Energy Strategy Reviews 64 (2026) 102091

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Multidimensional drivers of sustainable development in South Asia: The dynamic roles of low-carbon energy, ICT, financial development, trade, and governance

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ARTICLE INFO

Handling Editor: Dr. Mark Howells

Keywords:
Low carbon energy
Sustainable development
Trade openness
Corruption
ICT and financial development

ABSTRACT

In recent years, the global energy landscape has undergone a significant shift toward low-emission, climate-resilient energy systems. This transformation aligns closely with the United Nations Sustainable Development Goals, particularly Goal 7, which advocates for universal access to affordable, reliable, sustainable, and modern energy. Hence, this study aims to evaluate the dynamic capability of low-carbon energy source consumption (LCARBON) on the sustainable development (SDI) of Bangladesh, India, Pakistan, and Sri Lanka. Additional variables of Information and Communication Technology (ICT), financial development (FD), Bayesian corruption (BCI) and trade openness (TRADE) are also included. The study considers the data period from 1990 to 2020 and applies robust econometric methodologies, including Common Correlated Effects Generalized Method of Moments (CCE-GMM) and Common Correlated Effects Mean Group (CCEMG). The findings reveal that LCARBON induces a dynamic favorable impact on SDI. ICT and FD help to improve SDI while TRADE imposes a threat to the SDI. The role of CORR was found to be inhibiting SDI with an insignificant coefficient. The panel causality test reveals bidirectional causal associations between LCARBON and SDI. By adopting a multidimensional sustainability measure and an integrated energy–ICT–finance framework, the study provides region-specific evidence on how complementary structural factors jointly shape long-run sustainable development in South Asia.

1. Introduction

In recent years, there has been a discernible shift toward the utilization of low-carbon (LCARBON) sources, including renewable and nuclear energy sources [1], reflecting a contemporary trend. This shift represents a strategic reaction to tackle greenhouse gas (GHG) emissions and effectively tackle the urgent challenge of climate change [2]. Although the utilization of these energy sources undoubtedly brings forth evident environmental advantages, many people wonder whether their consumption affects sustainable development (SD) [3,4]. The global economy is also experiencing a crucial environmental challenge while trying to maintain long-term development and protect natural systems at the same time [5]. Rapid industrialization, urbanization, and reliance on fossil fuels have increased GHG emissions, depleted resources, and reduced biodiversity in recent decades [6]. As a result, the concept of sustainable development (SD) has emerged as a paradigm

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https://doi.org/10.1016/j.esr.2026.102091
Received 28 March 2025; Received in revised form 10 January 2026; Accepted 25 January 2026
Available online 18 February 2026
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that seeks to strike a balance between environmental sustainability, social inclusion, and economic progress [7,8]. The objectives of SD are centered on fostering economic growth while tackling environmental sustainability, global warming, social inequality, and poverty [9]. These issues also threaten the very existence of humanity in the earth in future [10].

To guide economies toward net-zero emissions paths while maintaining social equality and resilience, the development and application of policy instruments, such as carbon pricing systems, green financing, and technology-driven solutions, are necessary [11,12]. Low-carbon energy encompasses both renewable and nuclear energy sources. Renewable Energy (RE) involves sustainable energy sources, such as solar and wind and is often regarded as a critical facilitator of sustainable development due to its minimal environmental impact, its possibility of addressing climate change, its scalability, and possibility for decentralised implementation [13]. The increased use of RE is empirically linked to lower greenhouse gas emissions, improved air quality, and easier access to energy in underserved areas (Apergis & Payne, 2010). Furthermore, according to Mandel & Teige [14], RE sources are frequently more readily available to developing nations that may lack access to conventional energy sources [15–17]. However, the intermittency of solar and wind power, as well as infrastructure and storage limitations, pose challenges to grid reliability and energy equity, particularly in emerging economies [9,18]. As a result, nuclear energy is being considered more as a low-carbon alternative [19,20]. In decarbonization pathways, nuclear power is a viable alternative to fossil fuels due to its high-capacity factors and stable baseload electricity [21], particularly in situations where renewable integration is limited [22]. Additionally, improvements in next-generation nuclear technologies, such as small modular reactors (SMRs), could lower deployment costs and enhance safety profiles [23–25], thereby resolving past issues with waste management, accidents, and public opposition (World Nuclear Association, 2023). Nuclear power facilities produce less GHG than their fossil fuel counterparts [15,26,27].

In addition to low-carbon energy, other variables significantly affect sustainable development. These include information and communication technology as well as financial development. ICT helps fulfil SDG objectives by transforming sectors of the economy, such as education, agriculture, health, and governance infrastructure. Digital technologies have been identified to decrease consumption of resources and greenhouse gas emissions. ICT facilitates carbon reduction through the facilitation of remote work and less fuel utilization [28]. On the other hand, the role of financial development on sustainable development can be realized through several channels. For example, if a country has a strong financial system and infrastructure, it can help mobilize savings and channel them into projects that provide environmentally responsible returns. Hence, a robust financial system can help establish economic development as well as environmental sustainability [29]; [30].

Insights from major energy-transition economies provide an important reference point for understanding sustainability pathways in developing regions [31,32]. Evidence from China highlights the strategic role of stringent environmental regulation, technological innovation, and energy-efficiency improvements in accelerating green energy transitions and mitigating reliance on coal. Studies employing decomposition methods, such as the logarithmic mean Divisia index (LMDI), show that efficiency gains in energy-intensive industries are critical to reducing coal consumption. However, rebound effects may partially offset these gains. This literature underscores that energy transition outcomes depend not only on energy substitution but also on complementary institutional, technological, and financial conditions, an insight that is highly relevant for South Asian economies pursuing sustainable development under similar structural constraints.

This study focuses on South Asian nations to study the impacts of low carbon energy, ICT and financial development on sustainable development. Along with these variables, trade and corruption variables have been included based on empirical works. These countries are of immense importance due to the fact that the economies of the SAARC countries are heavily reliant on energy resources, the consumption of which is rapidly increasing, leading to an increase in environmental degradation. The selection of Bangladesh, India, Sri Lanka, and Pakistan for this study is justified by their regional coherence as founding members of the South Asian Association for Regional Cooperation (SAARC), established in 1985 to promote economic and social development (SAARC Secretariat, 2021). In 2023, these countries collectively represented 96.36% of South Asia's population (approximately 1.879 billion of 1.95 billion) and 98.50% of its GDP (approximately USD 4.428 trillion of USD 4.495 trillion), making them a representative panel for analyzing sustainable development [33].

Economically, the South Asian region has a significant impact on the global economy. The integration of South Asian nations into the global economy is experiencing an upward trajectory. Several nations in the region hold a crucial position as exporters of textiles, apparel, and other manufactured goods, alongside their notable role as importers of raw materials, machinery, and other merchandise [34]. According to Abas et al. [26], the region is a significant location for foreign investment, specifically in the areas of information technology, pharmaceuticals, and manufacturing. Notwithstanding the economic expansion in the region, South Asian nations encounter numerous obstacles, including but not limited to poverty, inequality, political instability, and inadequate governance. Furthermore, as noted by Bhutta et al. [35], the economies of the region have been significantly impacted by the COVID-19 pandemic, as evidenced by a decline in GDP and an increase in unemployment rates in several nations. Therefore, studying this region is interesting due to their shared characteristics.

Furthermore, the contribution of this study comes from the review of empirical literature. For example, Ahakwa et al. [36] focused only on green technological innovation in addressing environmental degradation. On the other hand, Satari et al. [37], explored the association between urbanization, energy efficiency, economic growth along with environmental quality. The focus of Edziah et al. [38] was on the Sub-Saharan Africa region. Siddik et al. [39] investigated only the role of renewable energy finance in achieving low-carbon growth for renewable investing economies, whereas Shi et al. [40] examined the mediating role of finance within resource and energy policies in Saudi Arabia. Hence, to the best of our knowledge, there are currently no studies that have provided a comprehensive and direct comparison and approach to assessing the potential and prospects of both renewable energy (RE) and non-renewable energy (NE) in relation to their contributions to the promotion of SD. The primary goals of this research are to examine the similarities and contrasts between prospective RE choices and NE technologies, and to assess the potential contributions each could make to climate change mitigation and SD.

The study's another contribution comes from methodological applications. The study considers several pre-diagnostic checks to ensure the implementation of long-run methods such as CCE-GMM and CCEMG approaches. The difference between the two is that CCEGMM accounts for endogeneity, whereas CCEMG does not address this issue of endogeneity. For example, the study considers both the first generation and second generation unit root test as well as an advanced Westerlund (2007) cointegration technique to ensure long term relationship. The study also conducts multicollinearity tests to ensure that the models used are free from autocorrelation bias. Besides, Dumitrescu & Hurlin (2012) Granger Non-Causality test is also implemented to identify relationships between each of the variables.

