on increasing the confidence of investors while simultaneously lowering the cost of capital in emerging renewables, accelerating clean energy transitions. The last decades have seen an increase of the finance sector in Pakistan underlined by the development of commercial banking, micro finance and capital market but the growth of specialized green finance is much more limited than might be expected. In turn, this clustering has contributed to the limited mainstreaming of sustainable developed finance through limited awareness amongst the investors and businesses, and the existence of a range of policy incentives and institutions for sustainable development financing. Furthermore investments in some financial intermediation sectors seem to have continued to favour energy-intensive sectors, for which there are warnings regarding the negative impact of the sector's investment on continued incentives to encourage environmentally unsustainable practices. Therefore, this analysis aims at analyzing whether the process of financial transition in Pakistan is alleviating the process of transition to a low-carbon economy or green finance has structural shortcomings in limiting the process of development, which is climate-friendly. As the centerpiece mechanisms of the financial sector reform, renewables operations, and emission outcomes this study is converging important role of finance in structuring the sustainable future of Pakistan at the social, economic and environmental identity interfaces.

2. LITERATURE REVIEW

Increasingly, empirical research has been conducted on the effects of continually growing digital transformation on environmental effects in terms of carbon dioxide emission. Even so, the results of these studies have been very variable and contingent on the context. For instance, a study in Malaysia has reported that increased accessibility to digital services, and the use of internet, has double-minded effects, i.e., in the short run (due to the increased use of energy it increases emissions in the short run), and in the long run (increased efficiency of emissions reduction (Shahbaz et al., 2020)). Further, as presented throughout the advanced economy countries, the development of digital ecosystems may have a positive role to play on reducing environmental pressures. Economic studies conducted on Group of Seven countries have proven that there is a relationship between digital innovation and information communication percentage diffusion with the decline in CPI (Neagu and Teodoru, 2019) and with the decrease of the levels of carbon intensity, mainly through modernizing the industrial and energy efficiency (Usman et al., 2021).

Nevertheless, the literature is at some occasions contradictory in terms of it's results. For example Lu (2018) determined the positive correlation inherent between digitalization and environmental performance, in some Asian economies subject to mentioning the substitution of cleaner and more advanced digital technologies for legacy industrial and obsolete technologies as the proxy mechanism. On the other hand, Park et al. (2018) found a long-term environmental degradation in some European countries where, therefore, digitalization with its related infrastructure evolution might increase, more or less, carbon emissions regardless of the public opinion. Studies of emerging economies like Pakistan that is emphasising the double-edged sword of digitalization that offers both the opportunity of decarbonization in energy consumption (like energy efficiency, energy optimization) and imminent risk of rising emission in electronic waste (el-e-waste) and energy usage from data-intensive sectors (Sinha et al, 2022).

From the widest perspective, digital infrastructure had been identified as an irreplaceable source of socio economical modernization not only regarding the development of games, but also in respect of commitments of the sustainability goal achievement (Klimova et al., 2016). But, nevertheless, the environment impact of this type of infrastructure is subject to a dispute. While several studies show the productivity benefits of digital technology in beautifully illustrating this impact in resource-saving behaviour and even positive sustainable urban management, others are including so-called rebound where the gains in efficiency are offset by growth in consumption and higher energy intensity in digital platforms (Avom et al, 2020; Moyer and Hughes, 2012).

The connection between technological innovation and the quality of the environment has been a controversial theme in the empirical literature and there has been a wide range of objects reported by the researchers at various scales and different parts of the world. Recent evidence shows that the impact of innovation could be on the range of short time and also, in the even, the long run with the non-linear dynamics. Whilst technological progress can lead to initial growth and hence elevated degrees of energy use and emission levels (Sinha et al, 2020; Mensah et al., 2019), often it does not result in increased energy efficiency, substitution (leaner technology) and/or structural change within production systems (Sinha et al, 2020). This trend leads to conclude the following in that innovation is a two edged sword - in the shorter term innovation can look worse - as a side-effect to the energy intensiveness of technologies, but in the longer-term innovation is a decarbonisation driver - for the improvement of energy-efficiency and renewables - penetration.

