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Evaluating energy sustainability and causal impact of belt and road initiatives (BRI) in energy-deficient Asian countries

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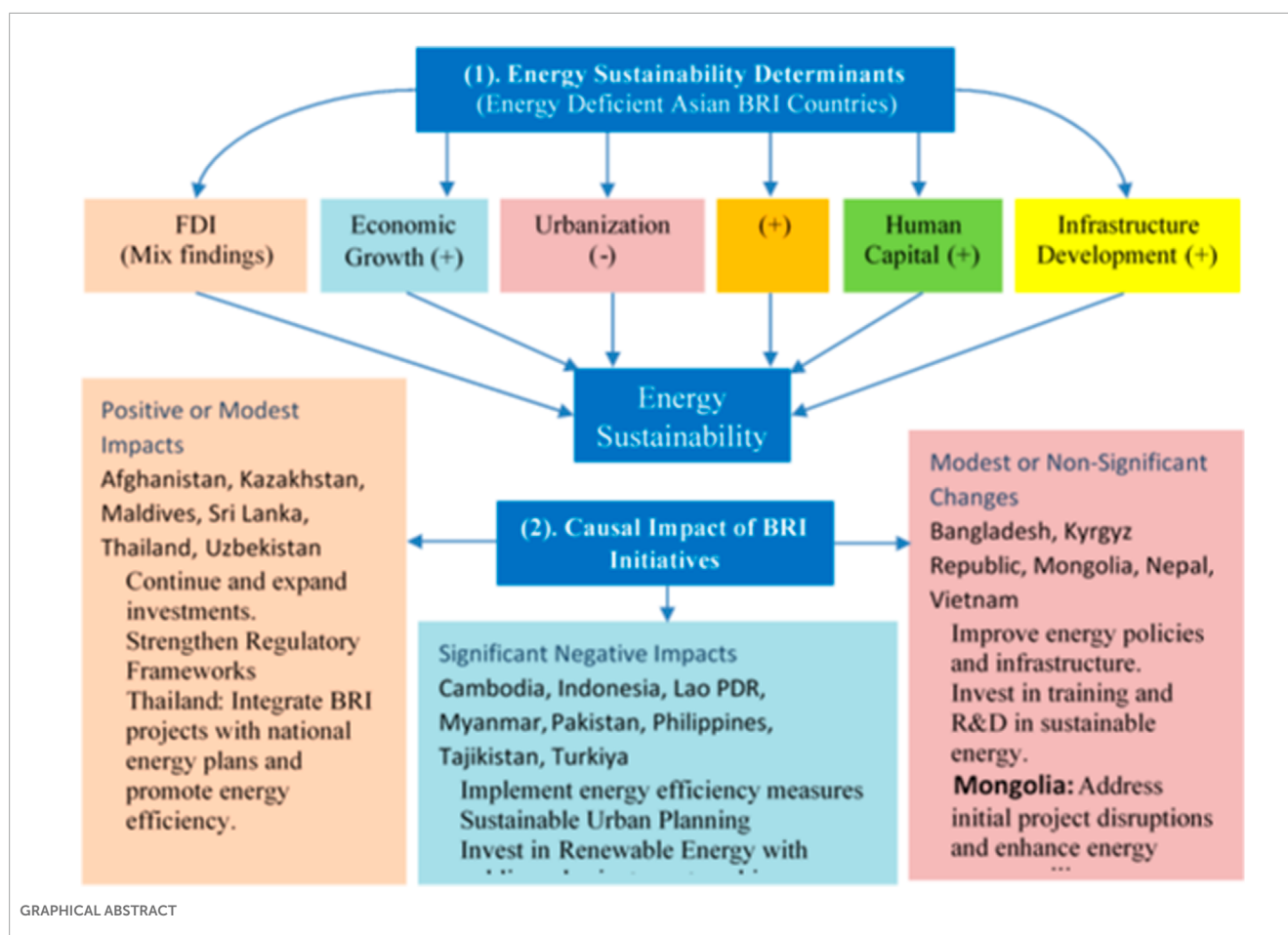
The strategic investment and international cooperation for sustainable energy supplies have grown within the Belt and Road Initiative (BRI) countries. Through such projects, BRI is believed to bring myriad benefits that engender trade and stimulating economic growth through investment in infrastructure. However, research that has targeted the causal impact of BRI initiatives on energy sustainability has markedly been lacking. The study aims to aid in filling this gap by analyzing the causal effect of BRI initiatives through an investigation of how BRI-related factors—FDI, economic growth, urbanization, trade openness, human capital, and infrastructure development—affect energy sustainability. The panel data of 20 Asian BRI energy-deficient countries have been taken into consideration for the time range of 2000–2022. This study carries out cross-sectional dependence tests, second-generation panel unit root and cointegration testing, panel quantile regression, and employ the Bayesian Structural Time Series (BSTS) approach in assessing the causal impact of BRI initiatives on energy sustainability. The panel quantile regression results reveal that economic growth, urbanization, trade, human capital, and infrastructure development significantly affect energy sustainability at various quantiles. Further, the causal impact analysis highlights the varied and significant effects of BRI initiatives on energy sustainability. Countries like Afghanistan, Maldives, and Uzbekistan should continue attracting investment for energy projects, while nations such as Bangladesh and Pakistan need to stabilize energy policies to manage short-term disruptions, and countries like Cambodia, Indonesia, and Turkey must balance rapid increase in energy demand with sustainable practices.

KEYWORDS

Bayesian structural time series, causal impact, economic growth, energy sustainability, infrastructure, panel quantile regression

1 Introduction

Through infrastructural investments, China's Belt and Road Initiative (BRI) is likely to address the challenges of energy sustainability in its member nations. The BRI sets a structured path forward by formalizing commitments to collaborate on energy infrastructure projects through Memorandums of Understanding (MoUs) with China. In addition, some other factors like foreign direct investment (FDI), economic growth,



infrastructure, urbanization, trade, and human capital significantly shape energy sustainability (Ayres et al., 2007; Azam, 2019; Jones, 1991; Mohammadi et al., 2023; Murshed et al., 2021; Narula and Narula, 2019; Osabuohien-Irabor and Drapkin, 2022).

The best-case scenario for energy-deficit BRI countries is to have a stable and sustainable energy supply where appropriate infrastructure and technology investment guarantees efficient energy use, leading toward renewable energy sources. This ideal is far from the actual situation for most of these countries. All these countries are currently fighting to acquire secure and reliable energy resources. These problems of infrastructure investments and greater international cooperation are what the BRI tends to channelize. Despite many discontinued efforts, large lacunae are still persist in reaching energy sustainability.

Literature on the subject identifies a wide range of variables affecting energy sustainability, including FDI, economic growth, urbanization, trade, human capital, and infrastructure development. It is outlined in studies that FDI can play a positive role in facilitating technology transfer and infrastructure development (Irfan and Ojha, 2023). At the same time, the relationship between economic growth, energy use, and sustainability is indeed a complex one (Ayres et al., 2007; Mohammadi et al., 2023). In addition, urbanization has held mixed findings on its impact on energy sustainability (Jones, 1991; Kammen and Sunter, 2016). It is well documented that the role that can be played by trade

and infrastructure in enhancing energy sustainability (Narula and Narula, 2019; Osabuohien-Irabor and Drapkin, 2022). However, one of the significant gaps related to the literature review is that no comprehensive study has tried to determine the causal impact of BRI initiatives on energy sustainability in energy-deficient Asian countries.