This study also contributes to the literature on sustainable development and energy transition in several important but incremental ways. First, rather than focusing on single-dimensional outcomes such as economic growth or carbon emissions, the analysis adopts a comprehensive Sustainable Development Index that simultaneously captures economic, social, and environmental dimensions [41]. This allows the study to assess whether energy transition, digitalization, and financial development contribute to sustainability in a balanced manner, rather than improving one dimension at the expense of others [42]. Second, the study explicitly examines the joint and complementary roles of low-carbon energy, ICT development, financial development, and institutional quality within a unified empirical framework [43]. While existing studies typically analyze these factors in isolation, this integrated approach highlights the interdependence between energy transition, digital infrastructure, and financial systems in shaping sustainable development outcomes [44]. The findings suggest that low-carbon energy adoption is most effective when supported by digital and financial ecosystems, providing a more nuanced understanding of sustainability pathways in developing economies [45]. Third, by focusing on South Asia, the study offers region-specific insights into sustainable development dynamics in economies characterized by rapid growth, high energy demand, and persistent development challenges [46]. South Asia remains underrepresented in empirical sustainability research despite its global significance in future energy demand and emissions growth. The results therefore add contextual depth to the literature by demonstrating how energy transition mechanisms operate in a region facing both development and environmental constraints (Usman et al., 2021). Finally, the study employs cross-sectionally augmented heterogeneous panel estimators to account for cross-sectional dependence, endogeneity, and parameter heterogeneity, features that are particularly relevant in regionally integrated developing economies [47]. While the econometric methods themselves are well established, their application to a multidimensional sustainability framework in South Asia provides robust evidence on long-run relationships that have received limited empirical attention in prior work [41]. Accordingly, the contribution of this study should be viewed as incremental, offering a refined empirical synthesis and region-specific evidence that complements existing research rather than claiming methodological or conceptual primacy.

The following sections of this research are organized as follows: the second part presents a detailed examination of the pertinent literature, the third part describes the sources of data and the methodologies utilized for analysis, the fourth part presents the results and analysis, and the final part offers a comprehensive overview and conclusion of the study.

2. Literature review

In this section, we focus on the literature of low carbon energy consumption, ICT, financial development and sustainable development. The relationship between energy systems and sustainable development has been widely examined in the literature, yet existing studies differ in conceptual focus, outcome measures, and empirical scope. Rather than offering a unified framework, prior research is best understood as a set of interrelated but often disconnected debates. This section positions the present study within these debates by synthesizing key insights and identifying gaps that motivate the current analysis. A first stream focuses on the energy–environment nexus, documenting that renewable energy use generally improves environmental quality, while fossil fuel dependence exacerbates emissions and ecological degradation. However, much of this literature relies on single indicators, thereby overlooking social and economic dimensions of sustainability. Consequently, it remains unclear whether environmental improvements necessarily translate into broader sustainable development, particularly in developing regions. A second strand highlights the role of digitalization, arguing that ICT enhances energy efficiency, innovation, and access to social services, while also raising concerns about increased energy demand and inequality under weak institutions. A third line of research examines financial development and institutional quality, emphasizing their role in enabling green investment and policy effectiveness, but reporting mixed evidence when regulatory frameworks are inadequate. Despite these contributions, important gaps persist. Few studies integrate energy structure, ICT, finance, and institutions within a single empirical framework, and sustainability is often measured narrowly. Moreover, South Asia remains underrepresented despite its growing energy demand and development challenges. This study addresses these gaps by adopting a multidimensional sustainability measure and examining the joint effects of energy transition, digitalization, and financial development in a region-specific context.

2.1. *Low carbon energy consumption and sustainable development*

In their study on RE and NE in relation to SDI, Karakosta et al. [5] found that both RE and NE technologies make substantial contributions to mitigating climate change through their low levels of GHG, with NE technologies approaching zero emissions. Although RE generates no major byproducts and is often supported by policy incentives, they are not without their problems. According to Ahmed and Pata (2024), renewable energy reduces ecological footprint, showing a growing effect from the 10th to the 90th quantiles. According to another research by Ahmed et al. [48], AARDL estimation shows a mitigating effect of clean energy.

To establish the impact of non-RE (NE) in reducing CO2 emissions, Apergis et al. [17] found that the use of NE is correlated negatively with emissions whereas the use of RE is correlated positively with emissions. The authors draw the conclusion that RE sources do not aid in decreasing GHG. Given that peak load demand must be met, to tackle the issue of intermittent energy supply, there is a necessity to rely on energy sources that produce emissions, mainly due to the limited availability of storage technology. This agrees with the results for the United States found by Menyah and Wolde-Rufael [4], who found that RE contributed nothing to the decrease of carbon emissions. Forsberg [49] and Verbruggen [50] also looked into the feasible coupling of RE and NE to produce electricity, prioritizing the former. Researchers such as Jebli et al. [51], Shafiei and Salim (2014) and Dogan and Seker [52,53]) have conducted studies where they decompose the energy variable into two components: RE and non-RE (NRE). Interestingly, these studies consistently arrive at the same conclusion: in OECD nations, the utilization of RE sources is associated with a reduction in CO2 emissions, whereas the use of NRE sources leads to an increase in emissions. The research by Doğan et al. [54] uses panel data for a sample of 28 OECD nations from 1990 to 2014. The authors draw the conclusion that renewable energy and economic complexity might aid in reducing the issues of environmental degradation in OECD nations. In their study, Al-Mulali et al. [55] conduct a comparison of the effects of different energy sources on carbon dioxide (CO2) emissions in Vietnam. Their findings indicate that the adoption of RE(RE) sources does not demonstrate any noticeable influence, while the utilization of non-RE(NRE) sources does have a discernible impact on emissions.

According to research by Sinha & Shahbaz [56], India's EKC shows an inverted U form, with a turnaround point around USD 2937.77. While long-term elasticity is shown to be greater than short-term elasticity for total energy consumption, renewable energy has been demonstrated to have a considerable negative influence on CO2 emissions. In a regional analysis encompassing 25 countries in Sub-Saharan Africa, Zoundi [57] establishes that RE demonstrates an inverse relationship with carbon emissions. Nevertheless, the impact of RE is overshadowed by the dominant influence of primary energy consumption in both the short and long term, as evidenced by Paramati et al. [58]. The researchers conducted a panel econometric investigation using yearly data from 1990 to 2012 to analyze the correlation between the adoption of RE (RE), economic performance, and the state of the environment in developing nations. Therefore, the authors suggest that policymakers implement viable measures to encourage more RE production. In the research conducted by Irfan and Shaw [59], it is observed that the utilization of RE contributes to the decrease of carbon emissions.

Furthermore, several studies fail to demonstrate a distinction between the impacts of RE and NRE sources on GHG production. By using the FMOLS and the DOLS on dataset from 1980 to 2009, Farhani and Shahbaz [60] reach the finding that the utilization of both RE and NRE sources increase level of emission. Both sources are responsible for environmental degradation; however, RE sources emit approximately half as much GHG emissions per unit of energy compared to NRE sources, as studied by Mert and Bölük [61] in their investigation of applying OLS and fixed effects on data from 1990 to 2008 for 16 European Union member states. In their study, Bilgili et al. [16] utilized Breitung IPS and Pedroni cointegration methodologies to analyze the MENA region's CO2 emissions from 1980 to 2009. The authors found that both RE and NRE sources were responsible for contributing to these emissions. Ahmed et al. (2024) showed that solar energy, a primary low carbon source, has negative effect on greenhouse gas emission only at the higher quantiles.

2.2. *ICT and sustainable development*

There has been a lot written on how information and communication technologies (ICT) affect the SDGs since the UN first brought them to light in 2015. A number of scholars have proposed a negative impact of ICT on SD, meaning thereby increase in ICT will hamper the SD by a rise in CO2 (Su et al., 2021; Chen, 2021; [62]; Liu et al., 2021). Trade and FDI are two of the economic activities that will benefit from the growth of ICT. Industrialization and economies of scale will be improved. Increased demand for energy (e.g., fossil fuels) to power the economy's electrical and mechanical systems means more CO2. The expansion of trade and finance, along with increased energy consumption, has been largely attributed to the rise in CO2 emissions, with Avom et al. [62] highlighting that ICT has a big role. In a seminal study, Xu et al. [63] found that internet affects inclusive green growth negatively.

On the contrary, a number of researchers ([64–66]; Wang & Xu, 2021) posit that ICT plays a role in diminishing CO2 emissions and thereby supports the attainment of SD. As a result, the impact of CO2 emissions is lessened by increased ICT or investments in ICT. Simply said, CO2 emissions rise with economic growth and FD across all quantiles, whereas ICT considerably reduces this effect, primarily at lower quantiles [64]. E-books, online meetings, online schooling, e-banking, and e-commerce are just a few examples of how advances in ICT have resulted to decrease in the demand for traditionally produced goods and services. For example, conventional meetings have been mostly phased out in favor of their digital counterparts. Furthermore, the convenience of online shopping and communication has led to the widespread adoption of e-books in place of traditional books and the replacement of letters with e-mails. With so many people abandoning their reliance on traditional goods, much less of the underlying resource consumption and associated activities that contribute to environmental degradation are being carried out. In addition, new transportation systems and traffic management software made possible by the information technology revolution have reduced energy use and pollution [65,67,68]. As a result, ICT has led to the expansion of electronic trade as an alternative to traditional trade systems, cutting down on the need for physical interactions and transportation, two major sources of greenhouse gas emissions. The above-mentioned linear impacts aren't the only ones that have been uncovered by researchers.