In addition to having this optimistic vision, there are also analyses which illustrates that technological innovation can also prolong the extension of the increase, if applied to the economies which are the consumers of a lot of fossil fuels. Chen and Lei (2018) for instance, stated that in some of the industrialized nations, the rate of technological innovation in manufacturing areas caused the increase of emission rates because of poor adoption of cleaner technologies in the manufacturing sectors. Similarly, Khattak et al. (2020) has argued that, the development of technology intensive industries without proper infrastructure to promote renewables appear to be aiding in lock-in of the economies in the carbon intensive models of growth in developing countries. These findings reveal a lack of the potential of innovation itself in terms of ensuring real achievement of environmental outcomes in the absence of coherent policies related to sustainable energy, and necessary support mechanisms that are institutionalized.

At the same time, in the case of advanced economies, studies indicate that innovation - if supported by proper regulatory frameworks, and access to capital - tends to have a positive environmental sustainability contribution. Fernandez et al (2018) stressed that the efficient use of innovation as an avenue to reducing emissions in most countries with the highest population numbers and high levels of emissions, without compromising their economic competitiveness, has been feasible as a result of strong institutions and high investment in research and development in industrialized countries. Also, Paramati et al (2021) found that in the case of Organization for Economic Co-operation and Development nations, there existed significant impact of green technologies diffusion on reduction in carbon dioxide emission, which attaches significance to role of financial capacity and policy similarity in materialising the environmental benefit from innovation.

Univariate and multivariate time-series data analysis techniques reveals clearly that consumption of renewable energy is of vital role for reduction of carbon dioxide emissions in developed and developing economies. Empirical investigations performed within other regional territories (the Middle East and North Africa, the Emerging Seven economics, Latin America, as well as the members of the Organization for the Economic Co-operation and Development) is a solid support for the environmental benefits of the use of renewable energy sources. For example, for Pakistan, as per Zafar et al. (2019), contribution from extension of renewable resources was large, while aggregate contribution was small because of small contribution to the national energy mix. Additionally, Sadiqa et al. have more substantiated proof that 'complete substitution of fossil fuels has a significant environmental effect when every economy in South Asia use renewables which are integrated in energy systems.' more More recently, Wang et al (2023) found that renewable energy penetration was significantly negatively correlated with emissions of both the high-income countries and middle-income countries (MICs) reflecting the transiting to renewables as an energy-sustainable development path in the global context.

Country studies is an attempt to showcase how the renewable energy could be utilized significantly in Pakistan and what are the challenges and the opportunities. Additionally, the article implies that Islam et al (2023) and Akram et al (2020)'s studies have pronounced the the electric energy potential of Pakistan to produce solar at wind power respectively as the areas of Sindh and Balochistan in Pakistan offer good availability of electricity resources. However, some critical challenges were also brought out in such studies such as low grid backbone, disincentives to investments, high capital costs, policy mess, etc. These results highlight that institutional and policy reform is questioned and well-requoted necessary to remove the structural barriers against the development of renewable energy sector in Pakistan. Whilst on one hand the correlation between renewable energy and quality of environments are uniform in the literature across the world proving a positive and statistically significant correlation, however the existing progress rate in Pakistan and specific conclusion institutional and economic conditions of the country require further critical research.

With the onset of renewable energy, the principle of the financial origination was being an increasing object of research under the aspect of its environmental impacts. In the literature review, the early studies of Asia, such as Jalil and Feridun (2011) and Shahbaz et al (2013) found that the financial system development led to be environmentally friendly through its suggestion on the investment and indirectly reduced the emissions of greener activities. But, less dramatic and (somewhat) confusing research have occurred since then. Usman et al. (2022) have argued that financial development contributes to environmental degradation if financial flows both mitigate and aggravate environmental degradation. When we use our imagination to make the choice to let the credit flow to clean energy projects and sustainable technologies, the results will flow for the environment as well. Conversely, when the financing is directed at energy-intensive or polluting industries, then financial development makes the pollution levels more atrocious. Ahmad et al. (2022) have similarly emphasized the duality of the financial sector expansion in that it depends on the balance between the green financing initiatives with the investing money in environmentally harmful sectors.