This research aims to assess the causal impact of BRI initiatives on energy sustainability in countries with Asian economies that lack sufficient energy resources. We also investigate how FDI, economic growth, urbanization, trade, human capital, and infrastructure development affect energy sustainability. To achieve the goals, we have focused on the following research questions: How do BRI initiatives impact energy sustainability in these countries? What role does FDI play in enhancing or compromising energy sustainability? How does economic growth influence energy sustainability? Additionally, how do urbanization and trade openness facilitated by the BRI contribute to or challenge energy sustainability? Finally, what is the role of human capital and infrastructure development in achieving sustainable energy goals? This study addresses a gap in the existing literature by examining the causal impact of BRI initiatives in energy-deficient Asian countries which has been largely overlooked. By answering these research questions, the study explains how BRI initiatives influence energy sustainability.

This study employs econometric approaches including cross-sectional dependence tests, second-generation panel unit root

tests, cointegration tests, panel quantile regression, and the BSTS approach to analyze the influencing factors of energy sustainability and causal impact of BRI initiatives. Key findings from the panel quantile regression indicate a significant impact of economic growth, urbanization, trade, human capital, and infrastructure development on energy sustainability across different quantiles. The causal impact analysis reveals that BRI initiatives have a varied and significant impact on energy sustainability across the selected Asian countries.

The organization of the study is as follows: [Section 2](#) reviews the relevant literature on energy sustainability and its influencing factors. [Section 3](#) outlines the methodology. [Section 4](#) presents and discusses the empirical results, including the findings from the panel quantile regression and causal impact analysis. Finally, [Section 5](#) concludes the study and offers recommendations for future research.

2 Literature review

FDI plays a critical role in countries' economic development and energy sustainability. It has a multifaceted impact on energy sustainability as evidenced by several studies. In Sub-Saharan Africa, FDI does not significantly impact clean energy consumption overall but shows positive effects in low-income countries and negative effects in middle-income countries, with a significant link to increased carbon dioxide emissions in both categories ([Nyeadi, 2023](#)). In the emerging seven economies (E7), higher FDI inflows promote energy diversification in the long run, although the effects vary in the short term due to country-specific factors ([Irfan and Ojha, 2023](#)). In Bangladesh, FDI enhances renewable electricity output but also increases the ecological footprint, indicating that while FDI aids in renewable energy adoption, it also contributes to environmental degradation, necessitating policies for cleaner FDI ([Murshed et al., 2021](#)).

In Asia, FDI improves regulatory quality and clean energy use, thus playing a crucial role in sustainable greenhouse gas emission reduction and supporting SDGs ([Abbas et al., 2021](#)). In OECD countries, FDI and trade openness enhance the benefits of technological innovation on energy consumption ([Gajdzik et al., 2024](#); [Osabuohien-Irabor and Drapkin, 2022](#)). [Adams et al. \(2020\)](#) found that FDI's impact on energy consumption is positive but not significant. They elucidate that its effects might be contingent on additional factors such as regional policies and infrastructure development.

As economies grow, their energy demand usually rises correspondingly; hence, more energy is consumed. [Ayres et al. \(2007\)](#) have the arguable view that with improved regulation, an economy can continue growing yet reduce its GHG emissions instead of an increase in the cost of energy through a carbon tax, which is disincentive to businesses and thus foster growth sustainably. Similarly, [Mohammadi et al. \(2023\)](#) reported that energy consumption has high elasticity in inducing growth for developed and developing countries. However, they cautioned that such policies aimed at reducing energy consumption may risk losing economic development, especially in the case of developing countries. Moreover that, [Saidi and Hammami \(2015\)](#) utilized data from 58 countries to demonstrate the argument

that energy consumption can drive growth. [Jia et al. \(2023\)](#) take into account the 90 BRI countries and find a two-way causal relationship between renewable energy consumption and economic growth, emphasizing the intricate relationship existing between energy use and financial performance. Similarly, China's subsidy policies and detailed electricity technologies were presented by a computable general equilibrium (CGE) model in [Jiang et al. \(2024\)](#) study and several carbon neutrality methods were proposed. By employing the marginal abatement cost curves (MACCs) model, the multiple pollutants were quantified in China's provincial level in the study of [Jiang et al. \(2023\)](#) and they concluded the lack of general equilibrium effects.

[He et al. \(2021\)](#) discussed the impact of renewable energy on low-carbon development in BRI countries and that renewable energy consumption is found to have bidirectional Granger causalities with economic growth. [Liu et al. \(2020\)](#) conducted a study across 33 BRI countries, returning results that, overall, there is still relatively low energy efficiency, especially in middle- and low-income nations. Therefore, specially designed policies should be designed for improving energy efficiency and bridging income inequality. In the study conducted by [Khan et al. \(2021\)](#), evidence showed that technological innovation, financial development, and FDI significantly influence both renewable and non-renewable energy consumption. From their results, it can be deduced that even though economic development has favored renewable energy, that brought about by FDI and technological innovation increased aggregate energy consumption. [Gu and Zhou \(2020\)](#) estimated the effect of emission reduction brought about by green energy investment projects across Belt and Road Initiative countries, which had significant carbon emission reductions resulting from such initiatives, hence underpinning energy transformations and sustainability goals.

Urbanization influences energy consumption patterns. The relationship between urbanization and energy sustainability is explored in various studies. [Kammen and Sunter \(2016\)](#) emphasize that cities must develop low-carbon, resilient energy systems to manage the high energy demands of growing populations. [Adams et al. \(2020\)](#) found that urbanization decreases CO₂ emissions in sub-Saharan Africa despite increasing transport energy consumption. [Rickwood et al. \(2008\)](#) highlight that higher-density, transit-oriented urban forms have lower per-capita transport energy use. [Jones \(1991\)](#) notes that urbanization increases overall energy consumption due to transportation and modernization of agriculture. [Broto \(2017\)](#) suggests spatial planning promoting flexibility in urban energy systems can foster sustainability innovations. [Yang et al. \(2018\)](#) reveal that the service industry is the largest consumer of energy and water and the biggest emitter of CO₂ in Shanghai and Beijing. [Seto et al. \(2017\)](#) emphasize that urban areas are critical for sustainable development due to high energy demand and emissions. [Fletcher and Mills \(2013\)](#) highlight the role of urban form in energy management, particularly cooling loads for office buildings in London. [Yang et al. \(2019\)](#) show that urbanization increases residential electricity consumption in China with significant regional variations.

Human capital, trade, and infrastructure are also important determinants of energy sustainability in BRI countries. Various studies highlight their collective influence on energy sustainability. [Azam \(2019\)](#) found that human capital significantly contributes to

economic growth in BRICS countries. Narula and Narula (2019) argues that energy trading is necessary for maintainable energy security and energy availability by reducing costs that support environmental and economic activities. Murshed (2020) describes the non-linear effects of ICT trade on transitions to renewable energy, enhanced energy efficiency, access to clean cooking fuel, and environmental sustainability in South Asia. An et al. (2021) have found that high-quality transport infrastructure and logistical services enormously reduce carbon emissions by conserving energy in the supply chain. Tan et al. (2023) emphasized that integrating clean energy into the mix is critical to delivering energy sustainability in BRI countries. According to them, financial and trade openness and infrastructure development greatly facilitates sustainable energy transitions. According to Tsaurai (2021), human capital development, financial development, and infrastructure development are the major factors that influence energy consumption in BRICS countries. Ullah et al. (2022) concluded that economic development, financial inclusion, energy efficiency, and governance positively affect sustainable development in 64 BRI countries.

