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Innovating for a Greener Future: Assessing the Impact of Renewable Energy, Resource Efficiency, and Technology on CO_2 Emission Reduction

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Abstract

This paper explores how CO2 is emitted in 30 developing Asian economies. Such countries differ in terms of income levels, such as low, middle, and high income, and the years between 1990 and 2022 are included in the study. It employs a powerful econometric model in which both the System Generalized Method of Moments (GMM) is used to overcome dynamic endogeneity and Two-Stage Least Squares (2SLS) is used to overcome potential reverse causality. This integrated methodology serves well to investigate the impacts of renewable energy use, the availability of natural resources, and technological innovation on the level of emissions. These findings of the study demonstrate a complex dynamic. There is presently a positive relationship between technological innovation and the rise in emissions, which can be attributed to the fact that technology is used to streamline the industrialization process that uses fossil fuels on a large scale. On the contrary, renewable energy and natural resources also contribute to the decrease in CO2 emissions. One of the biggest revelations is that production-oriented industrialization, particularly after China's entry into the WTO in 2001, has contributed greatly to the growth in global emissions. Since, in most cases, the area lacks powerful and effective environmental laws, this study emphasizes the necessity of modifications in policy. Steps such as promoting green innovation technology and introducing a price on carbon are crucial to uncoupling economic growth and emissions and creating an efficient global climate policy.

Keywords: CO_2 Emissions, Technological Innovation, Natural Resources, Renewable Energy, System GMM, EKC

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1. Introduction

The continued rise in atmospheric CO_2 concentrations has increased pressure on the international community to address climate change. This study investigates the complex relationships between CO_2 emissions and important economic and environmental factors, including natural resources, technological innovation, gross domestic product (GDP), urbanization, and energy consumption. As countries increasingly experience the consequences of climate change, adopting effective strategies to reduce CO_2 emissions has become more urgent. Renewable energy sources, including geothermal, solar, wind, and hydropower, are considered essential for reducing dependence on conventional energy. Similarly, technological innovation plays an important role in the energy sector, particularly in improving solar energy use. However, environmental degradation remains a major global concern, driven by industrialization, population growth, and increasing demand for consumer products. In addition, the depletion of natural resources is associated with inadequate environmental education, awareness, and responsible resource consumption. Human activities, particularly the combustion of fossil fuels and biomass, contribute substantially to atmospheric CO_2 emissions. Rising energy demand, economic activities, and agricultural production to meet growing food requirements further contribute to carbon emissions (Owusu et al., 2016).

Renewable energy, derived from replenishable sources such as sunlight, wind, and water, plays an important role in supporting sustainable economic growth. Although conventional energy sources contribute to economic development, their consumption also generates substantial CO_2 emissions. Therefore, transitioning toward renewable energy offers several environmental and economic advantages, including reduced emissions, improved energy security, and lower dependence on fossil fuels. In addition, renewable energy development creates employment opportunities through technological innovation and helps address environmental challenges such as pollution and global warming. By adopting renewable energy, countries can meet their growing energy requirements while improving environmental sustainability and supporting long-term economic development (Akella et al., 2009).

In recent years, international attention has increasingly focused on sustainable development practices because of growing concerns about environmental degradation and global warming. Conventional energy systems remain major contributors to CO_2 emissions, creating significant challenges for environmental protection. Consequently, identifying effective approaches to reducing emissions through technological innovation and clean energy consumption has become increasingly important. However, technological development does not necessarily improve the environment when economic activities continue to depend heavily on conventional energy sources.

CO_2 is a major anthropogenic greenhouse gas associated with climate change and environmental deterioration (Gradan et al., 2021; Wang et al., 2020). Continued carbon dioxide emissions threaten ecosystems and influence various aspects of human development. Furthermore, the environmental consequences of rising emissions may become more severe than previously anticipated. Therefore, reducing carbon emissions and improving environmental quality have become important priorities for sustainable and resilient economic development. These concerns highlight the need to examine the economic and technological factors responsible for changes in CO_2 emissions.

Raihan et al. (2022) and Voumik et al. (2023) identify increasing CO_2 emissions from economic activities as a major contributor to global warming. Their findings also emphasize the importance of understanding the underlying determinants of emissions. Similarly, Raihan and Tuspekova (2022) identify rapid urbanization, industrialization, and population growth as key factors driving rising CO_2 emissions. Growing populations, expanding industries, and increasing urban development generate additional energy demand, which can intensify environmental pressures. These developments increase atmospheric carbon concentrations and raise global temperatures. Therefore, sustainable development requires environmentally responsible industrial practices, efficient resource use, and effective strategies to reduce carbon emissions.

Urbanization also influences environmental quality through changes in consumption patterns, industrial structures, and economic activities. Increasing energy consumption and the inefficient utilization of natural resources can intensify environmental degradation, particularly in rapidly expanding urban areas. Furthermore, technological development and the extensive use of natural resources in manufacturing activities may increase environmental pressures when production processes remain dependent on conventional energy. However, urbanization may also provide opportunities to improve resource efficiency through better infrastructure, environmental awareness, and the adoption of cleaner technologies. Changes in resource extraction and energy consumption patterns further influence the environmental consequences of urban development.

Anser et al. (2021) suggest that urban economic development can create opportunities for economies of scale and the adoption of environmentally responsible technologies. Similarly, expanding metropolitan economies may facilitate the implementation of energy-efficient production methods and improve the utilization of available natural resources. These improvements can support environmental sustainability when appropriate technological and economic conditions are in place. However, rapid urbanization and industrial expansion may simultaneously increase energy consumption and CO_2 emissions. In addition, the growing demand for energy-related infrastructure can create environmental challenges, particularly where facilities require extensive land and resource utilization. Consequently, understanding the relationship between urbanization, technological development, energy consumption, and environmental quality is essential for identifying effective emission-reduction strategies.

1.1. Research Objective

- Assess the effectiveness of renewable energy consumption in reducing CO_2 emissions.
- Evaluate the role of technological innovation in influencing CO_2 emissions.
- Analyze the impact of natural resources on CO_2 emission mitigation.