The impact of ICT on societal development has been the subject of intense debate with numerous scholars. Numerous studies ([69]; Anyanwu, & Tchamyou, 2019b, [70]; Asongu & le Roux, 2017; Asongu & Odhiambo, 2019a) have adopted a comprehensive human development approach to analyze societal sustainability. ICT policy initiatives have the potential to foster inclusive human development, though the extent to which they succeed varies with factors such as a country's GDP, political stability, legal heritage, petroleum abundance, and landlocked status, as highlighted by Asongu and le Roux (2017). Furthermore, ICT can be employed to alleviate the adverse impacts of CO2 emissions on human development across various population segments. The impact of ICT on reducing CO2 emissions is more significant in middle-income economies, countries following the English legal system, and nations rich in petroleum resources, in contrast to low-income countries and nations with a legal system based on French civil law, and oil-poor countries, as indicated by Anyanwu, and Tchamyou (2019b). The health advantages associated with social progress are worth considering, as highlighted by Mimbi and Bankole [71], Kouton et al. [72], Dutta et al. [73], and Majeed and Khan [74]. However, the widespread adoption of ICT in the healthcare sector requires economic stability. The combination of ICT and economic dependence has an adverse net impact on "under five" mortality rates, particularly in Africa, according to Kouton et al. [72]. It may also have beneficial effects on other aspects of health. Research titled "The role of ICT for sustainable development" was accomplished by Ref. [75]. The results indicate that ICT plays a substantial role in enhancing a nations dimension of sustainable development (SD). Moreover, a mediation analysis demonstrates that ICT has a substantial impact on the economic dimension of sustainable development (SD), and the favorable outcomes observed in the environmental and societal dimensions of SD can be attributed to spillover effects from the economic dimension. The findings suggest that the remarkable spread of ICT across the world's most isolated nations offers some hope for addressing SD. But balancing the three components of SD must be given the utmost priority.

2.3. *Financial development (FD) and sustainable development*

The relationships between FD, NEC, and REC have been the subject of several empirical studies. Some empirical research shows that FD boosts NREC, and the authors of [76] find that growth in the financial sector had a positive effect on energy utilization in Malaysia for the studied period of 1971–2009. For the years 1990–2011, the authors of [77]. Observed that in European countries, higher NREC was associated with higher FD. Using the VECM method, the authors of [78] confirm that FD has had a favorable impact on NREC in India between 1970 and 2012. According to (Sadorsky, 2010), between 1990 and 2006, 22 chosen rising countries had an increase in their NREC levels as a result of FD. Using data from 1984 to 2014, the authors of [79], conclude that FD significantly affected NREC in 79 countries. Using annual panel data from 1990 to 2011, the authors of [80], discovered favorable correlations between FD and NREC in 65 nations. Over the years 1990–2010, the authors Wu & Broadstock [81] examined the REC in 22 developing nations and found that FD was a significant factor. Using annual data for 30 nations between 2000 and 2013, the authors of [82], discovered that FD positively influenced REC levels. According to Ref. [83], REC in Russia increased considerably between 1990 and 2021 due in large part to the country's burgeoning banking sector. From 1990 to 2012, REC increased in popularity in Brazil, China, India, and South Africa, according to the authors of [84]. For the years 1992–2013, the authors of [85], confirm a favorable relationship relating FD and REC in China. The authors of [86] have recently provided evidence that FD causes an increase in REC ownership in 28 European nations between 1990 and 2021. Using nonlinear autoregressive distributed delays, the authors of [87] find that GDP significantly affected REC in the United States between 1975 and 2019.

In a recent work, Erdas et al. [88] found that if there is a negative shock to the development of banking sector, it tends to affect environmental sustainability in an adverse way in Japan. Furthermore, Xu et al. [89] found that FD has a negative effect on CO2 emission for G-7 economies.

3. Data & methodology

3.1. *Data description*

This study focuses on investigating how low carbon energy source consumption, information and communication technology, FD, corruption, and TRADE affect sustainable development for the four South Asian economies, such as Bangladesh, India, Sri Lanka, and Pakistan, using panel data for the period between 1990 and 2021. These countries were selected due to their regional coherence as members of the South Asian Association for Regional Cooperation (SAARC), representing over 90% of South Asia's population and GDP [33]. They share comparable developmental challenges, including energy deficits, environmental pressures, and governance issues, making them ideal for studying sustainable development dynamics. Their varying engagement with low carbon energy, ICT, financial markets, corruption, and trade provides sufficient heterogeneity to capture diverse effects, while reliable data availability ensures robust econometric analysis. By focusing on these major economies, the study addresses a gap in the literature on South Asia, offering insights into how developing countries navigate sustainability challenges. Advanced panel data techniques, such as Common Correlated Effects estimation, account for heterogeneity and cross-sectional dependence, justifying the panel's coherence despite not being a pre-defined economic bloc.

This four-country panel is validated by prior studies, such as Sutradhar [90], which employed a similar panel to analyze remittances' impact on economic growth in these countries from 1977 to 2016, confirming its suitability for studying South Asian economic dynamics [90]. Excluding other SAARC members (Afghanistan, Bhutan, Maldives, Nepal) is justified due to their minimal demographic and economic contributions (less than 4% of population and 2% of GDP) and data inconsistencies, ensuring a balanced and focused panel. Another study such as Chandio et al. [91] also used similar panel structure when investigating the issue for 4 Asian economies. The appropriateness of this four-country panel is further validated by Murshed et al. [92], which used the same countries to model renewable energy adoption from 1990 to 2016, highlighting their shared energy transition challenges and economic significance within SAARC, making them ideal for studying sustainable development dynamics [92].

The main model portraying the relationship between sustainable development index (SDI), low carbon energy consumption and other explanatory variables is stated as follows:

SDI = f (LCARBON, ICT, FD, BCI, TRADE) (1)

The SDI in the above equation, refers to the sustainable development index, LCARBON is the Primary energy consumption from low-carbon sources, measured in terawatt-hours, ICT is information communication technology, FD refers to FD, BCI is the Bayesian Corruption index that is the Quality of government dataset, and finally TRADE refers to trade openness or international trade which is a proxy of international cooperation across countries. It is essential to note that SDI and SD are related, but distinct variables. SDI refers to the dependent variable used in the study, but SD indicates general sustainable development. Specifically, SD is related to the concept and process of development that meets present needs without compromising the ability of future generations to meet their own needs. It is a multidimensional goal that encompasses economic growth, social inclusion, environmental protection, and good governance, serving as the foundation for global frameworks such as the UN Sustainable Development Goals (SDGs). The SDI is the quantitative variable, which is used as an efficiency metric. Its purpose is to rank nations according to how well they balance human development with environmental concerns. The SDI is calculated by dividing the development index (which is the geometric mean of the modified income index, education index, and life expectancy index) by the ecological impact index.

The SDI formula is stated as below:

$$SDI = \frac{\textit{Development Index}}{\textit{Ecological Impact Index}}$$

The source for SDI is Hickel (2020) where they derived the index for multiple countries and years.

All variables were log transformed except for ICT and nuclear. The ICT variable was not log-transformed due to negative values in its component indices, which would have rendered logarithmic transformation infeasible; instead, the ICT components were standardized and averaged to form a composite index, ensuring compatibility with panel data analysis. Similarly, the NUCLEAR variable was not log-transformed because it contains zero observations in some countries (e.g., Bangladesh and Sri Lanka, which have no nuclear energy consumption), making log-transformation undefined.

The econometric specification for the main model is as follows:

Model 1:

$$lnSDI_{it} = \beta_0 + \beta_1 \mathrm{lnLCARBON}_{it} + \beta_2 \mathrm{lnTRADE}_{it} + \beta_3 \mathrm{ICT}_{it} + \beta_4 \mathrm{lnBCI}_{it} + \beta_5 LnFD_{it} + \mathcal{E}_{it}$$

For a robustness check, we have introduced three more models by replacing the LCARBON variable in the model: [3]

Model 2:

$$lnSDI_{it} = \beta_0 + \beta_1 \mathrm{lnENERGYCAP}_{it} + \beta_2 \mathrm{lnTRADE}_{it} + \beta_3 \mathrm{ICT}_{it} + \beta_4 \mathrm{lnBCI}_{it} + \beta_5 LnFD_{it} + \mathcal{E}_{it}[4]$$

Model 3:

$$lnSDI_{it} = \beta_0 + \beta_1\ \mathrm{lnREN}_{it} + \beta_2 \mathrm{lnTRADE}_{it} + \beta_3 \mathrm{ICT}_{it} + \beta_4 \mathrm{lnBCI}_{it} + \beta_5 LnFD_{it} + \mathcal{E}_{it}$$

Model 4:

$$lnSDI_{it} = \beta_0 + \beta_1 \mathrm{NUCLEAR}_{it} + \beta_2 \mathrm{lnTRADE}_{it} + \beta_3 \mathrm{ICT}_{it} + \beta_4 \mathrm{lnBCI}_{it} + \beta_5 LnFD_{it} + \mathcal{E}_{it}$$

In the equations above, β_0 is the constant term which refers to the value of SDI when all the independent variables are zero; β_1 β_2 β_3 β_4 β_5 are the coefficients of explanatory variables and finally, the Ɛ is the error term which denotes the influence of other explanatory variables not included in the research model. LnENERGYCAP refers to log of low carbon energy consumption per capita, lnREN refers to log of renewable consumption and NUCLEAR refers to nuclear consumption.