3 Methodology

3.1 Econometric model

This study develops an econometric model which is firmly rooted in theoretical principles and supported by empirical literature to investigate the factors influencing energy sustainability in BRI energy-deficient Asian countries. It systematically dissects the determinants impacting energy sustainability. The proposed econometric model is given in Equation 1 as follows:

$$ESI_{it} = \beta_0 + \beta_1 FDI_{it} + \beta_2 \ln(GDP_{it}) + \beta_3 URB_{it} + \beta_4 TR_{it} + \beta_5 HCI_{it} + \beta_6 IN_{it} + \varepsilon_{it} \quad (1)$$

where ESI_{it} represents the Energy Sustainability Index for country i at time t , FDI_{it} stands for Foreign Direct Investment, $\ln GDP_{it}$ is the natural logarithm of GDP, URB_{it} indicates urban population percentage, TR_{it} denotes trade as a percentage of GDP, HCI_{it} captures human capital index, IN_{it} refers to infrastructure proxy and ε_{it} is usual error term.

The theoretical basis for including these variables in the econometric model is grounded in both theoretical and empirical studies. FDI_{it} can lead to technological spillovers and enhance the energy infrastructure in host countries, thereby improving energy efficiency and sustainability (Osabuohien-Irabor and Drapkin, 2022). On the other side, in case of the shift to energy-intensive production methods, FDI_{it} can increase energy consumption and degrade the environment (Murshed et al., 2021). Incorporating FDI_{it} helps capture these dual effects and understand its overall impact on energy sustainability.

Higher economic growth generally means an increase in energy consumption but also provides the resources needed for investment in sustainable energy infrastructure (Mohammadi et al., 2023). Earlier research has found that, with the appropriate regulatory setting, economic growth contributes to elevating energy efficiency and lowering greenhouse gas emissions (Ayres et al., 2007). Thus,

including $\ln GDP_{it}$ in the model sets out to capture the dynamics of the economy on energy sustainability.

Generally, higher rates of URB_{it} correspond to increased energy demand for transportation, industry, and homes (Jones, 1991). On the other hand, urbanization can be an impetus for powder-efficient technologies and innovative, sustainable urban planning (Kammen and Sunter, 2016). Including URB_{it} in the model they are allowed us to study what such net effect urbanization have on energy sustainability.

TR_{it} can affect energy sustainability by exchanging energy-efficient technologies and best practices. Studies have shown that with increased trade activities, access to advanced technologies is generally bound to increase, which, in turn matter for energy efficiency and sustainability (Narula and Narula, 2019). Moreover, the impact of trade on changing the energy mix could be realized through improved access to renewable energies (Osabuohien-Irabor and Drapkin, 2022). Consequently, TR_{it} is factored in for analysis while assessing its role in energy sustainability.

HCI_{it} encapsulates education, skills, and health conditions. It contributes much to the sustainability of energy. Better energy management practices and adoption of sustainable technologies are related to higher levels of human capital (Azam, 2019). From this, including HCI_{it} in the model-assisted us in capturing the effect of human capital development on energy sustainability.

Energy sustainability can also be enhanced, especially by infrastructure development (IN_{it}) within the energy sector. Investments in green energy infrastructure—renewable sources of energy and efficient transmission networks—can reduce carbon emissions and increase energy efficiency accordingly (An et al., 2021). In this regard, introducing IN_{it} into the model provides a way to consider the impacts of infrastructure about energy sustainability.

3.2 Data sources

The data for this study spans from 2000 to 2022, covering 20 selected Asian BRI countries with significant energy resource deficiencies. This comprehensive dataset includes various indicators essential for analyzing energy sustainability and the impact of BRI initiatives. The primary data sources are the World Development Indicators (WDI) and the United Nations Trade and Development database. Table 1 below provides a detailed description of the variables used in the analysis.

The methodology involves several steps. First, descriptive statistics for all variables involved in the analysis are obtained. Next, a correlation matrix is constructed to examine the relationships among the variables. The correlation matrix provides a measure of the strength and direction of the linear relationship between pairs of variables. This step is essential to detect multicollinearity issues, which can affect the robustness of the regression analysis. First, a check for cross-sectional dependence proposed by Pesaran (2021) is performed to confirm if there is cross-sectional dependence among the variables that feature in this panel. The tests used in this work include the Breusch-Pagan LM, the Pesaran scaled LM test, the bias-corrected scaled LM test, and the Pesaran CD test.

Following the existence of cross-sectional dependence, second-generation panel unit root tests are conducted to establish the stationarity properties of the variables. The second-generation panel

TABLE 1 Description of variables.

Variable	Description	Source
ESI_{it}	Energy Sustainability Index – part of the Productive Capacities Index (PCI), this measures the availability, sustainability, and efficiency of energy sources, including renewable components	United Nations Trade and Development
FDI_{it}	Net inflows of foreign direct investment, expressed as a percentage of GDP.	WDI
$LnGDP_{it}$	Natural logarithm of GDP (adjusted to 2015 constant dollars)	WDI
URB_{it}	Urban population as a percentage of the total population, representing individuals living in urban areas as defined by national statistical offices. Data are compiled and adjusted by the United Nations Population Division	WDI
TR_{it}	Total trade (sum of imports and exports) as a percentage of GDP.	WDI
HCI_{it}	Human Capital Index – a component of the PCI, capturing education, skills, health conditions, and research and development integration within society. It includes metrics such as the number of researchers and research expenditures, and reflects gender dimensions through fertility rates, with higher fertility rates reducing the human capital score	United Nations Trade and Development
IN_{it}	Infrastructure proxy – fixed telephone subscriptions per 100 people, covering all types of fixed-line communications, including analogue lines, VoIP, and fixed wireless local loop subscriptions	WDI

unit root test to be used is the one proposed by Pesaran (2007) which accounts for cross-sectional dependence. A Westerlund panel cointegration test accounting for cross-sectional dependence is then applied to establish long-run equilibrium relationships within series.

In particular, panel quantile regressions are run to estimate the long-run parameters and to learn about heterogeneity in these relationships at different quantiles of the conditional distribution of the dependent variable. Quantile regression is a method that adds this dimension to the impact that explanatory variables have at various points of the distribution of the dependent variable.

$$Q_{y_{it}}(X_{it}) = \alpha_i(\tau) + X_{it}\beta(\tau) + \epsilon_{it}(\tau) \quad (2)$$

where in Equation 2, $Q_{y_{it}}(X_{it})$ denotes the τ -th quantile of the dependent variable y_{it} conditional on the explanatory variables X_{it} , $\alpha_i(\tau)$ represents the quantile-specific fixed effects, and $\beta(\tau)$ are the quantile-specific coefficients.

One of the advantages of quantile regression with panel data is that it allows for an analysis of the effect of explanatory variables along the entire distribution of the dependent variable, not just at the mean. This significantly helps understand how various factors influence energy sustainability at different levels. It may further reveal heterogeneous effects that traditional mean regression models often miss (Koenker and Bassett Jr, 1978). Moreover, panel quantile regression is robust to outliers and heteroskedasticity; therefore, it has advantages in analyzing data sets containing non-normal error distributions or different levels of variance (Koenker, 2005). However, it also has some disadvantages. In this respect, computational complexity may also be higher than in traditional regression methods with large datasets. Moreover, interpretation of the result is more complicated since it involves understanding the effects across multiple quantiles and how these impacts differ from the mean effects commonly estimated by conventional regression models (Yu et al., 2003).

This study utilizes the BSTS methodology to estimate the causal impact of BRI on ESI_{it} in energy-scarce Asian countries.