1.2. Problem Statements, Significance and Scope of the Study

This study addresses the relationship between renewable energy consumption, technological innovation, natural resources, and CO_2 emissions. Although these factors are important for environmental sustainability, their relationships with carbon emissions remain complex, particularly across countries experiencing different levels of economic development. Existing evidence does not fully explain how renewable energy, technological advancement, and natural resource utilization jointly influence emissions. Therefore, understanding these relationships is essential for developing effective environmental policies and balancing economic development with sustainability objectives. The study specifically examines whether renewable energy consumption helps reduce CO_2 emissions, how technological innovation influences emission levels, and whether natural resources support emission mitigation.

This study uses panel data from 1990–2022 to investigate CO_2 emissions across developing Asian economies. The analysis examines the effects of renewable energy consumption, technological innovation, and natural resources, while accounting for economic growth, urbanization, and energy consumption. The rapid industrialization, economic expansion, and urban development these economies experience make them particularly relevant for examining the relationship between economic development and environmental sustainability. Furthermore, differences in economic conditions and energy consumption patterns provide an important basis for understanding variations in emission levels. The findings are expected to provide useful evidence for developing policies that support renewable energy adoption, improve resource utilization, and encourage environmentally responsible technological advancement.

This study's novelty lies in examining renewable energy consumption, technological innovation, and natural resource rents within a common cross-country framework while accounting for differences across income groups. In particular, the positive estimated relationship between technological innovation and CO_2 emissions raises an important question about whether technological advancement necessarily

contributes to environmental improvement. Innovation may expand industrial production without reducing dependence on carbon-intensive energy sources. Therefore, examining these relationships together clarifies how energy composition, resource dependence, and economic development influence environmental outcomes. By considering these interconnected factors, the study contributes to existing discussions on renewable energy, technological progress, and environmental sustainability in Asian economies (Baloch et al., 2019; Godil et al., 2021; Ulucak, 2020).

2. Literature Review

The growing urgency of addressing climate change has encouraged research on CO_2 emissions, renewable energy, and technological development. Fossil fuel consumption remains a major contributor to carbon emissions and environmental degradation. As the need to meet international climate commitments increases, understanding the factors influencing CO_2 emissions has become increasingly important. Therefore, this literature review examines existing research on CO_2 emissions and their relationships with energy consumption, technological innovation, economic development, and other environmental factors.

Tang and Hu (2023) examined the relationship between land urbanization and CO_2 emissions, considering carbon emissions as the dependent variable and land urbanization, land use structure, land use intensity, and land use efficiency as independent variables. The study employed instrumental variables to examine the robustness of the findings. The results indicated that land urbanization increases urban CO_2 emissions, although the relationship follows a U-shaped pattern. However, improvements in land-use efficiency were found to reduce emissions by optimizing land utilization. These findings provide a basis for examining whether the environmental consequences of urbanization differ across national contexts.

Similarly, Kostakis et al. (2023) investigated the effects of economic growth, trade openness, energy consumption, globalization, and population density on CO_2 emissions in Middle Eastern and North African (MENA) countries from 1994 to 2014. The researchers employed econometric techniques, including Granger causality tests and the Generalized Method of Moments (GMM). Their findings showed that economic growth and energy consumption increase CO_2 emissions, whereas globalization and trade openness help reduce emissions. However, the long-run effect of renewable energy consumption was relatively small and statistically insignificant. Therefore, the study recommended encouraging non-fossil fuel consumption to address environmental degradation.

Esmaeili et al. (2023) examined the environmental consequences of human activities, particularly their implications for CO_2 emissions, human health, and environmental sustainability. The study treated CO_2 emissions as the dependent variable, with independent variables including foreign direct investment (FDI), clean energy consumption, and the interaction among economic difficulty, FDI, and economic complexity. Using data from 1995 to 2019, the researchers applied a panel quantile regression approach to examine these relationships. A distinctive aspect of the investigation was its consideration of the combined effects of economic complexity and FDI. The findings provided evidence concerning the Environmental Kuznets Curve (EKC) in the Next Eleven (N-11) countries. In addition, the study emphasized the need to expand environmental research and adopt effective measures to support sustainable development.

Jabeen and Khan (2022) examined green growth in Pakistan by considering economic, social, and environmental factors using time-series data from 1990 to 2019. They treated sustainable economic development as the dependent variable and included sustainable economic growth, environmental sustainability, natural capital, climate change, poverty, and employment as explanatory variables. The researchers employed structural equation modeling (SEM) within the MCED-5 framework. Their findings indicated that increases in net national income contributed to natural resource depletion. However, increases in adjusted net national income were associated with poverty reduction and employment growth, while adjusted net national income had no significant effect on carbon intensity. The model also examined variations in national poverty and carbon emissions relative to GDP. Therefore, the study suggested that Pakistan should move from weak sustainability towards strong sustainability to support economic development and natural resource conservation.

Chen et al. (2022) investigated the effects of green economic infrastructure on CO_2 emissions in Belt and Road Initiative economies from 2007 to 2019. The analysis covered several subregions, including Central Asia, South Asia, East and Southeast Asia, Europe, and MENA countries. The researchers employed panel data techniques, including GMM and fixed-effects and random-effects models. Their findings indicated that green logistics increased carbon emissions in Belt and Road Initiative economies, Central Asia, and MENA countries, whereas a negative relationship was observed in Europe. Similarly, internet use helped reduce emissions in East Asia, Southeast Asia, Europe, and the broader group of Belt and Road Initiative economies, while increasing emissions in MENA countries. Fossil fuel consumption was associated with higher emissions, whereas green technologies contributed to emission reductions. Therefore, the study emphasized the importance of adopting environmentally responsible practices and improving green infrastructure.

Cai et al. (2022) examined CO_2 emissions in South Asian countries using data from 1990 to 2018. Their findings indicated that non-renewable energy consumption and economic development contributed to increasing CO_2 emissions. However, renewable energy consumption and agricultural activities had relatively limited effects on emissions. The study also found that urbanization was associated with greater environmental degradation. The authors discussed these findings in relation to the Environmental Kuznets Curve hypothesis and its implications for sustainable development policies.