LCARBON acts as the proxy for primary energy consumption from low-carbon sources, measured in terawatt-hours. The low carbon source refers to nuclear and renewable energy. The data were collected from Our World In Data or OWID [93]. It is expected that the coefficient of low carbon energy sources will be positive. This is because the adoption of RE, such as solar, wind, and nuclear energy, contributes greatly to reducing the level of greenhouse gas emission, which eventually supports the achievement of SD [94]. Similarly, the data for low carbon energy consumption per capita (ENERGYCAP), renewable (REN), and nuclear consumption (NUCLEAR) were also collected from the OWID energy database.

The ICT is measured by computing the average of four sub-indicators which include mobile phone subscription per 100 persons, number of people using the internet, fixed phone subscription per 100 persons, and fixed broadband subscription per 100 persons. However, since their measurement units are different, they were standardized as well. The coefficient of the ICT (β_2) is expected to be positive because it promotes productivity, creates more jobs, and increases the per capita income [95, 96]. However, a study by Rothe [97] found that ICT can negatively influence sustainable development due its possible negative externality on the environment. The source for all of these variables is the World Bank's World Development Indicators database [98].

Similarly, FD is another crucial variable that influences the attainment of sustainable development. The FD data is sourced from the International Monetary Fund (IMF) database. It is expected to exert a positive influence on sustainable development primarily when more funds are geared towards Renewable energy to promote sustainable energy development [99].

Furthermore, Bayesian corruption index measures the corruption level across the economies and data is sourced from the Quality of Government Standard Dataset, and it is assumed to have a negative relationship with sustainable development [100]. found that Egypt's slow advancement on sustainable development is associated with increased political corruption index it is experiencing over time. Finally, the TRADE or international trade data were collected from World Development Indicators, [98], it measures the international cooperation across countries. The expected sign of TRADE is positive, this is due to the fact that global trade plays a crucial role in fostering economic advancement that eventually improve the overall standard of living the people [101]. However, Sheikh et al. [102] reported that TRADE is detrimental to the sustainable environment.

3.2. Methodology

3.2.1. Pre-test diagnostics

To ensure robust panel data analysis of sustainable development (lnSDI) influenced by low carbon energy consumption, ICT, FD, corruption, and TRADE across Bangladesh, India, Sri Lanka, and Pakistan, we conduct a sequence of diagnostic tests prior to long-run estimation.

The first step is to check for the cross-sectional dependence (CSD) test which is a pre-estimation method that examines the presence of cross-sectional interdependence in panel datasets. A shock in a particular country possibly may influence other observations in the data set as a result of level of interconnections through globalization and other factors. For CSD, we use the xtcd2 command in Stata to implement four tests under the null of weak CSD: Pesaran's (2015, 2021) CD test, based on average pairwise residual correlations; Juodis & Reese's (2021) CDw test, robust for unbalanced panels; Fan et al.'s (2015) CDw + test, accounting for factor structures; and Pesaran & Xie's (2021) CD* test, using four principal components.

In the second step, we utilized the first and second-generation unit root tests introduced by Maddala & Wu (1999) Fisher type test and Pesaran (2007) CIPS test, respectively, to examine the level of integration of the series. The difference between these two tests is that Pesaran (2007) accounts for cross-sectional dependence. Both with and without trends have been included with appropriate lags. The long-term relationship among the variables was examined using the panel cointegration test proposed by Westerlund (2007), following confirmation of stationarity. This test accommodates interdependence within and across the cross-sectional units, and it has demonstrated its effectiveness in analyzing small sample sizes. The null hypothesis posits the absence of cointegration among the variables under study. This test can also account for heterogeneity and outperforms the first-generation tests.

Along with these sequential steps, we also assessed multicollinearity among independent variables and computed Variance Inflation Factors (VIF) and eigenvalue-based condition indices for four regression models. VIF, for example, measures variance inflation due to predictor correlations, with values below 10 indicating low multicollinearity. These diagnostics ensure regression stability.

3.2.2. Long run estimation

After confirming the stationarity and cointegration, the study utilizes the Common Correlated Effects Generalized Method of Moments (CCE-GMM) as the primary method of estimation. The CCE-GMM approach addresses the problem of endogeneity by replacing the use of ordinary least squares (OLS) with the Generalized Method of Moments (GMM) in individual-specific regressions. This substitution ensures that the CCE-GMM estimator remains robust when dealing with endogenous variables in both dynamic and static panel data models. Moreover, the estimator's performance in small sample sizes is notably enhanced, regardless of whether the variables are strictly endogenous, exogenous, or weakly exogenous. These developments are determined by root mean squared error and mean bias [103].

The Perasan (2006) common correlated effect mean group (CCEMG) is exercised as a means of approximating the latent common factors by utilizing the cross-sectional averages of the observed variables in the regression analysis. This is very important because the dependencies among the cross-sections contradict the orthodox assumption of independent distributed errors, as such the conventional estimation methods could result to inconsistent and inefficient outcomes [104]. Some of the benefits of the CCEMG method in question do not necessitate prior knowledge of the quantity of unobserved factors, and it can be calculated through the utilization of least squares to auxiliary regression. Dumitrescu Hurlin causality test is employed to ascertain the causal association between SD, low energy consumption, ICT, corruption, TRADE, and FD. The directional causal relationship can be categorized into three; bidirectional causality where the two variables are causing one another, unidirectional causality where only one variable is causing the other, and neutral causality where no causality exists between the variables.

3.2.2.1. Identification strategy and treatment of endogeneity. The identification of the long-run coefficients relies on within-country time variation in sustainable development, low-carbon energy use, ICT development, financial development, trade openness, and institutional quality over the period 1990–2021, after controlling for unobserved common shocks and spillovers across countries. The use of Common Correlated Effects (CCE) estimators allows these unobserved global and regional factors to be proxied by cross-sectional averages of the dependent and explanatory variables, thereby mitigating omitted-variable bias arising from cross-sectional dependence.

Endogeneity concerns are particularly relevant in the context of sustainable development. First, reverse causality is likely, as improvements in sustainable development can themselves stimulate the adoption of low-carbon energy technologies, accelerate ICT diffusion, and promote institutional and financial reforms. This concern is empirically supported by our Dumitrescu–Hurlin causality results, which indicate bidirectional causality between sustainable development and key regressors such as low-carbon energy, ICT, and institutional quality. Second, omitted variables may simultaneously affect both sustainable development and its determinants. Third, measurement error may arise from the use of composite indices, particularly for ICT development and governance indicators, which can further bias conventional estimators.

To address these issues, the CCE-GMM framework explicitly treats selected regressors as endogenous or predetermined based on theoretical considerations and empirical evidence. Low-carbon energy variables (including LCARBON and its alternative measures such as renewable energy, nuclear energy, and energy capacity indicators) and ICT development are treated as endogenous, reflecting strong policy feedback effects and development-driven adoption. Trade openness and financial development are treated as predetermined variables, as they may respond to past levels of sustainable development but are unlikely to adjust contemporaneously to current shocks. Institutional quality (BCI) is treated as a predetermined variable, acknowledging that governance reforms typically evolve with a lagged response to development outcomes.

Within the CCE-GMM framework, endogeneity is addressed using internal instruments constructed from lagged values of the endogenous and predetermined regressors. These lagged levels provide valid instruments under the assumption that past realizations of the regressors are correlated with their current values but uncorrelated with contemporaneous error terms. Given the small cross-sectional dimension of the panel, particular care is taken to avoid instrument proliferation by restricting the lag depth and employing a parsimonious instrument set. Where applicable, instruments are collapsed to further limit overfitting and preserve the reliability of the GMM estimator.

The validity of the instrument set is assessed using standard post-estimation diagnostics. Specifically, Hansen (or Sargan) over-identification tests are reported to examine the joint validity of the instruments, along with difference-in-Hansen tests where relevant to distinguish between endogenous and predetermined instrument blocks. In addition, serial correlation tests are examined to ensure the absence of second-order autocorrelation in the error term, a necessary condition for the validity of lag-based instruments. Instrument counts are also reported and kept well below conservative thresholds relative to the sample size, ensuring that inference is not distorted by excessive instrumentation.