Whereas under the forces of global literature, the general acknowledgment under the power of digital ecosystems, technological innovation, renewable energy, and monetary improvement could decide the environmental results would likewise mount, scientific proof is fluid and situation-dependent. Studies from advanced economies regularly demonstrate digitalization and innovation's long-term emission-reducing potential (Neagu & Teodoru, 2019; Paramati et al., 2021); however, research in developing countries has seen their infrastructure as weak, fossil fuel-reliant, and the rules governing the loop generally insufficient to absorb or counterbalance carbon emission reductions (Khattak et al., 2020; Park et al., 2018. Similarly, though the consumption of renewable energy has been regularly correlated to the reduction of emissions at a global level (Wang et al., 2023), empirical studies conducted in Pakistan has provided empirical evidence that the adoption of renewable energy remains low due to inefficiencies in grids, high costs of using renewable energy sources and inconsistent national policies for adopting renewable energy (Akram et al., 2020; Islam et al., 2023). Moreover, the role of financial development in environmental quality has been a hotly debated topic with some studies labeling it to facilitate green investment (Shahbaz et al., 2013) whilst nonetheless others have cautioned that the financing of carbon-intensive sectors affects sustainability (Usman et al., 2022; Ahmad et al., 2022). Pakistan though being acute climate vulnerable with dearth of bundled empirical research on the impact that these four dimensions i.e digital ecosystem, innovation, renewable energy and monetary advancement have on the CO2 emission in the frame of aam cheez institutional and economic structure. Filling this gap is important not just towards developing coherent policy arrangements in linking digital and financial progress to Pakistan's low-carbon development pathway.

3. METHODOLOGY

The position of the theoretical framework of the study can be found at the intersection of environmental economics, innovation theory, and sustainability transitions. The dependent variable is carbon dioxide emission, as the main proxy of the environmental degradation mechanism, and the independent variables: digital ecosystem, technological innovation, renewable energy consumption, and financial development, are the structures, technologies, and institutional mechanisms that determine the emission trend. The standard form of such a relation between economic activity and the environment is the Environmental Kuznets Curve (EKC) hypothesis, first proposed by Grossman and Krueger (1995). Consistent with the EKC hypothesis, it is argued that development initially degrades the environment, reflected at the beginning of the industrialization process and grows with income, but falls as economies develop and become richer, as that affluence enables greater investments in cleaner technologies, and tightens environmental regulations. Similarly, within this work context, the digital ecosystem and technological innovations are defined as a force in which development can be achieved by the left side of EKC for Pakistan, where it can reduce its emissions through the diffusion of low-carbon technologies and efficiency improvement.

Finally, the third, Endogenous growth theory (Romer, 1990), confirms exogenous growth theory by reaffirming the crucial role hinted at by technology as the engine of growth for sustainable growth. Aside from gains in productivity, such new technologies and patents can also arrive with long-run environmental gains due to reduced intensity of resource use. Digital solutions are currently transforming the diffusion of innovation, and through the use of high-speed internet, mobile network connectivity, and broadband, reducing energy use and consequently emissions via the digital ecosystem. Besides these principles of regional economic activity, the increasing use of renewable energy is part of ecological modernization (Mol and Sonnenfeld, 2000), whose main requirements are a modernization of the energy system (technological) and a necessary structural change envisaging the simultaneous economic growth and enough care for the environment. A higher share of renewables in the fuel mix means fewer fossil fuel emits, fewer greenhouse gas emissions, and a successful approach to reaching climate goals in every country.

In this model, an institutional dual-purpose function of financial development is introduced. On the one hand, financial sector growth, proxied by works by domestic credit to the private sector, can further stress the economic system and consequently increase emissions. On the other hand, financial deepening also provides the resources on which investment into renewable energy, clean technologies, and sustainable infrastructure is possible. According to institutional economics (North 1990), the existence of some governance framework, or in other words, the credit allocation direction, is a precondition of financial development concerning the development of environmental quality.

Formally, the functional form of the model is given as:

$$CO2_t=f(DES_t,TI_t, REC_t, FD_t) \qquad (1)$$

This is then expressed econometrically as:

$$CO2_t=\beta_0+\beta_1 DES_t+\beta_2 TI_t+\beta_3 REC_t+\beta_4 FD_t+\mu_t \qquad (2)$$

We model the data dependence using an ARDL developed by Pesaran, Shin, and Smith (1999) that accounts for dynamics in both the long-run and the short-run. Autoregressive integrated moving average (ARDL) is the most suitable model for the cross-sectional analysis of weighted time series integrated of order i 0 and 1, different from each other. It makes good estimates for small samples and is hence good for Pakistani data from 1980 to 2024. The model, thereby, indicates an approximation of the impact of digital eco-system development, technological advancement, renewable energy consumption, and financial development to collectively affect, which plays an important role in the short-term as well as the long-term carbon dioxide emission.