Ahmed et al. (2022) investigated green economic development in South Asian countries by considering renewable energy, green innovation, and green trade. The study employed panel data covering 2000 to 2018 and applied several econometric techniques, including unit root tests, cointegration tests, fully modified ordinary least squares (FMOLS), and dynamic ordinary least squares (DOLS). The findings indicated that clean energy consumption positively influenced economic growth, while green innovation contributed to improved economic performance. Similarly, green trade supported sustainable development across the region. Therefore, the researchers emphasized the importance of encouraging green innovation and renewable energy consumption to promote sustainable economic growth in South Asia.

Onofrei et al. (2022) examined the relationship between economic growth and CO_2 emissions in 27 European Union member states using data from 2000 to 2017. The researchers employed econometric techniques, including DOLS, unit root tests, and cointegration analysis, to investigate the long-run relationship between economic development and emissions. Their findings revealed a positive relationship between GDP growth and CO_2 emissions, with an average estimated increase of 0.072%. However, the study also emphasized that higher income levels could increase demand for environmental protection. Therefore, the environmental consequences of economic development depend not only on economic growth itself but also on the nature and structure of development.

Godil et al. (2021) investigated the effects of economic growth, technological innovation, and renewable energy consumption on CO_2 emissions in China's transport sector using time-series data. They treated total CO_2 emissions as the dependent variable and included GDP, technological innovation, and renewable energy consumption as explanatory variables. The researchers employed the Quantile Autoregressive Distributed Lag (QARDL) approach to estimate short-run and long-run relationships. Their findings indicated that renewable energy consumption and technological innovation significantly reduced CO_2 emissions. Consequently, the study recommended policies that encourage technological innovation in the transport sector to support environmental sustainability and reduce emissions.

Zhang et al. (2021) examined the relationship between urbanization and environmental degradation using panel data from 2000 to 2012. CO_2 emissions were considered the dependent variable, while the explanatory variables included resident population urbanization, household registration population urbanization, population density, GDP per capita, heavy industry production, FDI, environmental regulation, and energy consumption. The researchers employed GMM and two-stage least squares (2SLS) estimation techniques. Their findings indicated that urbanization based on the resident population increased CO_2 emissions, whereas household registration urbanization was associated with lower

emissions. Therefore, the study demonstrated that different forms and stages of urbanization may have different environmental consequences and emphasized the importance of sustainable urban development policies in China.

Zhao et al. (2021) examined the relationships among financial risk, technological innovation, sustainable development, industrialization, population, and CO_2 emissions using a balanced panel dataset covering 62 countries from 2003 to 2018. CO_2 emissions were treated as the dependent variable, while financial risk, technological innovation, sustainable development, industrialization, and population size were included as explanatory variables. The researchers employed panel quantile regression, fixed-effects estimation, system GMM for robustness analysis, and unit root tests. The findings indicated that financial risk significantly influenced global CO_2 emissions, while technological innovation played an important role in the relationship between financial risk and environmental outcomes. The study consequently emphasized the importance of financial stability and technological development in supporting emission-reduction policies.

Khan, Hassan, Kirikkaleli, Xiuqin, & Shukai (2022) investigated CO_2 emissions in China by examining the effects of energy consumption, economic growth, and economic policy uncertainty. Given China's substantial contribution to global carbon emissions, the study considered the environmental implications of these economic factors. Using time-series data from 1970 to 2018, the researchers employed an autoregressive distributed lag (ARDL) approach, dynamic simulation, bounds testing, and diagnostic tests, including the Breusch–Godfrey and Jarque–Bera tests. The findings suggested that energy consumption and economic growth increased CO_2 emissions, whereas economic policy uncertainty was negatively associated with environmental degradation. In addition, the study emphasized renewable energy investment and policies aimed at reducing dependence on fossil fuels.

Chien et al. (2021) examined the relationship between sustainability and information and communication technologies (ICT) in BRICS countries, focusing on how ICT, economic growth, and financial development affect CO_2 emissions. The researchers used the Method of Moments Quantile Regression (MMQR) approach to examine how these relationships vary across emission levels. Their findings indicated that the environmental effects of these variables differed across emission quantiles. Therefore, the study provided policy implications for supporting sustainable development goals through appropriate economic, technological, and environmental strategies in BRICS economies.

Ulucak (2020) investigated the contribution of environmental technologies, renewable energy consumption, and non-renewable energy consumption to green growth in BRICS countries. Using panel data analysis, the study found that environmentally friendly technologies and renewable energy consumption supported green growth, whereas non-renewable energy consumption had adverse environmental implications. Furthermore, the findings indicated an inverted U-shaped relationship between environmental quality and income. The study also suggested that ICT could help reduce emissions, particularly in economies with relatively low emission levels.

Rahman et al. (2020) investigated the effects of CO_2 emissions, population density, and trade openness on economic growth in South Asian countries using data from 1990 to 2017. The researchers employed a panel cointegration approach to examine the relationships among these variables. Their findings revealed that CO_2 emissions and population density positively influenced economic growth, whereas trade openness had a negative effect. Furthermore, the study identified bidirectional relationships involving economic growth, trade openness, and CO_2 emissions. These findings provided implications for developing economic and environmental policies in South Asian countries.

Baloch et al. (2019) examined the relationships among natural resources, renewable energy consumption, GDP, and CO_2 emissions in five BRICS countries using panel data from 1990 to 2015. The researchers employed the Dumitrescu–Hurlin panel causality test and group-specific regression models. Their findings indicated that natural resources significantly reduced CO_2 emissions in Russia but increased emissions in South Africa. However, the relationship was statistically insignificant in Brazil, China, and India. Similarly, renewable energy consumption helped reduce environmental pollution across BRICS

countries. The results further indicated that GDP positively influenced CO_2 emissions in Brazil and China, whereas the squared GDP term had a negative effect, supporting the possibility of a nonlinear relationship between economic growth and environmental degradation.