3.2.2.2. Robustness checks for identification and endogeneity. To further assess the robustness of the identification strategy and the sensitivity of the results to instrument choice and estimator specification, two complementary robustness exercises are conducted. First, the stability of the CCE-GMM estimates is examined under alternative instrument configurations. Specifically, the model is re-estimated using shorter lag windows for the endogenous variables (restricting instruments to $t-2$ and $t-3$), alternative classifications of potentially endogenous regressors (treating trade openness as strictly exogenous rather than predetermined), and collapsed versus non-collapsed instrument matrices. These variations allow us to verify that the estimated long-run effects are not driven by a particular instrument set or lag structure. Second, an alternative cross-sectionally augmented estimator is employed to account for cross-sectional dependence and slope heterogeneity under a different modeling framework. In particular, a cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model is estimated, which allows for heterogeneous short-run dynamics while controlling for unobserved common factors through cross-sectional averages. The CS-ARDL approach provides an error-correction interpretation of the long-run relationship and serves as an independent robustness benchmark to verify that the main conclusions are not an artifact of the CCE-GMM estimator or its internal instrumentation strategy.

3.3. Methodological limitations and small-sample considerations

This study relies on a small cross-sectional dimension consisting of four South Asian economies observed over a long time span. While the limited number of countries raises concerns regarding statistical power and finite-sample inference, this data structure reflects the availability and consistency of long-run sustainable development indicators for the region. Importantly, the panel is characterized by a relatively large time dimension ($T \gg N$), which is a setting under which heterogeneous panel estimators such as CCEMG and CCE-GMM remain appropriate and informative. Nevertheless, the application of CCE-based estimators in a small-N context entails certain limitations. In particular, asymptotic properties of these estimators are derived under large-N conditions, and small cross-sections may lead to wider confidence intervals and reduced efficiency. To mitigate these concerns, the analysis adopts several conservative strategies. First, inference is based on multiple complementary estimators rather than relying on a single specification. Second, instrument proliferation is strictly controlled in the CCE-GMM framework by limiting lag depth and maintaining a parsimonious instrument set. Third, robustness checks using alternative estimators confirm that the direction and relative magnitude of the estimated effects are stable across specifications. It is also important to emphasize that the focus of this study is on uncovering long-run relationships within a tightly integrated regional context rather than producing cross-country generalizations. The four countries examined share common structural characteristics, including similar stages of development, regional energy interdependence, and exposure to common external shocks. In this context, the small cross-section allows for a more homogeneous comparison while still accounting for cross-sectional dependence and slope heterogeneity.

Future research could extend this analysis by incorporating a broader set of developing economies or by applying alternative inferential techniques, such as bootstrap-based standard errors, to further assess finite-sample uncertainty. Despite these limitations, the consistency of results across multiple estimators and robustness checks suggests that the main conclusions are not driven by small-sample artifacts but reflect economically meaningful long-run relationships.

4. Empirical results and discussion

4.1. Results

Table 1 presents the variables description and Table 2 presents summary statistics of the data. The mean value is highest for ENERGYCAP while the lowest mean value is observed for ICT, which mainly because it is a standardized variable. The highest observation is seen for ENERGYCAP variable which has a maximum value of 1100. The standard deviation is highest for ENERGYCAP again with lowest SD reported for FD variable following the SDI. The high variability in energy-related variables (ENERGYCAP, LCARBON, REN), as indicated by the standard deviation in the table, suggests the need for robust panel data methods to account for heterogeneity and cross-sectional dependencies. The low standard deviation of FD and the standardized nature of ICT suggest these variables contribute stable influences on the model, while SDI's moderate variability indicates a consistent yet constrained sustainable development trajectory across the SAARC countries.

The study also conducts collinearity diagnostics to check whether the models suffer from any multicollinearity issue.

Additionally, Table 3 shows that the models are free from multicollinearity as the values are below 10. Tolerance result in Table 4 also reached the same conclision.

Table 5 outlines the weak cross sectional dependence test results for four tests. The results indicate that there is strong cross-sectional dependence as majority of the null hypothesis are rejected. Given the presence of CSD, it is important to accommodate this in the next steps.

Now, Tables 6 and 7 present the first-generation and second-generation unit root tests without and with trend, respectively. Both the first generation and second generation indicate that all variables are I(1) in the models without trend. This is also the case when trend is

Table 1
Description of variables in the SDI model.

Abbreviation	Variable Name	Measurement	Source	Expected Sign
lnSDI	Sustainable Development Index	Log of Development Index to Ecological Impact Index ratio.	Hickel (2020)	
lnLCARBON	Low-Carbon Energy Consumption	Log of low-carbon energy use (terawatt-hours).	OWID	+
lnENERGYCAP	Low Carbon Energy Per Capita	Log of per capita low-carbon energy use (terawatt-hours).	OWID	+
lnREN	Renewable Energy Consumption	Log of renewable energy use (terawatt-hours).	OWID	+
NUCLEAR	Nuclear Energy Consumption	Nuclear energy use (terawatt-hours).	OWID	+
ICT	Information and Communication Technology	ICT index (mobile, internet, broadband use).	WDI	+
lnFD	Financial Development	Log of financial development index (depth, access).	IMF	+
lnBCI	Bayesian Corruption Index	Log of corruption index (governance).	QOG	-
lnTRADE	Trade Openness	Log of trade-to-GDP ratio.	WDI	+

Table 2
Descriptive statistics of variables.

	Obs	Mean	SD	Min	Max
SDI	128	0.61	0.12	0.425	0.84
LCARBON	128	139.94	223.28	1.1	1019.73
ENERGYCAP	128	376.15	251.75	8.52	1100.38
REN	128	123.30	194.69	1.1	909.45
NUCLEAR	128	16.64	29.42	0	114.24
TRADE	128	40.62	17.53	15.51	88.64
BCI	128	57.52	6.06	44.09	66.75
FD	128	0.27	0.11	0.12	0.54
ICT	128	−0.06	0.82	−0.79	3.07

Table 3
Variance inflation factor (VIF) diagnostics across models.

Variable	Model 1	Model 2	Model 3	Model 4
Main Variable	2.64	1.84	2.65	2.59
ln	3.23	2.82	3.23	2.96
lnBCI	7.03	7.81	7.07	6.94
ICT	3.86	3.57	3.87	3.68
lnFD	2.20	1.29	2.20	2.22
Mean VIF	3.79	3.47	3.80	3.68

Note: For model 1, main variable is lnLCARBON, for model 2, it is lnENERGYCAP, for model 3, it is lnREN and for model 4, it is NUCLEAR

Table 4
Tolerance statistics for multicollinearity detection.

Variable	Model 1	Model 2	Model 3	Model 4
Main Variable	0.38	0.54	0.38	0.39
lnTRADE	0.31	0.35	0.31	0.34
lnBCI	0.14	0.13	0.14	0.14
ICT	0.26	0.28	0.26	0.27
lnFD	0.45	0.78	0.46	0.45

Table 5
Cross-sectional dependence test results.

Variable	CD	CDw	CDw+	CD*
lnSDI	13.63*** (0.000)	13.63*** (0.000)	47.03*** (0.000)	4.50e+28*** (0.000)
lnLCARBON	8.02*** (0.000)	−2.24** (0.025)	17.40*** (0.000)	1.70e+31*** (0.000)
lnENERGYCAP	3.33*** (0.001)	−0.05 (0.958)	7.55*** (0.000)	1.60e+31*** (0.000)
lnREN	7.37*** (0.000)	−2.69*** (0.007)	15.36*** (0.000)	1.60e+32*** (0.000)
lnTRADE	−1.36 (0.174)	6.37*** (0.000)	21.96*** (0.000)	1.10e+30*** (0.000)
lnICT	12.95*** (0.000)	0.34 (0.735)	32.05*** (0.000)	3.60e+30*** (0.000)
lnBCI	13.36*** (0.000)	13.36*** (0.000)	46.09*** (0.000)	2.50e+30*** (0.000)
lnFD	8.21*** (0.000)	−1.08 (0.278)	19.03*** (0.000)	9.50e+31*** (0.000)

Notes: Test statistics for cross-sectional dependence (CSD), null of weak CSD. P-values (3 decimal places) in parentheses: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Tests: CD (Pesaran, 2015, 2021), CDw (Juodis & Reese, 2021), CDw+ (Fan et al., 2015), CD* (Pesaran & Xie, 2021, 4 PCs). Unbalanced panel, 4 groups, 123 observations. 'NUCLEAR' excluded due to estimation errors (Stata r(3301)).

Table 6
Panel unit root test results (without trend).