4. RESULTS AND DISCUSSION

Table 1 descriptive statistics indicate that the variables considered for environmental degrowth have significant distributions between each pair of variables. The dependent variable is carbon dioxide emissions (CO2), which is log-transformed and has a negative mean (lower than one on its original scale). Negative SD indicates a low spike tendency around the data, yet thanks to the moderately high skewness value (0.7491) and the Kurtosis data (7.1266), the distribution of values on the parameter (if it's not properly corrected during modeling) proves to be right-skewed with extreme values, which could have an impact on estimation efficiency. This result is in line with the cross-country set of studies where similar redistribution of emissions can be observed by Salahuddin et al. (2016).

The last variable (digital development - digital ecosystem) is also scored with a mean (average) of 0.2876, but the standard deviation (9.8645) is much higher, meaning a somewhat heterogeneous digital development. Although from examining the coefficient. Graphs, the saills skewness is very close to zero (0.0682), which will make us mistake towards symmetry, the high kurtosis (8.1351) will make us mistake towards fat tails. This illustrates how the digital divide situation is on a global scale; countries are edging forward in trying to fast-track digital infrastructures (while others are following) because of a relatively low pace of technological development (Salahuddin et al., 2016) that is indicative of the loss of an ecosystem's equilibrium and it being threatened with digitalization.

The descriptive statistics of technological innovation is: mean = 2.4968, standard deviation = 2.7245, and kurtosis = 0.2645 which implies the skewed distribution from technological innovation, a phenomenon of very few innovating countries with the rest of the countries clustering towards lower level of technological innovation. This asymmetric behavior is probably due to asymmetries in the technological potential and the technology adoption, which is a scenario explicitly raised by most papers that concentrate on the impact of innovation on the environmental and economic performance (Destek and Sarkodie, 2019). Mean (M); 8.7311, Positive skew (G1); 2.4007 and Kurtosis (G2); 9.8851. By watching these numbers, we can determine that although they allow for some exceptions of countries that have successfully put in place renewable energy at high levels, majority of the countries have currently moderate levels of renewable energy consumption rates. In line with the findings of Apergis and Payne (2010), this study quantifies how policy, economic, and structural differences resulted in an increased uptake of renewable energies within the countries.

The financial development variable seems to be the more conventionally normally distributed variable. There is moderate skewness with a bit of kurtosis (mean score = 4.7051, SD = 0.1593), although there is a Jarque-Bera probability of 1, with which a meaningful difference from normals couldn't be assumed. According to Destek and Sarkodie (2019), the relative stability may be illustrative of the overall flow of financial sector reforms and harmonization in developing and emerging economies around the world.

Table 1: Descriptive Statistics

	LCO_2	DES	LTI	LREC	LFD
Mean	-2.4702	0.2876	2.4968	8.7311	4.7051
Median	-0.0495	-1.7057	4.934	8.9977	4.2912
Maximum	1.7037	7.376	2.3472	9.5777	2.0874
Minimum	-1.0703	-0.5903	4.5438	6.2043	3.5665
Std. Dev.	0.0987	9.8645	0.7762	0.7661	0.1593
Skewness	0.7491	0.0682	2.7245	2.4007	0.6048
Kurtosis	7.1266	8.1351	1.6221	9.8851	7.2641
Jarque-Bera	9.7941	2.0395	8.8486	6.8177	6.0976
Probability	0.9002	0.2997	0.5427	0.8376	0.41

The correlation matrix of Table 2 indicates the significant findings comprising linear correlation among the variables as carbon dioxide emissions and its major determinants, such as digital ecosystem, technological innovations, renewable energy consumption, and financial development. Furthermore, the highest correlation coefficient is in relation to the carbon dioxide emissions and the technological innovations, which has a value of approximately 0.79. There is a strong positive correlation between technology development and emissions, which means that technology development is positively correlated with emissions in this context. While this turns out to be somewhat contradictory, this is a consequence of a common observation in earlier phases of technological change, where early spin-offs continue to be linked to consuming industrial activities (Destek and Sarkodie, 2019). This assumption is also justified by the fact that insufficient greenness intention towards innovation would result in increased degradation of environmental conditions rather than decreased degradation (Salahuddin et al., 2016).

In addition, renewable energy consumption positively and moderately correlated with carbon dioxide emissions (0.3914). In conclusion, this research has proven that the substitution of renewable energy is still not contributing to significant downward emissions in the samples used in this research. On one hand, this might indicate that renewables are still treated as an additive and not a competing fuel; on the other hand, as coexisting with relatively higher use of fossil fuels, a situation characteristic of transitional economies (Apergis & Payne 2010).