Jiang and Guan (2016) investigated the factors contributing to global CO_2 emission growth across developed, developing, and industrialized countries. The study examined emissions from different fossil fuel sources, including coal, oil, and natural gas, using time-series data covering 1995 to 2009. The researchers employed structural decomposition analysis (SDA) to identify the main contributors to emission growth. Their findings indicated that coal-related emissions increased by 2,794 Mt. In developing countries excluding China, coal and natural gas emissions increased by 967 Mt and 814 Mt, respectively. Similarly, natural gas-related emissions increased by 471 Mt in developed countries and 132 Mt in China. However, oil-related CO_2 emissions declined by 506 Mt in developed countries.

Technological innovation can improve production efficiency and facilitate the adoption of cleaner energy systems. However, the environmental consequences depend on the nature of the technologies developed and the energy sources that support their operation. Innovation in conventional industrial production may increase energy consumption and CO_2 emissions, whereas technological improvements that support renewable energy and energy efficiency may contribute to emission reductions. Godil et al. (2021) emphasized the potential of technological innovation and renewable energy to reduce emissions in the transport sector, while Zhao et al. (2021) examined the environmental implications of technological development across a broader international sample. Therefore, a positive coefficient for technological innovation should not necessarily be interpreted as evidence that all forms of innovation increase emissions. Rather, the relationship should be understood in the context of the innovation indicator, economic conditions, and countries included in the analysis.

2.1. Technological Innovation and Carbon-Intensive Development

Existing empirical studies provide valuable but varied evidence across countries and estimation approaches. For example, Godil et al. (2021) found that technological innovation was associated with lower transport-sector emissions in China, whereas the present study estimates a positive relationship between technological innovation and CO_2 emissions in the sampled economies. Similarly, Baloch et al. (2019) reported that the environmental consequences of natural resource utilization differed across BRICS economies. These differences suggest that industrial composition, national energy systems, and how technological innovation is measured may influence the estimated relationships. In addition, comparisons across income groups can help determine whether these relationships remain consistent among economies at different stages of development. Therefore, this study contributes to this discussion by examining these factors within a common framework, although the findings should be interpreted in light of the underlying data and estimation assumptions.

2.2. Research Gaps and Contribution

Camarero et al. (2013) examined the determinants of CO_2 emission convergence among 23 Organisation for Economic Co-operation and Development (OECD) countries using time-series data from 1960 to 2008. The study used CO_2 emissions as the dependent variable and included energy intensity and the carbonization index as explanatory variables. The researchers employed the Phillips and Sul (2007) methodology to examine convergence patterns. Their findings identified four convergence clubs among OECD economies. The first club included Greece and Portugal, while the second comprised Australia, Finland, Japan, New Zealand, Norway, and Switzerland. The third club consisted of Austria, Canada, Denmark, and the Netherlands. The fourth included Belgium, France, Germany, Iceland, Sweden, and the United Kingdom. However, Italy and Spain demonstrated an upward trend in CO_2 emissions, indicating differences in emission patterns across OECD economies.

2.3. Theoretical Framework

2.3.1. Environmental Kuznets Curve (EKC) Hypothesis

The Environmental Kuznets Curve (EKC) hypothesis proposes an inverted U-shaped relationship between environmental degradation and per capita income. According to this hypothesis, environmental degradation initially increases with economic development. However, after income reaches a certain level, further economic growth may improve environmental quality. Therefore, the relationship between GDP expansion and environmental degradation may change as economies move towards higher stages of development. Beyond the turning point of the inverted U-shaped curve, environmental degradation, including certain forms of pollution such as sulfur dioxide, is expected to decline as per capita income increases.

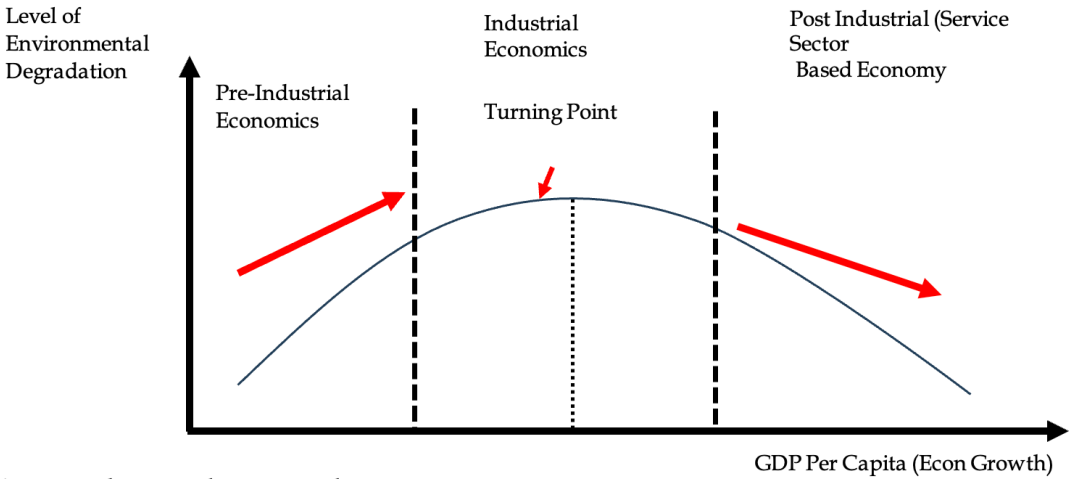


Figure 1: Theoretical Framework

The Environmental Kuznets Curve takes its name from Kuznets' earlier work on the relationship between income inequality and economic development. Subsequently, the EKC framework was applied to examine the relationship between economic growth and environmental degradation. However, whether an inverted U-shaped relationship applies to different environmental indicators remains debated (Esmaeili et al., 2023). The EKC hypothesis suggests that the relationship among natural resources, ecological footprints, and economic growth is not necessarily linear. Research applying this hypothesis examines nonlinear relationships between income and environmental quality (Esmaeili et al., 2023). In particular, the hypothesis proposes that environmental degradation may increase during the initial stages of economic development before declining as income rises. Figure 1 illustrates this relationship and the possibility that economic development may eventually offset some of the environmental damage associated with earlier stages of economic expansion. Furthermore, the EKC framework considers the implications of natural and human resources for environmental quality, while ecological footprints indicate environmental degradation.