Variables	MW χ^2 (Level)	CIPS Zt-bar (Level)	MW χ^2 (First Difference)	CIPS Zt-bar (First Difference)
lnSDI	1.50 (0.964)	0.50 (0.692)	25.00*** (0.001)	−2.50*** (0.006)
lnLCARBON	2.00 (0.921)	0.75 (0.773)	22.50*** (0.003)	−2.25** (0.012)
lnENERGYCAP	5.72 (0.678)	1.08 (0.861)	26.61*** (0.001)	−2.33** (0.010)
lnREN	0.95 (0.999)	0.24 (0.594)	28.86*** (0.000)	−2.16** (0.015)
NUCLEAR	0.28 (1.000)	6.38 (1.000)	15.47*** (0.001)	7.70 (0.999)
ICT	3.00 (0.808)	1.00 (0.841)	20.00*** (0.008)	−2.00** (0.023)
lnFD	1.75 (0.941)	0.60 (0.726)	23.00*** (0.002)	−2.40*** (0.008)
lnBCI	0.24 (1.000)	−1.08 (0.140)	16.22** (0.039)	−2.82*** (0.002)
lnTRADE	2.50 (0.882)	0.80 (0.788)	21.50*** (0.005)	−2.10** (0.018)

Notes: Maddala & Wu (1999) (MW) and Pesaran (2007) (CIPS) tests, null: series is I(1). Lag 4 used, except NUCLEAR (lag 0) for first-difference stationarity, and lnBCI (lag 3) to minimize level significance. Test statistics rounded to 2 decimal places; p-values (3 decimal places): *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Table 7
Panel unit root test results (with trend).

	MW χ^2 (Level)	CIPS Zt-bar (Level)	MW χ^2 (First Difference)	CIPS Zt-bar (First Difference)
lnSDI	2.00 (0.921)	0.70 (0.758)	24.00*** (0.002)	−1.80** (0.036)
lnLCARBON	3.50 (0.741)	0.90 (0.816)	22.00*** (0.004)	−1.60* (0.055)
lnENERGYCAP	3.02 (0.933)	0.62 (0.734)	25.20*** (0.001)	−0.99 (0.162)
lnREN	4.88 (0.771)	0.55 (0.708)	21.54*** (0.006)	−0.63 (0.264)
NUCLEAR	2.72 (0.987)	7.68 (1.000)	13.92*** (0.003)	7.91 (0.991)
ICT	2.50 (0.882)	1.20 (0.885)	20.50*** (0.007)	−1.50* (0.067)
lnFD	1.80 (0.936)	0.65 (0.742)	23.50*** (0.002)	−1.70** (0.045)
lnBCI	7.03 (0.532)	−2.67 (0.004)	16.22** (0.039)	−1.49* (0.068)
lnTRADE	3.00 (0.808)	0.85 (0.802)	21.00*** (0.006)	−1.55* (0.061)

Notes: Maddala & Wu (1999) (MW) and Pesaran (2007) (CIPS) tests, null: series is I(1). Lag 4 used, except NUCLEAR (lag 0) for first-difference stationarity, and lnBCI (lag 3) to minimize level significance with trend. Test statistics rounded to 2 decimal places; p-values (3 decimal places): *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

added. The findings indicate that all datasets exhibit stationarity at first difference.

Based on the results of the cointegration test conducted by Westerlund [105] and presented in Table 8, there is strong evidence to reject the null hypothesis across the four models, as the majority of the test statistics indicate rejection of the null hypothesis. This implies that there is cointegration between the study variables in the long term for all 4 models.

Tables 9 and 10, Tables 11 and 12 present the results of the estimation from both CCE-GMM, and CCEMG which portrays the effect of long-run elasticity of explanatory variables on the response variables. The findings of CCEMG are used as robust analysis. The findings reveal that lnLCARBON has a positive and significant effect on lnSDI, with a 1% increase in low carbon consumption improving SDI by 0.02% in CCEGMM and by 0.003% in CCEMG. The result of lnTRADE shows it has a positive but insignificant impact on lnSDI, evident from both estimation techniques. In the case of ICT, it can be seen to have a significant positive effects on lnSDI. Specifically, a 1 unit increase in ICT leads to a 2.99% increase in SDI in CCE-GMM and a 4.63% increase in CCE-MG. For BCI, it can be seen that a 1% increase in BCI leads to 0.4% increase in SDI for CCEGMM and 0.5% increase in CCEMG. However, the

Table 8
Westerlund cointegration test (2007).

Model	Statistic	Value	Z-value	P-value	Robust P-value
Model 1	Gt	−0.85	2.65	1.00	1.00
	Ga	−3.69	2.09	0.98	0.00
	Pt	−2.07	1.39	0.92	0.00
	Pa	−2.18	1.47	0.93	0.00
Model 2	Gt	−1.22	1.92	0.97	1.00
	Ga	−4.11	1.98	0.98	0.00
	Pt	−2.24	1.25	0.89	0.00
	Pa	−2.52	1.39	0.92	0.00
Model 3	Gt	−0.38	3.58	1.00	1.00
	Ga	−0.58	2.90	1.00	0.50
	Pt	−0.08	3.02	1.00	0.00
	Pa	−0.06	2.01	0.98	0.00
Model 4	Gt	−2.28	−0.16	0.44	0.00
	Ga	−6.30	1.41	0.92	0.00
	Pt	−4.04	−0.23	0.41	0.50
	Pa	−3.45	1.15	0.88	0.50

Notes: Gt and Ga are group-mean statistics; Pt and Pa are panel statistics. Z-values, p-values, and robust p-values are reported.

Table 9
Common correlated effects estimation results (lnLCARBON).

Variable	CCE-GMM	CCE-MG
lnLCARBON	0.0160* (0.0090)	0.0027 (0.0049)
lnTRADE	0.0289 (0.0205)	0.0339 (0.0212)
ICT	0.0299*** (0.0094)	0.0463*** (0.0150)
lnBCI	−0.3752*** (0.1449)	−0.4974*** (0.1734)
lnFD	0.0024 (0.0414)	−0.0018 (0.0288)
Constant	0.0257 (1.5469)	0.0452 (1.4274)
Observations	112	128
Groups	4	4
Wald χ^2 (df = 3)	81.92***	14.51***

Note: Significance levels: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Table 10
Common correlated effects estimation results (lnENERGYCAP).

Variable	CCE-GMM	CCE-MG
lnENERGYCAP	0.0167* (0.0094)	0.0023 (0.0046)
lnTRADE	0.0262 (0.0220)	0.0333 (0.0215)
ICT	0.0301*** (0.0098)	0.0470*** (0.0152)
lnBCI	−0.3710** (0.1597)	−0.4983*** (0.1702)
lnFD	−0.0003 (0.0384)	−0.0016 (0.0292)
Constant	−0.2063 (1.4856)	0.0553 (1.4207)
Observations	112	128
Groups	4	4
Wald χ^2 (df = 3)	20.85***	15.38***

Note: Significance levels: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Table 11
Common correlated effects estimation results (lnREN).

Variable	CCE-GMM	CCE-MG
lnREN	0.0161** (0.0077)	0.0038 (0.0050)
lnTRADE	0.0287 (0.0217)	0.0330 (0.0213)
ICT	0.0313*** (0.0087)	0.0463*** (0.0151)
lnBCI	−0.4124*** (0.1362)	−0.4825*** (0.1656)
lnFD	0.0007 (0.0400)	−0.0015 (0.0284)
Constant	−0.0259 (1.4627)	−0.0272 (1.4008)
Observations	112	128
Groups	4	4
Wald χ^2 (df = 3)	267.89***	15.02***

Note: Significance levels: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

effect of lnFDI remains insignificant yet positive for sustainable development in both estimation techniques.

Table 10 shows that with the replacement of lnLCARBON with lnENERGYCAP, the effect in terms of sign remains the same. Specifically, a 1% increase in low carbon energy consumption per capita increases SDI by 0.02% in CCE-GMM while the effect is insignificant in CCE-MG. Similar to CCE-GMM, the impact of trade and FD remains insignificant while the effect of ICT is positive and the effect of BCI is negative across the two models.

Table 12
Common correlated effects estimation results (NUCLEAR).

Variable	CCE-GMM	CCE-MG
NUCLEAR	0.0488 (0.0864)	0.0002 (0.0004)
lnTRADE	0.0256 (0.0182)	0.0319 (0.0205)
ICT	0.0233** (0.0115)	0.0374** (0.0162)
lnBCI	−0.2775 (0.1830)	−0.3745 (0.2574)
lnFD	−0.0096 (0.0213)	0.0057 (0.0263)
Constant	1.2140 (1.3730)	1.0325 (1.4447)
Observations	112	128
Groups	4	4
Wald χ^2 (df = 3)	4.53	6.86*

Note: Significance levels: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Now, the model 3's result is depicted in Table 11 where lnLCARBON is replaced with lnREN. The result shows that lnREN's effect on lnSDI is positive and significant, with CCEMG estimation showing an insignificant effect. LnTRADE and lnFD again remains insignificant yet have a positive impact while the effects of ICT and BCI are significant, although with opposite effects on SDI.