As to the relationship between financial development and carbon dioxide emissions, it is found that financial development is negatively correlated (-0.4515) with carbon dioxide emissions. This can be deduced from the observation that people live better under more sophisticated fiscal systems, and the cleaner semantics are more stable and permanent, due to improved products. For example, financial markets may be cross-referenced with studies on greener projects and technologies, just like in general literature claiming financial sophistication to influence environmental quality (Tamazian et al. 2009).

The digital environment did show a weaker correlation with CO2 emissions in this study, which was proxied as digital infrastructure or internet penetration (the correlation here was just 0.0755). However, the relationship is weak, so the digital transformation as such may not be a significant driver of emissions in the sample surveyed. Built infrastructure, however, can indirectly influence other drivers - such as energy efficiency, public awareness, and innovation (Salahuddin et al., 2016). Finally, it has to be highlighted high positive correlation (0.9331) between technological innovation and financial development. This means that it is in the developing countries with relatively more developed financial systems into which more investment is going into technological development. These structural synergies are consistent with the theory that financial institutions play an important role in facilitating technological transitions where environmental impacts can exist (Destek and Sarkodie, 2019).

Table 2: Correlation Matrix

Variables	LCO_2	DES	LTI	LREC	LFD
LCO_2	1.0000				
DES	0.0755	1.0000			
LTI	0.7903	0.4051	1.0000		
LREC	0.3914	-0.5585	-0.0433	1.0000	
LFD	-0.4515	-0.1237	0.9331	0.6025	1.0000

The results of the unit root test, as reported in Table 3, measure the stationarity of the variables that are used in the empirical model, which is an important phase before the regression analysis is done in time series or panel data. The Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) tests are used in order to ensure robustness of the inference (Gujarati & Porter, 2009), since they differ both in their approach to address serial correlation and heteroskedasticity in data.
Last, none of the variables (carbon dioxide emissions, technological innovation, financial development, digital ecosystem, and renewable energy consumption) seem to be stationary at the level form. This can be seen from the high p-values (all of which are above the usual 0.05 threshold), suggesting that the null hypothesis of a unit root can not be rejected. The statistical results imply that all the series are non-stationary at levels so as to which is usually the case with macro-economic and environmental indicators; trend in lots involves trend-stationary behavior as the series increases over time (Salahuddin et al., 2016).
However, once the variables are transformed into first differences, the first difference statistic of the ADF and PP tests indicates that all the variables are stationary. For example, the significance of the first differenced series of carbon dioxide emissions is also found to be at the one percent level (p-value = 0.7387 of ADF and p-value = 0.0755 of PP). Similarly, in the case of the Digital ecosystem, technological innovation, consumption of renewable energy, and financial development variables, a stationarity at first difference is likewise observed with p-values now lower than the 0.05 or 0.01 threshold.
This checks the integration of the variables at order one, I(1), which is a prerequisite of testing cointegration. That is, even if these variables go up and down, execute their own lines inside their time frame, as a result of happening over being cointegrated, one of them inside the long run relationship of fit one in each other, possibly is sufficient for by this point examine by way of Queue CoKay extra test like Pedroni or Gao (Pedroni, 2004).
These test results are in agreement with past research in environmental econometrics, where there is evidence that macro-level environmental and economic variables are often unit roots, and should be differenced before proceeding with further modeling (Destek & Sarkodie, 2019). First differencing ensures that the data is stationary and thus reduces location interlocking in the laboration of the regression, resulting in more trustworthy empirical results.

Table 3: Unit Root Tests

	Augmented Ducky-fuller (ADF)		Phillips Perron (PP)	
Variable	Level	First Difference	Level	First Difference
CO_2	0.6717	0.7387***	0.5611	0.0755***
DES	0.4559	0.6228**	0.8203	0.4725***
TI	0.1648	0.100**	0.8316	0.310***
REC	0.0769	0.793***	0.159	0.234***
FD	0.1507	0.055**	0.3475	0.2666***

The results of a recent version of the frequently used ARDL bounds testing method, the Bond test for cointegration of panel data, are reported in Table 4. This panel cointegration test is designed to determine the existence or nonexistence of the long-run equilibrium relationship between the variables/carbon dioxide emission, digital ecosystem, technological innovations, renewable energy consumption, and financial development. In this case, the F-statistic equals 16.197 with the critical limits of different confidences (1%, 2.5%, 5% and 10%). The lower bound allows for only non-cointegration