Brodersen et al. (2015) introduced a novel BSTS method based on state space models, estimating the causal relationship by filtering it against other signals. The BSTS model is expressed in Equation 3 as:

$$y_t = Z_t\alpha_t + X_t\beta + \epsilon_t \quad (3)$$

where y_t is the observed ESI_{it} , α_t is the hidden state vector, Z_t is the observation matrix, X_t represents the explanatory variables (FDI_{it} , $LnGDP_{it}$, URB_{it} , TR_{it} , HCI_{it} , IN_{it}), and β is the vector of coefficients.

The study incorporates a dummy variable, capturing the effect of MoU. This dummy variable is set to 1 from the year after which MoU was signed to join BRI onwards and stays 0 for all periods before MoU signing. In Equation 4, innovation vector ϵ_t is assumed to be normally distributed with mean zero and variance σ^2 :

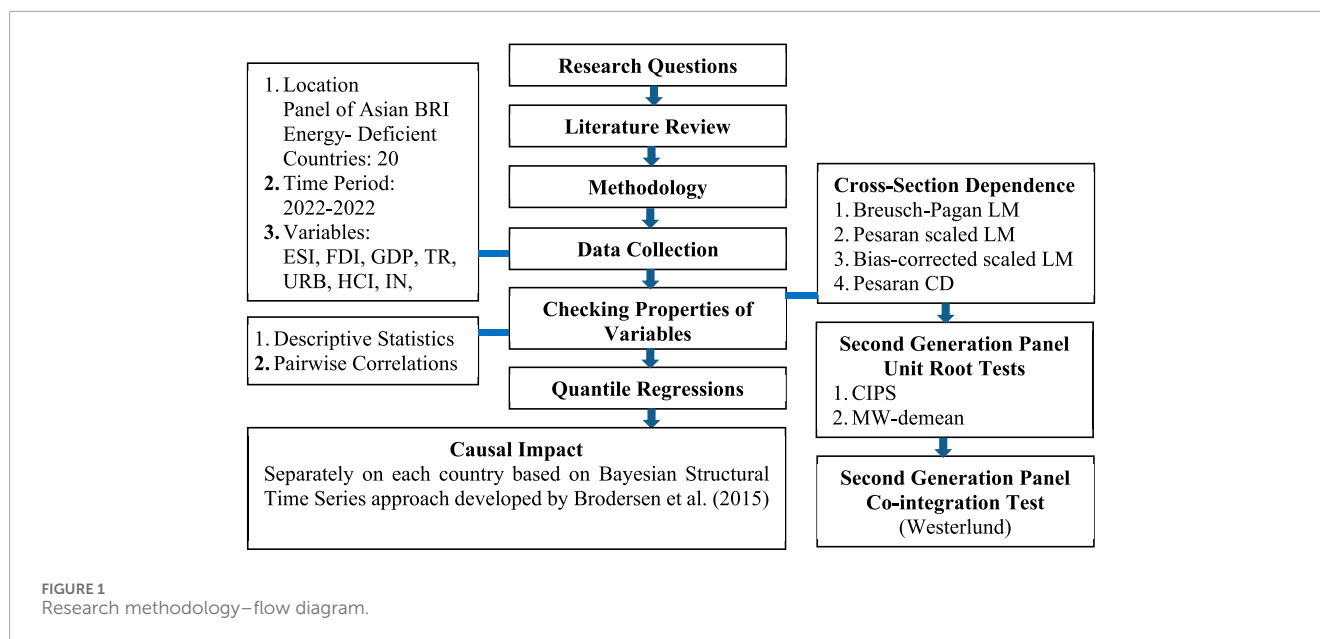
$$\epsilon_t \sim N(0, \sigma^2) \quad (4)$$

In this paper, the BSTS approach is applied separately for each selected BRI country to project their contribution to ESI_{it} . The counterfactual analysis contrasts the observed ESI_{it} with the case where the BRI MoUs were not signed. Brodersen et al. (2015) emphasize that such a counterfactual scenario is an essential aspect of quantifying the causal impact of BRI initiatives on energy sustainability.

The BSTS approach allows flexibility in terms of including a myriad of external covariates and adaptation to different economic conditions, and thus, it fits perfectly in this study. Also, Bayesianism is robust for quantifying uncertainty, increasing the reliability of causal impact estimates Brodersen et al. (2015).

Assigning prior distributions to the model parameters is a crucial step in the Bayesian approach. Let β represent the coefficients for the explanatory variables, with its prior distribution denoted as $p(\beta)$. Prior distributions are also assigned to the state space model parameters, reflecting beliefs about their plausible values (Box and Tiao, 2011; Brodersen et al., 2015).

Inference in Bayesian analysis involves updating model parameter assumptions based on observed data. The posterior



distribution of the parameters is derived using Bayes' theorem given the observed ESI_{it} data y_t as expressed in Equation 5:

$$p(\alpha_t, \beta | y_t) \propto p(y_t | \alpha_t, \beta) (\alpha_t, \beta) \quad (5)$$

Markov Chain Monte Carlo methods, such as Gibbs sampling or Metropolis-Hastings algorithms, are used to sample from the posterior distribution, facilitating the estimation of model parameters and latent states (Box and Tiao, 2011; Brodersen et al., 2015).

The causal impact is determined by comparing the observed ESI_{it} with the counterfactual scenario in which BRI initiatives were not implemented. The counterfactual is simulated by projecting the model forward, assessing what ESI_{it} have been without the BRI MoUs. The causal impact is the difference between the observed and counterfactual ESI_{it} (Brodersen et al., 2015). This analysis is applied to various post-MoU periods, providing insights into the effectiveness of BRI initiatives on energy sustainability.

The BSTS approach offers a robust framework for evaluating the causal impact of BRI on energy sustainability in Asian countries. Its adaptability to different conditions and the inclusion of explanatory variables ensure a comprehensive and reliable analysis, providing valuable insights for policymakers. The whole methodology is summarized in Figure 1.

4 Empirical results

Table 2 presents the descriptive statistics for the variables included in the study. These statistics summarize the central tendency, dispersion, and shape of the distribution of each variable. The descriptive statistics reveal substantial variability across the variables. For instance, the ESI_{it} has a mean value of 49.095 with a standard deviation of 16.625, indicating significant differences in energy sustainability among the countries studied. The FDI_{it} shows

a mean of 3.655% of GDP, but its high standard deviation of 4.920 and wide range (from -37.173 to 43.912) highlight considerable fluctuations in FDI inflows.

Similarly, $LnGDP_{it}$ and URB_{it} exhibit moderate variability, with standard deviations of 1.716 and 16.628, respectively. TR_{it} reflects diverse trade activities among the countries which has a high mean value of 82.301 and a wide range from 0.175 to 220.407. The HCI_{it} and IN_{it} also show notable differences in human capital development and infrastructure across the sample countries. The skewness and kurtosis values of some variables such as FDI_{it} indicate the presence of outliers or non-normal distribution patterns and have distributions with significant asymmetry and peakedness.

The correlation matrix in Table 3 reveals several notable relationships among the variables. ESI_{it} shows a moderate positive correlation with URB_{it} (0.662), HCI_{it} (0.726), and IN_{it} (0.633), indicating that these factors are associated with higher energy sustainability. ESI_{it} also has weaker positive correlations with FDI_{it} (0.159), $LnGDP_{it}$ (0.208), and TR_{it} (0.439). Additionally, the correlation matrix indicates that there is no high correlation between the explanatory variables, suggesting that there is not a problem of possible multicollinearity among them.