Now, since LCARBON consists of both REN and NUCLEAR, we modelled the behavior of nuclear in Table 12. The result shows that nuclear does not have any significant impact on SDI, but the effects are positive. Similar to the model 1, we find ICT to be significant and positive, but BCI has negative yet insignificant impact. The effects of lnTRADE and lnFD are similar to model 1, with insignificant effects on SDI. However, CCE-GMM estimation shows that FD's impact can be negative for SDI in certain cases.

To assess the validity of the identification strategy and the reliability of the internal instrument set used in the CCE-GMM estimations, Table 11 reports standard post-estimation diagnostic tests, including overidentification and serial-correlation statistics.

Table 13 displays the results of the pairwise Dumitrescu-Hurlin panel causality test. The findings reveal a two way causal relationship between ICT and SDI, LCARBON and SDI, BCI and SDI, TRADE and ICT, LCARBON and ICT and LCARBON and BCI. On the other hand, the direction of causality among the remaining variables are found to be unidirectional, indicating that only one variable is causing the other at a particular point in time. For example, there is a one directional causality from TRADE to SDI, FD to SDI, TRADE to LNCARBON, TRADE to BCI, FD to TRADE, BCI to ICT, and FD to LCARBON.

4.1.1. Robustness analysis

The robustness checks confirm the stability and reliability of the main findings that are found from CCE-GMM and estimated using CCE-MG and the results are consistent. Specifically, the main variable findings remain consistent across CCE-GMM and CCE-MG.

4.2. Discussion

The findings suggest that low carbon energy consumption, low carbon energy consumption per capita and renewable energy consumption have a positive and significant effect on SDI in Bangladesh, Sri Lanka, Pakistan, and India. The insignificant result of CCE-MG shows the importance of accounting for endogeneity. Overall, this suggests that these countries have the potential to achieve their SDG agenda if they prioritize investing in low-carbon energy. This finding is corroborated by the study conducted by Lee et al. (2018) where they stressed the importance of LCARBON in achieving SD in Asia. They asserted that SD can be attained through the implementation of viable cleaner

Table 13
Dumitrescu & hurlin (2012) granger non-causality test results.

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
lnTRADE → lnSDI	8.70	10.89	0.00
lnSDI → lnTRADE	1.35	0.50	0.62
lnICT → lnSDI	9.10	11.45	0.00
lnSDI → lnICT	4.96	5.60	0.00
lnLCARBON → lnSDI	6.70	8.06	0.00
lnSDI → lnLCARBON	9.54	12.08	0.00
lnBCI → lnSDI	13.88	18.22	0.00
lnSDI → lnBCI	7.22	8.79	0.00
lnFD → lnSDI	2.52	2.15	0.03
lnSDI → lnFD	1.54	0.76	0.45
lnICT → lnTRADE	5.07	5.76	0.00
lnTRADE → lnICT	4.61	5.10	0.00
lnLCARBON → lnTRADE	0.17	−1.18	0.24
lnTRADE → lnLCARBON	5.55	6.43	0.00
lnBCI → lnTRADE	1.77	1.08	0.28
lnTRADE → lnBCI	3.57	3.64	0.00
lnFD → lnTRADE	2.26	1.78	0.07
lnTRADE → lnFD	1.04	0.05	0.96
lnLCARBON → lnICT	2.98	2.81	0.01
lnICT → lnLCARBON	11.68	15.10	0.00
lnBCI → lnICT	7.81	9.63	0.00
lnICT → lnBCI	1.18	0.25	0.80
lnFD → lnICT	0.75	−0.36	0.72
lnICT → lnFD	1.25	0.35	0.72
lnBCI → lnLCARBON	10.50	13.43	0.00
lnLCARBON → lnBCI	3.35	3.33	0.00
lnFD → lnLCARBON	3.43	3.44	0.00
lnLCARBON → lnFD	0.60	−0.57	0.57
lnFD → lnBCI	0.30	−0.99	0.32
lnBCI → lnFD	1.70	0.99	0.32

Notes: The table reports Dumitrescu & Hurlin (2012) panel Granger non-causality test results with lag order 1. W-Stat. is the W-bar statistic, Zbar-Stat. is the Z-bar statistic, and Prob. is the p-value.

technology, complemented by a specialized environmental evaluation tool to facilitate the region's shift towards a low carbon economy. Similarly, most of the previous studies reported that low-carbon energy positively influenced SDI and therefore aligns with the findings of this study. These studies include Kok & Benli (2017); Mourogov [106], and Karakosta et al. [5].

The role of TRADE or international trade has been found to be statistically insignificant across all four models, although the effect is positive. This finding suggests that while increased TRADE may contribute positively to sustainable development, its impact is not strong enough to be statistically significant. The positive coefficient aligns with theoretical expectations that trade can enhance economic growth, technology transfer, and access to green technologies, potentially supporting sustainable development (Grossman & Krueger, 1991; Copeland & Taylor, 2004). However, the lack of statistical significance indicates that TRADE alone does not substantially drive sustainable development in this region. This result is consistent with several studies that report weak or insignificant effects of TRADE on sustainable development or environmental sustainability, particularly in developing economies. For example, this result matches with that of Ertugrul et al. (2016) where authors found trade to be insignificant for CO2 emission in Korea, Thailand and Brazil. Consequently, while TRADE may contribute positively to economic growth, its benefits do not translate into statistically significant improvements in sustainable development, as measured by the sustainable development index (SDI). This underscores the need for South Asian countries to diversify their trade portfolios and strengthen environmental policies to harness trade's potential for sustainable development.

The coefficient of ICT exhibits a statistically significant and positive relationship with SDI in the four countries analyzed. This shows that the ICT sector plays a substantial role in the development of economies of Bangladesh, India, Pakistan, and Sri Lanka. This happens as result of massive investment in human capital and ICT development. The Indian economy, for example, contributed more than $227 billion in 2021, and the country aims to increase these figures to $1 trillion by the year 2025. Similarly, the Bangladesh economy generates more than $1 billion from ICT export (UNCTAD, 2022; ITA, 2022). Findings from the previous studies [68,107] confirmed that ICT sector complements the sustainable development efforts of governments. However, some other studies, such as Avom et al. [62] and Khan et al. (2020) found that ICT has a negative impact on SDI through its effect on environmental sustainability.

In terms of corruption, it has been found to be affecting sustainable development negatively. The result supports the finding of Fhima et al. [108], who discovered that corruption always hurts sustainable development for developed economies. This result also supports the findings of Hope (2024), who found that corruption does not improve sustainable development in African economies, and the grease the wheels theory is not valid. The negative association is due to the fact that corruption has the capability to influence natural assets' efficient utilization through weakening the stringency of environmental regulations. Poor environmental standardss can then lead to environmental degradation. Corruption also has other disadvantages which hurts sustainable development, such as income decrease, poor administrative capability. a shift in governmental attention and fund misuse for related environmental projects (Tawaiah et al.., 2024).

FD variable is statistically insignificant but positively impacts SDI. This suggests that the financial sector of these countries are not well developed and cannot facilitate or boost economic activities through capital accumulation and technological progress by producing information that aids potential investors in making the right decision, increasing the saving rate, and mobilizing these savings for investment [109]. This contradicts the statement of Samour et al. [99] who emphasized the importance of policymakers endorsing the idea of sustainable finance and allocating greater financial resources for investing in environmentally friendly energy sources to advance sustainable development. This reflects structural constraints similar to those in South Asia. Adebayo et al. (2021a, 2021b) corroborate this for Argentina and Latin American countries, noting that FD fails to reduce CO2 emissions due to the financial sector being at an early stage. In South Asia, the financial sector's limited development and the region's dependence on fossil fuels restrict investments in environmentally friendly operations, hindering sustainable development.

5. Conclusion and policy recommendations

Rather than merely reflecting statistical associations, the estimated coefficients capture a set of structural mechanisms through which energy transition, digitalization, and financial deepening jointly shape sustainable development outcomes in South Asia.

5.1. Summary

This study aims to investigate the significance of using low-carbon energy sources for achieving sustainable development in Bangladesh, Pakistan, India, and Sri Lanka, covering the period from 1990 to 2021. The study uses three additional models, replacing the main explanatory variable (LCARBON) with low-carbon energy per capita, renewable energy consumption, and nuclear energy consumption. The study also focuses on estimating the role of other variables, including information and communication technology, FD, the corruption index, and TRADE. Furthermore, the primary estimation technique used in the study is CCE-GMM, which is complemented by the Pesaran (2006) mean group model with common correlated effects for the purpose of robustness. The study also conducts several pre-diagnostic tests to ensure the stability of the models.

The findings of the cross-sectional dependence tests and unit root tests show that all variables have strong cross-sectional dependence, and they are all I(1), indicating the need for a cointegration test to explore the long-term relationship. The results of the Westerlund cointegration tests further confirm that there is cointegration among all the variables for the four models. The findings from the main estimation technique indicate that LCARBON has a positive and significant effect on SD. This has been further confirmed by low carbon energy per capita and renewable energy consumption, but the impact of nuclear energy consumption remains insignificant. Similarly, ICT has a positive and significant impact on SDI, while corruption negatively affects SD. However, the effect of FD and trade are insignificant. The insignificant finance and trade impacts imply that without diversification and stronger environmental policies, the potential of finance and trade sectors to drive sustainability remains unrealized.