2.3.2. Conceptual Framework

2.4. Relationships between CO_2 Emissions and Explanatory Factors

Consumption of Renewable Energy: Renewable energy consumption generally has a lower carbon footprint than conventional fossil fuel energy sources and can therefore help reduce CO_2 emissions. Consequently, increasing renewable energy consumption plays an important role in improving environmental sustainability. The conceptual framework also suggests that income and environmental degradation may be related nonlinearly under the EKC hypothesis. However, the reported empirical model does not include an explicit squared income term. Therefore, the findings should not be interpreted as a direct statistical test of the EKC turning point. Instead, the EKC provides a broader theoretical perspective for examining differences in economic development and CO_2 emissions (Esmaeili et al., 2023; Kostakis et al., 2023).

Technological Innovation: The relationship between technological innovation and CO_2 emissions varies across countries and economic systems. Evidence from MENA countries suggests that, under the DOLS approach, technological innovation may contribute to increased CO_2 emissions. One possible explanation is that certain technologies, including data storage and cloud services, require substantial energy consumption and may consequently increase emissions. Natural Resources: Natural resources may have an inverse relationship with CO_2 emissions and play an important role in developing policies and strategies for addressing climate change and environmental degradation. These resources include land-use patterns, forests affected by deforestation and agriculture, fossil fuels such as coal, oil, and natural gas, water resources, and mineral resources. However, fossil fuel extraction and consumption contribute to CO_2 emissions, while urbanization may reduce the natural environment's capacity to absorb carbon emissions.

Urbanization: The relationship between urbanization and CO_2 emissions is complex. Rapid urbanization can increase energy consumption and CO_2 emissions through industrial expansion and growing infrastructure demand. However, effective urban planning, smart-city development, and improved energy efficiency may help reduce emissions. Similarly, technological advancements in urban areas can influence energy consumption and environmental quality while supporting economic development. Therefore, appropriate urban planning and effective emissions management are essential for environmental sustainability.

Consumption of Non-Renewable Energy: Non-renewable energy sources, particularly coal, oil, and natural gas, are associated with CO_2 emissions. However, nuclear energy has different direct-emission characteristics compared with fossil fuels. In addition, using non-renewable energy resources creates environmental challenges, including waste disposal and resource management.

GDP: Economic growth is generally associated with increasing CO_2 emissions because industrial expansion and agricultural activities require additional energy and resources. Consequently, the relationship between GDP and emissions highlights the continuing challenge of balancing economic development with environmental sustainability.

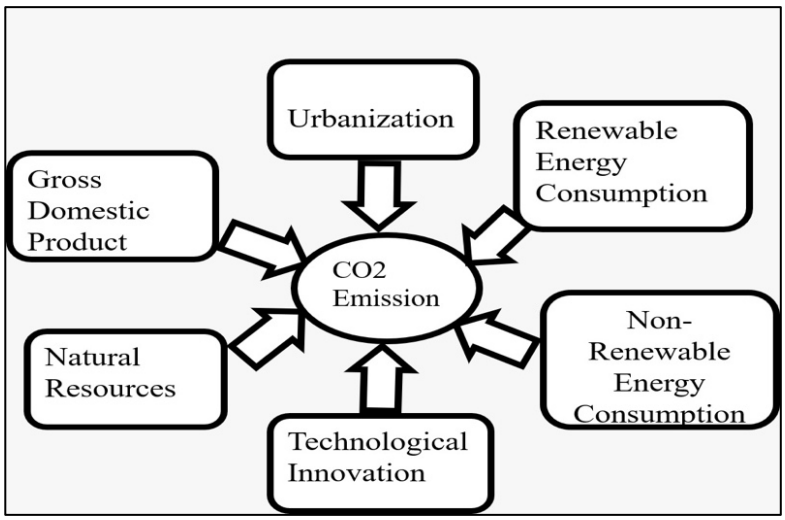


Figure 2: Conceptual Framework

The diagram illustrates the proposed relationships between CO_2 emissions and the explanatory variables (adapted from Baloch et al., 2019).

3. Models and Methods

3.1. Model Specification

To assess how renewable energy consumption, technological innovation, natural resources, urbanization, non-renewable energy consumption, and GDP growth rate are associated with CO_2 emissions in developing Asian countries, we developed the following econometric model:

CO_2 emission = f (Renewable Energy consumption, Technological Innovation, Natural Resources, urbanization, Non-Renewable Energy Consumption and GDP growth rate)

$$CO2_{it} = \propto_0 + \propto_1 (REC_{it}) + \propto_2 (TI_{it}) + \propto_3 (NR_{it}) + \propto_4 (URB_{it}) + \propto_5 (NREC_{it}) + \propto_6 (GDP_{it}) + \varepsilon_{it}$$

Where:

$\propto_0$ is the intercept

$\propto_1, \propto_2, \propto_3, \propto_4, \propto_5, \propto_6$, are the coefficients of the explanatory variables.

ε_{it} denotes the error term, which shows omitted variables in the specified model.

3.2. Data and Source

Research is based on panel data from 1990 to 2022 of 30 countries: Pakistan, Bangladesh, India, Indonesia, Malaysia, Myanmar, Thailand, Viet Nam, Nepal, Maldives, Bhutan, Armenia, Azerbaijan, Kazakhstan, China, Tajikistan, Kyrgyz Republic, Sri Lanka, Turkmenistan, Uzbekistan, Japan, Korea rep, Kuwait, Saudi Arabia, Singapore, Oman, Qatar, Bahrain, Israel, United Arab Emirates. Data were collected from WDI and UNCTAD

Table 1: Summary of Variables

Code	Variable Name	Measurement Unit	Source	E. Sign
Dependent Variable				
CO_2	Carbon Dioxide Emission	Kt (kiloton)	WDI	
Independent Variables				
REC	Renewable energy Consumption	Dividing the consumption of primary renewable energy by the total gross inland consumption of energy	WDI	_
TI	Technology Innovation	Patents and Intellectual Property Rights Index and R&D expenditure to measure the Technological innovation.	WDI	**+**
NR	Natural Resources	Total Natural Resources rents % of GDP	WDI	**-**
Control Variables				
URB	Urbanization	Urban population (% of total population)	WDI	-
NREC	Non-Renewable Energy Consumption	Fossil fuel energy consumption (% of total)	WDI	+
GDP	Gross Domestic Product	Gross Domestic Product	WDI	+

Source: By the author

3.3. Estimation technique

The empirical approach is organized into sequential stages. First, data selection and methodology take priority, followed by a comprehensive literature review and an analysis of cross-sectional dependence. Subsequently, the Hausman test is conducted on the dataset. Finally, the Generalized Method of Moments (GMM) estimation is employed to draw insightful conclusions from the data.