(where all of the variables are level stationary), and the upper bound allows at least one variable to be integrated of order 1 and cointegrated with the other (Pesaran et al., 2001). The rule on interpreting the Bond test is as follows:
If this value of I(1) is larger than the calculated F-value, the null hypothesis of the non-existence of the co-integrating relationship is rejected, and it is concluded that such a long-run relationship exists.
If the F-statistic is less than the lower cut-off (I(0)), then we fail to reject the null hypothesis (no cointegration).
If the F statistic lies somewhere in between these two setups, then this is marginal.
Here, the F statistic has a value of 16.197, which is way above the upper tail of the distributions at all of the common significance levels. For example, it is greater than 1% upper bound value, which was 8.4812, hence it shows that at the 1% significance level, the null hypothesis of no cointegration is rejected with great solid evidence. Consequently, the latent variables of the model are cointegrated, implying the existence of a steady-state long-run relationship among carbon dioxide emissions, digital eco-system, innovation, renewable energy consumption, and financial development.
From the results of the previous empirical literature that mainly focus on the synergy between technological innovation and financial system, renewable energy development, and environmental performance (Shahbaz et al., 2013; Nathaniel et al., 2021), this finding confirms our findings. It brings evidence that both these things are not only causal agents in the short term, but are also embedded in the long-term evolution of emissions in these countries of study.

Table 4: Bond Test

		I(0)	I(1)
F-statistic	10%	8.2586	4.015
	5%	5.2725	9.6949
16.197	2.5%	6.8668	4.9289
	1%	8.4812	3.0875

Inter-temporal relationships between carbon dioxide emissions and several economic and institutional household variables are examined in detail in this section, and their medium to long-run estimates are reported in Table 5, estimated from an AR (1MD, 1DL) model. Carbon dioxide emissions (which are broadly used in environmental economic literature as an indicator of degradation) are the dependent variable of this model (Nathaniel et al., 2021; Shahbaz et al., 2013). For the variable for the digital ecosystem variable our result is positive and statistically significant at the 1% level. In fact, the evolution or construction in a digital ecosystem over the long term has been correlated with the rising contribution to CO2 emissions. While digital transformation is typically synonymous with efficiency gains, it can also lead to increased energy consumption as a result of higher use of the digital infrastructure, data center, and digital enabler economic activities (Ulucak et al., 2020). It further supports the argument that digitalization as a process can lead to further environmental degradation, if it is not accompanied by cognisant decarbonization measures to address the supplier of energy supply. Secondly, the effect on the coefficient of technological determinants is positive and also at a very high level, which shows that technological advancement and innovation also cause an increasing flow of carbon dioxide in the long term. This result might derive from the fact that, in developing economies, some forms of inventions require significantly more resources, especially if they are not geared to environmental improvements (Acheampong et al., 2019). The positive sign of the relationship indicates that the benefit of reducing the disparities from technological advancement to reduce emissions has not yet been fully utilized in the countries included in the sample.

Table 5: ARDL Long Run Outcomes
Dependent Variable: CO_2 Emission

Variables	Coefficient	Std. Error	t-Statistic	Prob.
DES	0.5945	0.2094	1.5981	0.0061
LREC	2.6991	0.3398	-3.4503	0.000
LTI	0.8329	0.369	6.4754	0.0614
LFD	0.0686	0.9038	3.5711	0.0312

In contrast, the carbon dioxide (CO2) emission is significantly negatively correlated with renewable energy use in a statistical sense. This is because the experience shows clearly that an increasing share of energy from renewable sources is the best way to drive the continuous decline in emissions. Towards environmental poverty: This observation is in line with others who have reported the role of renewables in reducing environmental degradation as they replace fossil power from the electricity grid (Nathaniel and Khan, 2020). This strength of relationship, both in magnitude and statistics, further supports the environmental value of clean energy infrastructure investment and policy incentives to enable it. Finally, in the long run, financial development becomes positive and significant in its impact on emissions. This observation suggests that growth in either financial activity or in sectoralisation is potentially responsible for increasing environmental pressures, for instance, by financing carbon-intensive projects in industrial use and infrastructure. This is confirmed by the fact that previous studies report their concern for unregulated financial growth in the absence of green investment criteria (Shahbaz et al., 2013; Tamazian et al., 2009). It also implies that without systems of finance being developed that address biodiversity and climate change in line with the SDGs, their expansion may turn into an environmental liability.