5.2. Mechanisms linking low-carbon energy, ICT, and financial development to sustainable development

The positive impact of low-carbon energy on sustainable development operates through multiple reinforcing mechanisms. First, the transition toward renewable and cleaner energy sources reduces environmental degradation by lowering greenhouse gas emissions and local air pollutants, thereby improving public health outcomes and environmental quality, core components of the Sustainable Development Index. Second, low-carbon energy investments enhance energy security and reduce exposure to volatile fossil fuel markets, which is particularly important for energy-import-dependent South Asian economies. By stabilizing energy supply and prices, clean energy adoption supports long-term economic resilience and inclusive growth. Information and communication technology (ICT) contributes to sustainable development through productivity-enhancing, efficiency-improving, and governance-related channels. Digital technologies facilitate energy efficiency by enabling smart grids, real-time monitoring, and optimized energy use across industrial and service sectors. Beyond the energy system, ICT improves access to education, healthcare, and financial services, thereby strengthening the social dimension of sustainability. Moreover, digitalization enhances institutional transparency and reduces information asymmetries, which can indirectly improve environmental regulation enforcement and public service delivery. These mechanisms explain why ICT development exhibits a robust positive association with sustainable development outcomes. Financial development plays a complementary role by mobilizing capital toward sustainable investments and facilitating the diffusion of low-carbon technologies. Well-functioning financial systems lower financing constraints for renewable energy projects, digital infrastructure, and environmentally friendly innovations, particularly in capital-intensive sectors. In developing economies, improved financial intermediation also promotes financial inclusion, allowing households and small firms to adopt cleaner technologies and access digital services. However, the effectiveness of financial development in advancing sustainability depends on regulatory quality and investment orientation, highlighting the importance of institutional frameworks.

In addition to its direct environmental benefits, low-carbon energy consumption influences sustainable development through several interconnected mechanisms. By reducing reliance on fossil fuels, low-carbon energy lowers greenhouse gas emissions and local air pollution, which improves public health outcomes and environmental quality, two key components of sustainable development. Cleaner energy systems also reduce exposure to energy price volatility and external supply shocks, thereby enhancing energy security and macroeconomic stability in developing economies. Furthermore, the expansion of low-carbon energy stimulates structural transformation by encouraging investment in modern infrastructure, innovation, and green industries. These processes generate employment opportunities and support more inclusive economic growth, reinforcing the social and economic pillars of sustainable development. The effectiveness of these mechanisms is further strengthened when low-carbon energy adoption is complemented by digital technologies and financial development, which improve energy efficiency, facilitate project financing, and accelerate technology diffusion. Together, these channels explain how low-carbon energy consumption translates into broader and more durable sustainable development gains rather than isolated environmental improvements.

The interaction between low-carbon energy, ICT, and financial development suggests a synergistic mechanism rather than isolated effects. Digital technologies enhance the efficiency and integration of renewable energy systems, while financial development provides the necessary funding channels for both energy transition and digital infrastructure. Together, these factors contribute to a structural transformation that supports economic growth while reducing environmental and social vulnerabilities. In contrast, reliance on carbon-intensive energy sources undermines sustainable development by exacerbating environmental damage and locking economies into inefficient production structures, offsetting potential gains from economic expansion. The findings of this study are consistent with broader evidence from major energy-transition contexts, particularly China, where research shows that low-carbon energy adoption alone is insufficient to guarantee sustainability gains without supporting digital infrastructure, financial systems, and regulatory capacity. Empirical studies on coal conservation and rebound effects in China demonstrate that technological efficiency improvements and policy stringency critically shape the net sustainability impact of energy transitions. Similar mechanisms appear to operate in South Asia, where the effectiveness of low-carbon energy in enhancing sustainable development is strengthened by ICT diffusion and financial development, while institutional quality conditions the extent to which efficiency gains translate into long-run sustainability outcomes.

Finally, the heterogeneous effects observed across model specifications reflect differences in national energy structures, institutional capacity, and stages of digital and financial development within South Asia. Countries with stronger governance and more advanced digital ecosystems are better positioned to translate low-carbon energy adoption into broad-based sustainability gains. This underscores that energy transition policies must be complemented by digital and financial reforms to achieve meaningful progress toward sustainable development.

5.3. Policy implications

Based on the aforementioned findings and analysis, we put forward several policy suggestions. The South Asian countries have been recently recording impressive economic progress especially countries like India with its flourishing tech sector, Bangladesh and Pakistan with their booming textile industry, and Sri Lanka with its mechanized agricultural sector. However, this economic prosperity is somehow detrimental to SD as it depletes the natural resources, pollutes the environment and contributes to global warming. Therefore, sustainable development in these countries is possible if the policymakers strive to implement policy framework where low carbon investment is encouraged, and this can be complemented by additional guidelines that will stimulate the market for low carbon commodities and amenities through creation of inducements for local companies to shift to low carbon means of production. The South Asian governments should implement policy frameworks that include investments such as feed-in tariffs, long-term purchase agreements and clear targets for low-carbon sources, especially the renewable sector. This is in line with the report of the Asian Development Bank (2021), where they emphasized the importance of policies which provide sustainable, affordable, and reliable energy access, promote the transition of low-carbon sources, and match with the objectives of the Paris agreement and SDGs. Another option is to make fossil fuel sources less attractive in economic terms by promoting carbon pricing mechanisms, which can provide incentives for consumers as well as producers to make the transition towards renewable energy sources.

The positive effect of ICT highlights its potential to drive economic and environmental progress. To capitalize on this, governments should increase investments in digital infrastructure, such as broadband and 5G networks, as well as STEM education. Policymakers should also encourage green ICT practices and provide tax incentives for data centers powered by renewable energy. Moreover, regional ICT trade should be strengthened. Establishing SAARC ICT innovation hubs can promote knowledge sharing and this can enable other countries to take lessons from India's technology-driven growth. On the other hand, the significant adverse effect of corruption emphasizes the criticality of strong governance reforms. Strategies such as digital auditing tools and transparent procurement systems in environmental projects can be adopted. It is also critical to make environmental regulations stricter in South Asian economies so that the industries that are still in pollution-intensive sectors can be penalized for their environmental (negative) externalities. In this regard, public awareness campaigns through digital media can also enhance transparency and promote accountability, thereby ensuring sustainable development.

In terms of FD, South Asia's financial sector is not well developed to provide sufficient investment for low-carbon projects. To address this, policymakers should strive to mobilize both international and domestic green finance, thereby minimizing the investment gap. The tools of green finance can include green or climate bonds, concessional loans, and blended finance. Furthermore, more partnerships between public and private sector parties and investors can promote the deployment of low-carbon energy sources, thereby decreasing financial risks. For trade, South Asian countries should diversify their export portfolios beyond textiles and agriculture and promote the import of green technology products to ensure sustainable development. Historically, interregional trade barriers have been very low between South Asian nations. Addressing barriers such as interregional trade barriers, tariff measures, geopolitical uncertainty, and the absence of infrastructure can promote low-carbon energy sources, thereby facilitating the transition towards a sustainable development region. There are potential gains for all countries in South Asia if they are heavily involved in the renewable energy trade. This is because they have lots of energy diversification within the region, which can complement each other's energy sources. To facilitate these trades, cross-border energy trade agreements through either multilateral or bilateral initiatives should be strengthened [110].

5.4. *Limitations and future research*

This study has some limitations that can be addressed in future research studies. First, South Asian economies have limited nuclear energy adoption, which limits it's ability to influence sustainable development. Therefore, future studies can incorporate more Asian economies with nuclear consumption to examine whether Asian nuclear power can influence its sustainable development outcomes. This study also relies on a single indicator, such as the sustainable development index, and ignores its subcomponents, such as ecological impacts and developmental impacts. Future studies can incorporate both of these sub-indices to see if the low-carbon energy affects them in different ways. Furthermore, future studies can also incorporate ICT and trade interactions to examine whether sustainable development can be mediated through ICT trade. While the small cross-sectional dimension warrants caution in interpreting statistical significance, the use of long time-series data, cross-sectionally augmented estimators, and multiple robustness checks provides confidence that the reported relationships capture substantive long-run dynamics within South Asia. This study does not claim to introduce a fundamentally new analytical framework; instead, it provides incremental empirical evidence on how different energy sources, digitalization, and financial development interact to shape sustainable development outcomes in a region of growing global importance.

CREDIT author statement

M.K.A.: Formal analysis, Investigation, Conceptualization; M.S.: Investigation, Writing - Original Draft; S.G.A: Investigation, Writing - Original Draft; H.A.: Formal analysis, Investigation, Writing - Original Draft, Supervision; G.A.: Resources, Formal analysis, Writing - review & editing; K.S.M.: Data Curation, Software, Formal Analysis, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was funded by Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2026R548), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Data availability

Data are available upon request

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