3.4. Dynamic Panel Data Model-System GMM

This study tests its hypothesis using System Generalized Method of Moments analysis. Dynamic panel data can lead to several econometric issues, such as Country-specific characteristics (e.g., geography and demographic structures) that persist over time and correlate with the explanatory variables. The residual term (U) of the model contains the unobserved country- specific effects, v, and the observation-specific errors

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For panel estimation, the credibility of the findings depends not only on coefficient significance but also on the assumptions underlying the instruments and the dynamic specification. In addition, reporting the number of instruments, the relevant overidentification test, and serial-correlation diagnostics is important when assessing System GMM results. Given the extended 1990–2022 observation period, estimator selection and the treatment of cross-country heterogeneity require particular care. The presented estimates

are therefore interpreted as reported associations unless appropriate diagnostics have established their identifying assumptions.

1. The fixed effect is contained in the error term in all three equations.
2. The existence of a dependent variable. GEN increases the autocorrelation problem in the model.
3. The panel data has a short time period (e.g., T = 16) and a large number of countries (i.e., N = 29). To address problems one and two, two-stage least squares (2SLS) is typically used in the literature.

Yet, the statistics from the first stage of a 2SLS regression may yield unreliable inference. When instruments are weak, both the OLS and fixed-effects IV estimators can be biased. To cope with problem number two, the difference GMM uses first differences. Blundell and Bond (1998) used first differences to transform the equations and found that first-differenced GMM estimators are ineffective when both time and the time series are limited. This is because weak solutions exist for the differenced equations. Solution 2k uses historical data for the first-differenced dependent variable. For short-T and large-N panels, the Arellano-Bond first-differenced-in-difference estimators were developed. In panel data, the persistence of a shock to a country's fixed effect diminishes over time, and the correlation between the dependent variable and the error term becomes negligible in later periods. This context is important for choosing an estimator. Arellano and Bond (1991) developed a first-differenced GMM estimator to address endogeneity in dynamic panel models. However, Blundell and Bond (1998) showed that the first-differenced estimator can be weak and biased in panels, especially when the dependent variable is highly persistent. This weakness arises because lagged levels of the variables become poor instruments for the first-differenced equations.

To address this limitation, Blundell and Bond (1998), building on Arellano and Bover (1995), developed the System GMM estimator. This method augments the first-differenced equations with level equations. It uses two sets of equations: one that instruments differences with lagged levels, and another that instruments levels with lagged differences. A key requirement is an additional moment condition: the first differences of the explanatory variables are uncorrelated with the country-specific fixed effects. This allows the lagged first differences to serve as valid instruments in the level equations, yielding a more efficient and consistent estimator.

4. Empirical Findings and Discussion

Table 3 presents descriptive statistics for the variables included in the empirical analysis.

Table 3: Descriptive Statistics of the Variables

Descriptive Statistics				
Variables	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
CO_2	5.051140336	9223.37203685	9223.37203685	9223.37203685
REC	.0025839646	75.3659098606	6.50134116719	9.95079868758
TI	1	1426644	42774.62	158844.596
NR	.0001692661	95.9000000000	29.4011949906	27.4662285952
URB	66.10200000	10944686.2000	293270.718589	922337.203685
NREC	8.854000000	100.000000000	52.6465023356	27.6747907732
GDP	41.80000274	82.8093290262	4.75032616928	6.78353076004

Source: By the author

Table 3 presents descriptive statistics for the variables used in the study. CO_2 measures range from 5.05 to 9223.37, with a high mean and standard deviation, reflecting high variability in the data. Renewable Energy Consumption (REC) measures from 0.0026 to 75.37, with a mean of 6.50, reflecting negligible to some varied use of renewable sources. Technological Innovation (TI) measures range from 1 to over 1.4 million, reflecting high variability in trade activities among nations. Natural Resource Rents (NR) measures show high variability, ranging from nearly zero to nearly 95.90%, with a mean of 29.40%. Urbanization (URB) measures range from a minimum of 66.10 to a maximum exceeding 10,000,000, reflecting huge variability in the number of urban dwellers. Non-Renewable Energy Consumption (NREC) has a mean of 52.65%, with a minimum measure of 8.85 to a maximum of 100%, reflecting its primary use in the industry's total consumption. Finally, GDP per capita measures have a mean of 4.75,

with a minimum of approximately 41.80 and a maximum of 82.81, and a moderate standard deviation, reflecting variability in development across the dataset.

Table 4: Hausman Test Result

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG (GDP PER CAPIT)	-9942.827	3337.293	-2.979309	0.0030
C	84661.76	28807.90	2.938839	0.0034
R-squared	0.017240	Mean dependent var		1.51E-11
Adjusted R-squared	0.015297	S.D. dependent var		107482.9
S.E. of regression	106657.7	Akaike info criterion		25.99657
Sum squared resid	5.76E+12	Schwarz criterion		26.01322
Log likelihood	-6601.128	Hannan-Quinn criter.		26.00310
F-statistic	8.876285	Durbin-Watson stat		0.076663
Prob(F-statistic)	0.003028			

Source: the author

4.1. Hausman Test

Because CO_2 = f(GDP) and GDP = f(CO_2), simultaneity may introduce endogeneity into the model. We initially examined endogeneity using the Hausman test. The reported specification motivates the consideration of instrumental-variable estimators. Table 05 Results of Panel Generalized Method of Moments (Middle-Income Countries)