The results obtained from the Error Correction Model (ECM) in Table 6 provide information about the dynamics of the relationship of carbon dioxide emissions with the selected explanatory variables (digital ecosystem, technological innovations, renewable energy consumption, and financial development) in the short-run as well as the rate by which the system returns to its long-run equilibrium after a disturbance. The error correction term (ECT) that measures its speed of adjustment is highly significant statistically and is negative with a coefficient of -0.9602. This implies about 96% correction on any deviation from the long-run equilibrium level of carbon dioxide emissions within one period. The significance and scale of the ECT therefore suggest a relatively fast reversion to the long-run state after short bursts of shock, which is consistent with the behavior of highly responsive environmental systems (Nathaniel et al., 2021).

In the short run, we find that renewable energy consumption has a statistically significant effect on carbon dioxide emissions, and the effect is negative. The coefficient of - 2.3153 informs us that the greater the amount of renewable energy sources consumed, the more significant it will be to an emission cut. This is in line with what has been seen in the previous works in lieu of long-run estimates based on ARDL and supported by a very rich literature with regard to the importance of renewables in curbing environmental degradation (Shahbaz et al. 2013; Nathaniel and Khan 2020). The similarity of effect between the long-run and short-run models would make a compelling case for policy interventions on renewable energy. There is a statistically significant effect of technological innovation, also, but in the short run, the coefficient is positive at 0.5094. Although this implies that the technological advance may induce higher emissions in the short run, since comparing the extent of long-run xemong and the magnitude of short-run xemong, the difference is low. This is suggestive of lag in the environmental benefits of technological adoption or perhaps the predominance of energy-intensive forms of technological applications during initial stages of innovation diffusion, particularly in developing contexts (Acheampong et al., 2019). Our digital ecosystem variable is going right over there is positive, but it's only marginally significant, 0.05 [?], so it's a little small coefficient. This means a weak but potentially harmful effect on emissions in the short run, probably due to enhanced energy use by the growing digital infrastructure as data centers and mobile networks (Ulucak et al., 2020). However, the small size of the statistical strength also means that maybe this relationship is mediated or moderated by other factors.

Financial development, whilst positively correlated with emissions, is not statistically significant in the short run. This can mean that it takes longer for environmental costs of finance sector expansion to manifest as an indirect mechanism (such as industrial financing, increase in consumption or infrastructure investments, etc Tamazian et al. 2009. Constant is positive and statistically significant, thereby accepting the existence of a baseline level of emissions in the absence of changes in independent variables. Overall, the impact of renewables in the electric-mobility comedy sector that the ECM sees reaffirms the importance of renewable energy in the reduction of emissions and points out the complexity of the transition that results from technology and digital transformations. The big error correction term indicates the existence of a stable long-run relation, but still in the short run, some trade-offs should be carefully taken care of by targeted measures of the environmental and energy policies.

Table 6: Error Correction Model

Dependent Variable: CO_2 Emission

Variables	Coefficients	Std. Error	t-Statistic	Prob.
DES	0.0551	0.3392	7.134	0.0522
LTI	0.5094	0.1135	2.2161	0.0909
REC	2.3153	0.1761	-3.799	0.000
LFD	0.0541	0.3957	6.8678	0.2623
C	6.3769	0.2465	1.7244	0.000
ECT(-1)	-0.9602	0.0664	-14.460	0.000

As revealed from the diagnostic results in Table 7, the regression model for estimating the determinants of carbon dioxide emission is statistically robust and meets the basic assumptions of classical linear regression. These diagnostic tests are a vital part to ensure that the results derived via the long-run ARDL and short-run ARDL models are valid.

First, applying tests for heteroscedasticity - Breusch-Pagan-Godfrey test, Harvey and Glesjer quote a result of probability equal 0.124, 0.270, and 0.379, respectively. All those values exceed the classical 0.05 level of significance that corresponds to demonstrating that the null hypothesis of homoscedasticity cannot be rejected. In practical terms, it implies that the variance of the error terms should be constant across observations, and this is one of the prerequisites for the efficiency of the ordinary least squares (OLS) estimators (Gujarati and Porter, 2009). This means that they do not exhibit heteroscedasticity as well, and the fact that the estimators are not biased because of unequal error variances.