The cross-sectional dependence tests, as shown in Table 4, indicate significant cross-sectional dependence among the panel time series variables. The Breusch-Pagan LM, Pesaran scaled LM, Bias-corrected scaled LM, and Pesaran CD tests all yield extremely high test statistics with p-values of 0.0000, indicating strong evidence of cross-sectional dependence (Breusch and Pagan, 1980; Pesaran, 2021). Given the presence of cross-sectional dependence, the most suitable approach to examine the stationarity of the variables is to employ second-generation panel unit root tests, which are designed to account for such dependencies (Pesaran, 2007). This ensures more reliable and valid results in the context of panel data analysis.

The panel unit root tests, as presented in Table 5, reveal significant insights into the stationarity of the variables under investigation. At their levels, the majority of variables (ESI_{it} , FDI_{it} ,

TABLE 2 Descriptive statistics.

Stats	ESI_{it}	FDI_{it}	$LnGDP_{it}$	URB_{it}	TR_{it}	HCI_{it}	IN_{it}
Observation	460	460	460	460	460	460	460
Mean	49.095	3.655	24.725	39.563	82.301	35.482	7.499
Median	50.638	2.316	24.967	35.470	70.126	36.494	5.186
Maximum	75.293	43.912	27.809	78.214	220.407	58.652	29.052
Minimum	13.383	-37.173	21.370	13.397	0.175	10.864	0.019
Standard Deviation	16.625	4.920	1.716	16.628	44.551	8.892	6.868
Skewness	-0.325	1.295	-0.120	0.605	0.559	-0.182	1.086
Kurtosis	2.114	25.832	1.731	2.357	2.601	3.297	3.454

Source: Authors' calculations.

TABLE 3 Correlation matrix.

Variables	ESI_{it}	FDI_{it}	$LnGDP_{it}$	URB_{it}	TR_{it}	HCI_{it}	IN_{it}
ESI_{it}	1						
FDI_{it}	0.159	1					
$LnGDP_{it}$	0.208	-0.287	1				
URB_{it}	0.662	0.124	0.463	1			
TR_{it}	0.439	0.409	-0.221	0.211	1		
HCI_{it}	0.726	0.155	0.231	0.474	0.475	1	
IN_{it}	0.633	0.081	0.343	0.614	0.206	0.501	1

Source: Authors' Estimates.

$LnGDP_{it}$, URB_{it} , TR_{it} , HCI_{it} , and IN_{it}) show non-stationarity, as indicated by both the Maddala and Wu (MW) and Cross-sectional Augmented Im, Pesaran, and Shin (CIPS) tests. Specifically, the p-values for these tests are generally above conventional significance levels (0.05), suggesting the presence of unit roots.

For instance, the MW test for ESI_{it} without trend reports a chi-square value of 42.871 with a p-value of 0.349, while the CIPS test without trend gives a Zt-bar of 0.171 with a p-value of 0.568, indicating non-stationarity. Similar patterns are observed across other variables at their levels, such as FDI_{it} (MW test p-values of 0.051 and 0.042) and URB_{it} (MW test p-values of 0.914 and 0.158), corroborating the presence of unit roots.

However, when these variables are differenced, they become stationary, as evidenced by both the MW and CIPS tests at the first difference. For ΔESI_{it} , the MW test reports highly significant chi-square values (251.049 without trend and 214.954 with trend) with p-values of 0.000. The CIPS test further supports this stationarity with Zt-bar values of -16.313 and -7.869, both with p-values of 0.000. Similar results are observed for ΔFDI_{it} , $\Delta LnGDP_{it}$, ΔURB_{it} ,

ΔTR_{it} , ΔHCI_{it} , and ΔIN_{it} , where the tests consistently show p-values of 0.000, indicating strong evidence of stationarity at the first difference.

Therefore, based on these results, it is clear that while the variables exhibit non-stationarity at their levels, they become stationary after differencing. Consequently, second-generation panel unit root tests, which account for cross-sectional dependence, are appropriate for this analysis (Pesaran, 2007). These findings underscore the necessity of using differenced data to ensure the reliability and validity of further econometric analyses involving these variables.

The results of the Westerlund panel cointegration test presented in Table 6 indicate that the variables exhibit cointegration in the long run under certain conditions. Specifically, when considering the scenarios "without trend and panel means" and "with trend and panel means," both tests for "some panels are cointegrated" and "all panels are cointegrated" yield significant results (p-values of 0.0170 and 0.0128 for some panels, and 0.0769 and 0.0158 for all panels, respectively). These findings suggest that

TABLE 4 Cross-section dependence tests.

Variable	Breusch-pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
ESI_{it}	3004.4900	144.3803	143.9257	51.2764
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
FDI_{it}	496.3944	15.7177	15.2632	7.2954
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
$LnGDP_{it}$	4164.5520	203.8902	203.4357	64.5006
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
URB_{it}	3419.1690	165.6529	165.1983	57.3619
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
TR_{it}	1023.7490	42.7704	42.3159	5.7708
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
HCI_{it}	3076.8690	148.0932	147.6387	52.4926
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
IN_{it}	1227.7280	53.2343	52.7798	3.7166
	(0.0000)	(0.0000)	(0.0000)	(0.0002)

Note: probability values of test statistic are in parentheses.

Source: Authors' Estimates.

the variables are cointegrated in the long run, implying a stable long-term relationship among them.

4.1 Energy sustainability determinants

The Panel Quantile Regression Estimates (PQRE) in Table 7 reveal insightful findings regarding the factors influencing ESI_{it} in the context of the BRI countries. The results are also summarized in Figure 2. The results show varying impacts across different quantiles. FDI_{it} demonstrates a negative and insignificant impact on ESI_{it} in most of the quantiles except 50th and 60th quantiles. It suggests that FDI_{it} can lead to increase energy consumption. The negative coefficients, although not statistically significant at lower quantiles, become more pronounced at higher quantiles. It suggests that as countries receive more FDI_{it} , the detrimental impact on ESI_{it} becomes more evident. This can be attributed to the importation of energy-intensive technologies and lax environmental regulations in many developing countries which lead to higher energy consumption.

$LnGDP_{it}$ consistently exhibits a significant positive impact on ESI_{it} across all quantiles. It indicates that higher $LnGDP_{it}$ levels lead to better ESI_{it} outcomes. Many studies have therefore confirmed this relationship by identifying that economic growth generally improves ESI_{it} through the stimulus of investments in energy infrastructure and efficiency. For example, Mohammadi et al. (2023) identify that economic growth has considerably improved

ESI_{it} in both developed and developing countries. Ayres et al. (2007) also explained that through better management rather than a carbon tax, which only raises the price of energy, economic growth can be sustained along with mitigated GHG emissions while improving energy efficiency and promoting sustainable growth.

URB_{it} has a significant negative impact on ESI_{it} across most quantiles. This suggests that URB_{it} increases energy consumption due to higher energy demands for transportation and the modernization of agriculture. Jones (1991) notes that URB_{it} increases overall energy consumption due to these factors, which is consistent with the findings of this analysis. However, the impact of URB_{it} on ESI_{it} diminishes in higher quantiles, possibly reflecting better energy management and efficiency measures in more urbanized regions. Kammen and Sunter (2016) emphasize that cities must develop low-carbon, resilient energy systems to manage the high energy demands of growing populations.