Table 5: Panel GMM Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
RE	-2343.488	531.7818	-4.406860	0.0000
TI	2.310519	0.136816	16.88772	0.0000
NR	-354.0145	149.5067	-2.367884	0.0182
URB	-0.119860	0.013335	-8.988171	0.0000
NREC	488.0937	123.2455	3.960337	0.0001
GDP	7.27E-08	9.18E-09	7.917442	0.0000
C	36911.37	10837.94	3.405756	0.0007
Period fixed (dummy variables)				
R-squared	0.894923	**Mean dependent var**		112330.1
Adjusted R-squared	0.888451	**S.D. dependent var**		266819.0
S.E. of regression	89114.58	**Sum squared resid**		4.90E+12
Durbin-Watson stat	0.431148	**J-statistic**		3.21E-26
Instrument rank	39			

Source: the author

Table 05 presents the results of panel GMM for countries classified as middle-income, while Table 06 shows the differences between panel GMM results for middle-income countries and those for low-income and middle-to-high-income countries in developing Asia. The endogenous variable in this study is carbon emissions (kilotons). The 2SLS instruments are weighted by 656 unbalanced panel observations over 33 periods in 20 cross-sectional units from 1990 to 2022. Association between Renewable Energy Consumption and CO_2 Emissions: A unit increase in the exogenous variable of renewable energy consumption is associated with a decrease in CO_2 emissions by 2343.49 units. This negative association is highly significant (p = 0.0000), which indicates that renewable energy is associated with lower emissions. This result is consistent with evidence discussed by Cai et al. (2022), Esmaeili et al. (2023), and Ulucak (2020). Association between Technological Innovation and CO^2 Emissions: A unit increase in technological innovation is associated with a 2.31-unit increase in CO_2 emissions. This positive relationship is statistically significant because the p-value is 0.0000. However, one possible explanation is that some technologies stimulate industrial activities.

The income-group estimates in Table 6 indicate that the association between renewable energy consumption and emissions is negative in both reported groups, whereas technological innovation remains positively associated with emissions. However, natural resource rents have opposite coefficient

signs and are not statistically significant in either group at conventional thresholds. These differences align with the evidence reported by Baloch et al. (2019), who likewise document variation in the environmental associations of natural resources across economies. Moreover, the magnitude of the reported coefficients should not be compared mechanically across income groups without checking variable scaling, group composition, and estimation consistency. Consequently, the findings support a cautious discussion of heterogeneity rather than a claim that a single policy instrument will produce identical results in all countries.

4.1. Comparative Interpretation Across Income Groups

Association between Natural Resources and CO_2 Emissions: The estimated negative coefficient indicates that a one-unit increase in natural resource use is associated with a 354.01-unit decrease in CO_2 emissions. The model is significant at the 0.0182 level, indicating an association rather than a moderating effect. Association between Urban Population and CO_2 Emission: **A** one percent increase in urban population is associated with a 0.1199-unit decrease in carbon emissions, which is highly significant (p = 0.0000). This indicates that urbanization can also reduce emissions, perhaps due to resource or technological efficiency. However, these results differ from findings reported by Cai et al. (2022) and Abbas et al. (2023). Table 06 Results of Panel Generalized Method of Moments (Low- & High-Income Countries)

Table 6: Panel Generalized Method of Moments (Low- & High-Income Countries)

Low income					**High income**				
Var	**Coeff.**	**Std.error**	**t-Stat**	**Prob.**	**Var**	**Coeff.**	**St. Error**	**t-Stat**	**Prob.**
RE	-4331.90	1763.713	-1.91	0.05	**RE**	-8672.5	3744.8	-2.3	0.00
TI	1.40532	0.527711	8.34	0.00	**TI**	1.9	0.1	10.4	0.00
NR	-1948.5	3463.424	-0.85	0.39	**NR**	197.3	449.9	0.4	0.66
URB	-20521.9	3724.648	-2.82	0.00	**URB**	-3834.1	724.7	-5.2	0.00
NREC	2321.50	474.3902	6.28	0.00	**NREC**	455.9	161.8	2.8	0.00
GDP	2.52E-01	4.18E-08	8.40	0.00	**GDP**	9.62E-08	1.28E-08	7.5	0.00
C	265675.5	192356.2	2.42	0.01	**C**	392804.7	68036.1	5.7	0.00
R^2	0.654522	**Mean dep var**		427689.6	**R^2**	0.900377	**Mean dep var**		141989.9
Adj. R	0.651298	**S.D. dep var**		1495397.	**Adj. R**	0.898515	**S.D. dep var**		338347.2
S.E.R.	883046.0	**S.S resid**		5.01E+14	**S.E. R**	107777.9	**S.S resid**		3.73E+12
F-stat	203.0317	**D-W stat**		0.428090	**DW stat**	0.486720	**J-statistic**		8.51E-24

Source: the author

Consumption of Non-Renewable Energy Resources: An increase of one unit of non-renewable energy consumption raises CO_2 emissions by 488.09 units, ceteris paribus. This shows a strong positive association, statistically significant at p = 0.0001. This result is consistent with Ulucak (2020). GDP vs. CO_2 Emissions: For every one-dollar rise in GDP, CO_2 emissions increase slightly. Although the percentage rise is small, the large magnitude of GDP could still have a large impact. It is statistically significant (p-value of 0.0000) and can be compared with the analysis presented by Khan et al. (2022). The regression results show a strong positive association between fossil fuel consumption and GDP and CO_2 emissions, while renewable energy consumption, urbanization, and natural resource usage are linked to lower emissions. Technological innovation, despite its positive correlation, may reflect increased industrial activity that contributes to emissions. Although the model reports a high R-squared value, potential serial correlation, instrument validity, and estimator suitability require further investigation.

These empirical patterns have implications for the relationship between economic development and decarbonization. In particular, renewable energy expansion is consistent with lower estimated emissions, whereas the positive innovation coefficient suggests that technology policy alone may be insufficient without changes in the energy mix. Similarly, differences across income groups indicate a need to consider national institutional capacity, industrial structure, and resource dependence when interpreting the estimates (Baloch et al., 2019; Ulucak, 2020).