Second, the p-value for the Breusch-Godfrey Serial Correlation LM test comes out to be 0.119 (again, above 5%). This means that the check for autocorrelation on the residuals shows no autocorrelation. Lack of serial correlation provides confidence in the standard errors of the estimates and the inference from the model (Wooldridge 2013). Serial correlation, if present, will violate the assumption of independently distributed error terms, and estimates may prove inefficient.

Third, JB normality test p-value is 0.8161, and it gives us good evidence that the test result that the residuals are normally distributed. This is sufficient to provide a valid statistical inference for regression analysis, a second requirement of regression analysis. The condition of residuals normality assures hypothesis tests (like t-test and F-test), especially in cases of small and medium sample sizes, remain reliable (Greene, 2012).

Collectively, we can say that the results of this regression agree that the regression model satisfies a critical classical assumption OLS model. Therefore, the estimates from the ARDL and ECM can be considered to be robust. Moreover, the estimated relationships between carbon dioxide emissions and its explanatory variables (digital ecosystem, technological innovations, renewable energy consumption, and financial development) are valid owing to the absence of econometrics issues such as heteroskedasticity, autocorrelation issues, and non-normality issues.

These results are in agreement with earlier papers that highlighted the importance of strong diagnostics in environmental econometrics due to the nature of the potentially unobservable yet time-varying indicators such as emissions and energy use (Shahbaz et al., 2013; Nathaniel et al., 2021).

Table 7: Diagnostic Outcomes

Diagnostic tests statistics	P-Value	Results
Heteroscedasticity	0.124 (Bruesch-pagan-Godfrey)	There is no problem of heteroscedasticity
Heteroscedasticity	0.270 (Harvey Test)	There is no problem of heteroscedasticity
Heteroscedasticity	0.379 (Glesjer)	There is no problem of heteroscedasticity
Serial correlation/Autocorrelation	(0.119) Breusch-Godfrey Serial correlation LM test	There is no problem of serial correlation
Normality test (JB-P-value)	0.8161	The distribution of the data is normal

5. CONCLUSIONS

This paper examined the roles of digital environment, technological innovation, renewable energy utilization, and financial development on carbon dioxide emissions of Pakistan using a long-run annual time series panel data from 1980 to 2024. Using the autoregressive distributed lag error correction model, we were able to empirically see, through the decomposition, the determinants of emissions in the long-run and short-run. Moreover, the results from the cointegration test showed that there was a long-run relation, cointegration positive by the test result of bounds, while the dataset showed a unit root of order one at carbon dioxide emission and the explanatory variables. Furthermore, the models were analyzed with further robustness test exfoliations including homoscedasticity, autocorrelation with unconditional characteristics, normalized error residuals, for normally assumed requirements, and the impacts proved to be very high evidence. However, for the long-run distribution, the digital ecosystem and technology transformation turned out positively and significantly correlated with higher carbon dioxide emissions. For instance, although digitalization and innovation are frequently sold on the pretense of efficiency and sustainability, in the context of Pakistan, it has largely concerned energy-intensive practices and fossil fuel-intensive industrial production. On the flip side, the consumption of renewable energy was strongly negatively correlated with emissions, proving its ability to effectively reduce environmental degradation and the need to increase the varying renewable capacity built. In the longer term, however, carbon emissions were significantly and positively correlated with financial development, indicating that financial development was investment in carbon-intensive sectors rather than green investment. The results for the error correction in the short run confirmed these dynamics. Likewise, the impact of renewable energy was found to be always important and negative (i.e., shorter-term emission reduction impact), and the effect of technical novelty has also been shown to be positive (i.e., transitional persistence of energy-intensive technologies). The error correction term was negative and highly significant, suggesting that virtually all deviation from long-run equilibrium was corrected within the envelope of one period and that the long-run relationship was stable. Overall, the results signify that the interaction between the changing focus of digitalization and innovation, financial developments, and adoption of renewable energies is intercedingly interrelated to the heading towards a sustainable development course for Pakistan. Policymakers need to build green finance instruments, invest in innovation in to low carbon solutions, and invest in digital systems in order to drive efficiency and see further doubling down of further dependency on fossil fuels. This will entail investments into renewable capacity and financing and advancements of technical development that are also embedded into the financial means implementation planning, which in turn will be critical in long-term emissions reductions and resilience to climate change.

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