TR_{it} shows a positive impact on ESI_{it} across all quantiles, with significant positive coefficients indicating that increased TR_{it} activities contribute to better ESI_{it} . This agrees with findings by Narula (2018) who argues that energy trade is key to attaining sustainable energy security since it assures the availability of energy and sustains environmental and economic activities. Another positive effect of TR_{it} on ESI_{it} may reflect the gains from technology transfers and innovation associated with international trade. According to Osabuohien-Irabor and Drapkin (2022), trade openness enhances the advantage that technological innovation has

TABLE 5 Panel unit root tests.

Variables	Panel unit root test (MW)				Panel unit root test (CIPS)			
	Without trend		With trend		Without trend		With trend	
	χ^2	p-value	χ^2	p-value	Z_t -bar	p-value	Z_t -bar	p-value
Variables at level								
ESI_{it}	42.871	0.349	23.148	0.985	0.171	0.568	-0.851	0.197
FDI_{it}	55.664	0.051	56.733	0.042	-0.803	0.211	-1.099	0.136
$LnGDP_{it}$	34.833	0.702	38.927	0.518	1.583	0.985	0.453	0.675
URB_{it}	28.468	0.914	48.918	0.158	9.223	1.000	4.876	1.000
TR_{it}	41.313	0.413	44.845	0.276	2.98	0.999	4.541	1.000
HCI_{it}	33.770	0.746	46.433	0.224	2.432	0.992	-0.067	0.473
IN_{it}	27.744	0.929	20.881	0.995	-0.049	0.480	0.305	0.620
Variables at first difference								
ΔESI_{it}	251.049	0.000	214.954	0.000	-16.313	0.000	-7.869	0.000
ΔFDI_{it}	172.287	0.000	100.513	0.000	-9.393	0.000	-1.996	0.023
$\Delta LnGDP_{it}$	218.676	0.000	84.718	0.000	-6.834	0.000	-1.711	0.044
ΔURB_{it}	84.248	0.000	93.278	0.000	5.925	1.000	-4.076	0.000
ΔTR_{it}	93.332	0.000	175.628	0.000	-3.578	0.000	-8.389	0.000
ΔHCI_{it}	208.766	0.000	167.485	0.000	-3.761	0.000	-5.337	0.000
ΔIN_{it}	122.457	0.000	102.077	0.000	-9.543	0.000	-4.429	0.000

Source: Authors' Estimates.

TABLE 6 Panel cointegration test - westerlund.

Type	Without trend and panel means	With trend	With panel means	With trend and panel means
Some panels are cointegrated	-2.1205	-1.2369	-1.4440	-2.2328
	(0.0170)	(0.1081)	0.0744	(0.0128)
All panels are cointegrated	-1.4260	-1.6795	-1.0768	-2.1496
	(0.0769)	(0.0465)	0.1408	(0.0158)

Source: Authors' Estimates.

on energy use toward a more sustainable environment in its use, which goes to underscore this analysis.

HCI_{it} significantly and positively impacts ESI_{it} across all quantiles, highlighting the importance of education, skills, and health conditions in promoting sustainable energy use. The positive coefficients across all quantiles indicate that higher levels of HCI_{it} are associated with better ESI_{it} outcomes. Azam (2019) found that HCI_{it} significantly contributes to economic growth and energy

sustainability in BRICS countries, reinforcing the critical role of HCI_{it} in energy management and sustainability. Higher levels of education and skills can lead to more efficient energy use and the adoption of sustainable energy practices, supporting the positive relationship observed in this analysis.

IN_{it} development also shows a significant positive impact on ESI_{it} across all quantiles. The positive coefficients indicate that investments in IN_{it} , particularly in green energy and logistics,

TABLE 7 Panel quantile regression estimates.

Variables	q10	q20	q30	q40	q50	q60	q70	q80	q90
FDI_{it}	−0.0360	−0.0388	−0.0405	−0.0424	−0.0445*	−0.0471*	−0.0502	−0.0523	−0.0554
	(0.0435)	(0.0350)	(0.0307)	(0.0273)	(0.0259)	(0.0281)	(0.0349)	(0.0413)	(0.0519)
$LnGDP_{it}$	10.72***	10.37***	10.14***	9.896***	9.628***	9.280***	8.889***	8.615***	8.214***
	(1.271)	(1.025)	(0.899)	(0.801)	(0.764)	(0.829)	(1.025)	(1.209)	(1.517)
URB_{it}	−0.329***	−0.302***	−0.285***	−0.267***	−0.246***	−0.220***	−0.190*	−0.170	−0.139
	(0.123)	(0.0989)	(0.0868)	(0.0771)	(0.0734)	(0.0797)	(0.0988)	(0.117)	(0.146)
TR_{it}	0.0325***	0.0331***	0.0335***	0.0339***	0.0344***	0.0350***	0.0357***	0.0361***	0.0368**
	(0.0122)	(0.00980)	(0.00859)	(0.00763)	(0.00724)	(0.00787)	(0.00978)	(0.0116)	(0.0145)
HCI_{it}	0.540***	0.574***	0.595***	0.618***	0.644***	0.677***	0.715***	0.741***	0.779***
	(0.121)	(0.0976)	(0.0856)	(0.0762)	(0.0727)	(0.0789)	(0.0976)	(0.115)	(0.144)
IN_{it}	0.197***	0.200***	0.201***	0.203***	0.205***	0.207***	0.210***	0.212***	0.215**
	(0.0701)	(0.0565)	(0.0495)	(0.0440)	(0.0417)	(0.0453)	(0.0564)	(0.0666)	(0.0837)
R-squared	0.550	0.631	0.639	0.665	0.656	0.690	0.697	0.689	0.649
Observations	460	460	460	460	460	460	460	460	460

Note: Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

Source: Authors' Estimates.

enhance ESI_{it} by reducing carbon emissions and improving energy efficiency. An et al. (2021) found that high-quality transport IN_{it} significantly reduces carbon emissions through energy conservation in the supply chain, promoting ESI_{it} . Similarly, Tan et al. (2023) highlighted the critical role of clean energy inclusion in the energy mix for ensuring ESI_{it} in BRI nations, finding that financial and trade openness coupled with IN_{it} development significantly promote sustainable energy transitions.

The empirical findings in Table 7 highlight the importance of economic growth, international trade, education, and infrastructure in promoting energy sustainability. The negative impact of URB_{it} at suggests that rapid URB_{it} poses challenges to ESI_{it} , which can be mitigated through effective energy policies and management practices.

4.2 Causal impact of BRI on energy sustainability

During the period following the signing of MoUs under the BRI, the causal impact on the ESI reveals a diverse range of outcomes among the energy-deficient Asian countries. The findings reported in Table 8 and Figure 3 show the varying responses to the BRI initiatives.

In Afghanistan, the actual ESI was 0.34 compared to the predicted −2.4, with a 95% confidence interval (CI) ranging from −6.7 to 2.5. This resulted in an absolute effect of 2.8, indicating

a 110% relative effect, albeit with a p-value of 0.075, suggesting a modest increase in energy sustainability. This positive outcome can be attributed to the infusion of foreign investments and infrastructure development under the BRI, which can improve energy access and efficiency (He et al., 2021).

Bangladesh exhibited a different trend with an actual ESI of 0.39 versus a predicted 0.61, leading to an absolute effect of −0.22 and a 75% relative effect, though the p-value of 0.145 indicates that this result is not statistically significant. This outcome may reflect initial disruptions or adjustments in energy policies and infrastructures post-MoU signing.