4.2. Robustness Check

In economics and finance, robustness assessments are an integral part of applied empirical study. After researchers establish their primary findings, they usually look for other processes that might explain them and provide further analyses using control and alternative instrumental-variable models. and limited-information maximum likelihood (LIML) estimators

Table 07: The Result of Robustness Check

Variable	Coeff.	Std. Error	t-Statistic	Prob.
RE	-2248.320	543.3556	-4.137843	0.0000
TI	2.504736	0.131469	19.05188	0.0000
NR	-228.6160	140.7394	-1.624392	0.1048
URB	-0.097898	0.013428	-7.290593	0.0000
NREC	563.7935	107.1370	5.262360	0.0000
GDP	6.06E-08	8.86E-09	6.846834	0.0000
C	28272.90	9723.474	2.907695	0.0038
R^2	0.880642	**Mean dependent var**		112330.1
Adjusted R^2	0.879538	**S.D. dependent var**		266819.0
Regression S.E.	92606.44	**Sum squared resid**		5.57E+12
F-stat	798.0687	**Durbin-Watson stat**		0.487838
Prob (F-stat)	0.000000	**Second-Stage SSR**		5.57E+12

Source: the author

4.3. Panel 2SEGLS

Two-stage least squares (2SLS) is an instrumental-variable estimation method that addresses endogeneity under appropriate instrument validity assumptions. It differs from ordinary least squares because endogenous regressors are instrumented.

Table 08: Panel Two-Stage EGLS

Variable	Coefficient	Std. Error	t-Statistic	Prob.
RE	-2248.320	522.8676	-4.299980	0.0000
TI	2.504736	0.126512	19.79841	0.0000
NR	-228.6160	135.4326	-1.688043	0.0919
URB	-0.097898	0.012922	-7.576267	0.0000
NREC	563.7935	103.0973	5.468560	0.0000
GDP	6.06E-08	8.52E-09	7.115120	0.0000
C	28272.90	9356.836	3.021630	0.0026
Effects Specification				
			S.D.	**Rho**
Period random			0.000000	0.0000
Idiosyncratic random			89114.58	1.0000
Weighted Statistics				
Adjusted R-squared	0.879538	**S.D. dependent var**		266819.0
S.E. of regression	92606.44	**Sum squared resid**		5.57E+12
F-statistic	798.0687	**Durbin-Watson stat**		0.487838
Prob(F-statistic)	0.000000	**Second-Stage SSR**		5.57E+12
Instrument rank	7			
Unweighted Statistics				
R-squared	0.880642	**Mean dependent var**		112330.1
Sum square Resid.	5.57E+12	**Durbin-Watson stat**		0.487838

Source: the author

Table 8 displays the results of a panel Two-Stage EGLS regression for CO_2 emissions (in kilotons) as the dependent variable. The model includes several explanatory variables and covers data from 30 countries or regions over 33 years (1990-2022), accounting for unbalanced panel data.

5. Conclusion & Policy Recommendations

5.1. Conclusion

This study shows that CO_2 emissions are heavily influenced by economic factors, energy choices, and technology. Fossil-fuel consumption and GDP show a strong link with CO_2 emissions, underscoring that carbon-intensive economic growth and dependence on non-renewable fuel sources are key drivers. Conversely, consumption of renewable fuel sources, the degree of urbanization, and natural resource management are linked to reduced CO_2 emissions. However, innovation shows a positive relationship with CO_2 emissions, perhaps because it is more directly associated with industrialization than with clean energy sources.

5.2. Policy Recommendations

To exploit the potential of renewable energy sources to reduce CO_2 emissions, policies should aim to maximize investment in renewable energy infrastructure. To this end, governments can offer tax incentives or subsidies to businesses and households to encourage the use of renewable energy sources. However, the positive association between technological innovation and emissions indicates that innovation policy should place greater emphasis on cleaner production and energy efficiency. Innovation policy should address sustainable practices. This can include funding research and development in green technology, encouraging industries to develop cutting-edge technology, and offering grants and tax exemptions to companies that embrace sustainable operations. In addition, the negative association between natural resource rents and emissions suggests that the regulations on resource extraction should be strengthened, and that sustainable practices in agriculture, forestry, and mineral resource management should be encouraged. There may also be value in establishing monetary rewards for communities that depend on these natural resources.

5.3. Limitations and Directions for Future Research

The study has several limitations that also provide directions for future research. First, the selected innovation measure combines a broad account of technological activity with emissions outcomes; future studies could distinguish general patenting from environmentally oriented patents and energy-saving innovation. Second, the sampled economies differ in industrial structure, income level, and resource dependence. Accordingly, future research could explore interactions between renewable energy consumption and innovation, as well as variations in institutional and regulatory settings. Third, the long observation period and the reported variation in country coverage call for further assessment of panel balance, cross-sectional dependence, and the suitability of alternative estimators. In addition, future research may investigate whether relationships differ across energy-intensive and less energy-intensive sectors, using transparent instrument diagnostics and comparable measurement units. These extensions would help explain the conditions under which innovation contributes to emissions reductions without changing the central research questions examined in this study (Baloch et al., 2019; Godil et al., 2021; Zhao et al., 2021).

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Appendix

List of Entities/ Countries

These Asian economies are included in the study to see the connection between carbon emissions and other variables, with a disaggregated analysis of carbon emissions.

Table A1: Developing Asian Countries

S. No	Entities	S. No	Entities	S. No	Entities
1	Pakistan	11	China	21	Japan
2	Sri Lanka	12	Bangladesh	22	Israel
3	Armenia	13	Viet Nam	23	Singapore
4	Azerbaijan	14	Nepal	24	Bahrain
5	Kazakhstan	15	Malaysia	25	United Arab Emirates
6	Tajikistan	16	Kyrgyz Republic	26	Korea Rep
7	Bhutan	17	Indonesia	27	Kuwait
8	Maldives	18	India	28	Saudi Arabia
9	Myanmar	19	Thailand	29	Oman
10	Turkmenistan	20	Uzbekistan	30	Qatar