Cambodia displayed a substantial negative absolute effect. The actual ESI was 12 compared to a predicted 21, with a 95% CI of 14–28. The absolute effect was −8.4, resulting in a relative effect of −42%, which is statistically significant with a p-value of 0.017. This negative impact might be due to the increased energy consumption from rapid industrialization and urbanization spurred by BRI projects, which often precede improvements in energy sustainability (Barsky and Kilian, 2001).

Indonesia also showed a significant negative absolute effect with an actual ESI of 1.7 compared to a predicted 4.3, yielding an absolute effect of −2.6 and a relative effect of −59%, with a significant p-value of 0.003. Similar to Cambodia, the negative impact may be attributed to increased energy demand outstripping the improvements in energy infrastructure initially (Mohammadi et al., 2023).

Kazakhstan's actual ESI was 3.8 versus a predicted −1.5, resulting in an absolute effect of 5.3, with a 95% CI of −3.3 to 18. Although

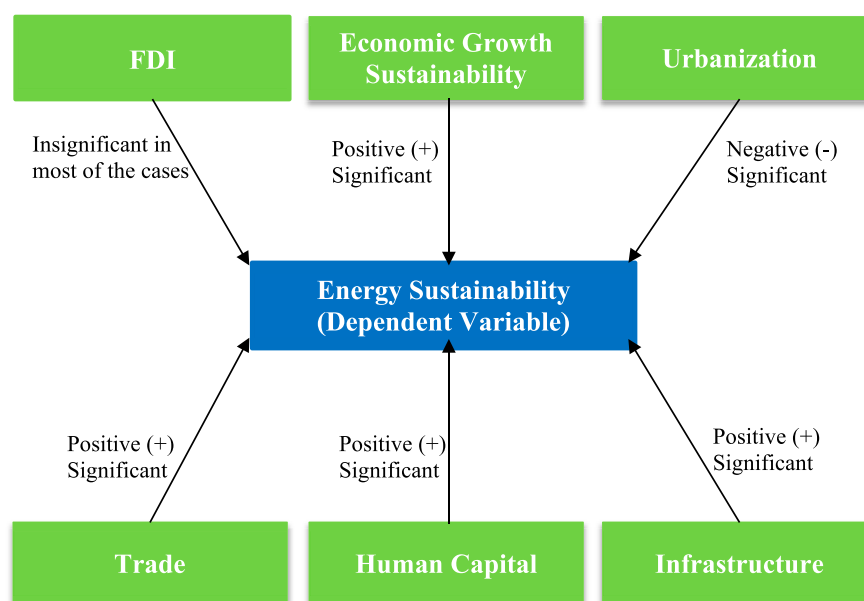


FIGURE 2
Summary of panel quantile regression results.

this indicates a 93% relative effect, the p-value of 0.254 suggests it is not statistically significant. The positive but insignificant impact might reflect the early stages of BRI projects where benefits are yet to fully materialize (Zhang et al., 2021). In contrast, the Kyrgyz Republic showed an actual ESI of 3.7 against a predicted 5, leading to an absolute effect of -1.3 and a relative effect of -35% , with a p-value of 0.358, indicating no significant impact. This could be due to the limited scale or slower implementation of BRI projects in the region (Khan et al., 2021).

Lao PDR exhibited a negative absolute effect, wherein the actual ESI was 4.7 while it was predicted to be at 8.5; therefore, having an absolute effect of -3.8 while the relative effect was -44% , thus indicating evidence of some negative impact on energy sustainability of BRI. This may be due to characteristics of the infrastructure programs being more initial energy-intensive than their sustainability attributes in the long term (Gu and Zhou, 2020).

In the case of Malaysia, its actual ESI was 3 compared with a predicted value of 3.7; the absolute effect was thus -0.68 and the relative effect -1.20% with a p-value of 0.248, making it not significant. The Maldives' case turned in an actual ESI of 13 as against the predicted 11, hence having an absolute effect of 1.9 and a relative effect of 20%, the p-value is 0.088, which implies that it is again not statistically significant. Such outcomes may be a reflection of the BRI projects' moderate scale and effect in these countries (Osabuohien-Irabor and Drapkin, 2022).

Mongolia's actual ESI was 5.9 compared to a predicted 15, yielding an absolute effect of -8.9 and a relative effect of -81% , with a p-value of 0.285, indicating no significant impact. Myanmar demonstrated a significant negative absolute effect with an actual ESI of 3.3 versus a predicted 6.5, resulting in an absolute effect of -3.2 and a relative effect of -47% , with a p-value of 0.002. Nepal's actual ESI was 0.36 compared to a predicted 0.51, leading to an absolute effect of -0.15 and a relative effect of -18% , with

a p-value of 0.140, indicating no significant impact. These results might be due to the varying stages of implementation and scale of BRI projects (Adams et al., 2020).

The actual ESI for Mongolia was 5.9 compared with a predicted 15, producing an absolute effect of -8.9 and a relative effect of -81% , while the p-value was 0.285, indicating no significant impact. Myanmar had an absolute significant negative effect where the actual ESI was 3.3 against the predicted 6.5, producing an absolute effect of -3.2 and a relative effect of -47% with a p-value of 0.002. The actual ESI of Nepal against the predicted 0.51 was 0.36. Its absolute effect was therefore -0.15 , whereas the relative effect stood at -18% with a p-value of 0.140, hence no significant impact. These results might be due to the varying stages of implementation and scale of BRI projects (Adams et al., 2020).

Pakistan followed an actual ESI of 0.63 against the predicted 1.3, resulting in -0.67 absolute effect and a relative effect of -40% , with a p-value of 0.086 which indicate that the present result is definite at almost probably modest negative impact. The Philippines, however, had a very strong absolute effect wherein the actual ESI was 2.5 against the predicted 3.7, hence giving it an absolute effect of -1.2 and a relative effect of -31% with a p-value of 0.004. These negative effects are postulated to be possibly caused by the immediate increase in energy consumption driven by such infrastructure development (Saidi and Hammami, 2015).

Sri Lanka's actual ESI was 0.99 versus a predicted 0.85, leading to an absolute effect of 0.14 and a relative effect of -32% , with a p-value of 0.360, indicating no significant impact. Tajikistan demonstrated a significant negative absolute effect with an actual ESI of 1.6 against a predicted 6.9, resulting in an absolute effect of -5.3 and a relative effect of -84% , with a p-value of 0.047. This could reflect the short-term disruptions and increased energy consumption associated with large-scale infrastructure projects (Futcher and Mills, 2013).

TABLE 8 Causal impact on ESI after MoU on BRI.

Country	Actual	Prediction	95% CI	Absolute effect	95% CI	Relative effect	p	MoU year
Afghanistan	0.34	−2.4	[−6.7,2.5]	2.8	[−2.2,7.1]	−110%	0.075	2023
Bangladesh	0.39	0.61	[0.21,1.0]	−0.22	[−0.66,0.18]	75%	0.145	2019
Cambodia	12	21	[14,28]	−8.4	[−16,−1.2]	−42%	0.017	2013
Indonesia	1.7	4.3	[3,5.5]	−2.6	[−3.7,−1.2]	−59%	0.003	2015
Kazakhstan	3.8	−1.5	[−14,7]	5.3	[−3.3,18]	−93%	0.254	2015
Kyrgyz Republic	3.7	5	[−18,17]	−1.3	[−13,22]	−35%	0.358	2013
Lao PDR	4.7	8.5	[6.4,11]	−3.8	[−6,−1.6]	−44%	0.002	2018
Malaysia	3	3.7	[0.88,7.1]	−0.68	[−4.1,2.1]	−1.20%	0.248	2017
Maldives	13	11	[7.8,13]	1.9	[−0.79,4.9]	20%	0.088	2017
Mongolia	5.9	15	[−25,40]	−8.9	[−34,30]	−81%	0.285	2013
Myanmar	3.3	6.5	[4.5,11]	−3.2	[−8,−1.3]	−47%	0.002	2016
Nepal	0.36	0.51	[0.20,0.83]	−0.15	[−0.47,0.17]	−18%	0.140	2017
Pakistan	0.63	1.3	[0.2,2.4]	−0.67	[−1.8,0.43]	−40%	0.086	2013
Philippines	2.5	3.7	[2.9,4.7]	−1.2	[−2.2,−3.9]	−31%	0.004	2017
Sri Lanka	0.99	0.85	[−1.1,1.7]	0.14	[−0.68,2.1]	−32%	0.360	2017
Tajikistan	1.6	6.9	[−0.063,12]	−5.3	[−10,1.7]	−84%	0.047	2018
Thailand	1.6	−1	[−4.4,2.8]	2.7	[−1.2,6]	769%	0.087	2014
Turkiya	1.4	3	[2,4.5]	−1.6	[−3.1,−0.64]	−52%	0.003	2015
Uzbekistan	2.7	−0.049	[−2.2,2.9]	2.8	[−0.21,4.9]	149%	0.041	2015
Vietnam	4.6	5.5	[3,7.6]	−0.93	[−3,1.6]	−11%	0.213	2017

Source: Authors’ Estimates.

Thailand’s actual ESI was 1.6 compared to a predicted −1, yielding an absolute effect of 2.7 and a relative effect of 769%, with a p-value of 0.087, suggesting a significant positive impact. This positive impact may be due to effective integration of BRI projects with existing energy infrastructure (Tan et al., 2023). Turkiya exhibited a significant negative absolute effect with an actual ESI of 1.4 compared to a predicted 3, resulting in an absolute effect of −1.6 and a relative effect of −52%, with a p-value of 0.003. Uzbekistan’s actual ESI was 2.7 versus a predicted −0.049, yielding an absolute effect of 2.8 and a relative effect of 149%, with a p-value of 0.041, indicating a significant positive impact. Vietnam’s actual ESI was 4.6 against a predicted 5.5, resulting in an absolute effect of −0.93 and a relative effect of −11%, with a p-value of 0.213, suggesting no significant impact.

These findings underscore the diverse impacts of BRI initiatives on ESI across different countries. While some countries like Cambodia, Indonesia, and Turkiya showed significant

negative impacts, others like Thailand and Uzbekistan exhibited positive effects. These results highlight the varied economic and environmental responses to BRI initiatives, emphasizing the need for tailored policy interventions to enhance energy sustainability in participating countries (Abbas et al., 2021; He et al., 2021). The varying impacts can be theoretically supported by the differences in the scale, implementation, and integration of BRI projects, as well as the initial conditions of the countries’ energy infrastructures and policies (Khan et al., 2021; Osabuohien-Irabor and Drapkin, 2022).

5 Conclusion, policy recommendations, and limitations of the study

The findings of this study provide significant insight into the relationship between BRI initiatives and energy sustainability in

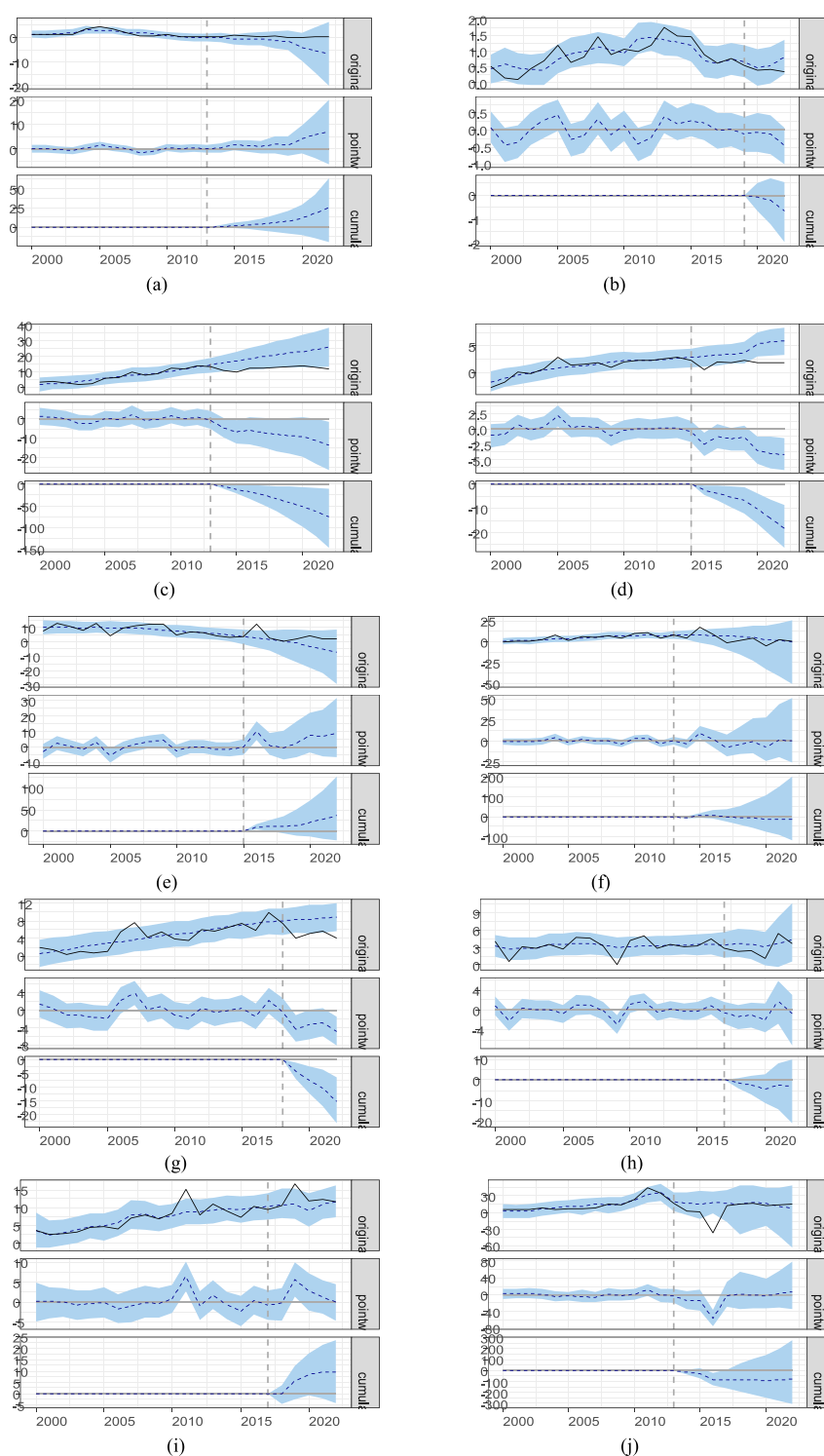


FIGURE 3
(Continued).

selected energy-deficit Asian countries. The study establishes the strong positive effect of economic growth on energy sustainability. Indeed, the assertion is that countries, when growing economically, are ready to put more investments into technologies and infrastructure for sustainable energy, thereby enhancing their

energy sustainability. Economic growth provides wherewithal to invest in energy efficiency and renewable energy projects. The positive effect of trade openness on energy sustainability indicates that international trade can be instrumental in inducing access to advanced energy technologies and practices. Human capital

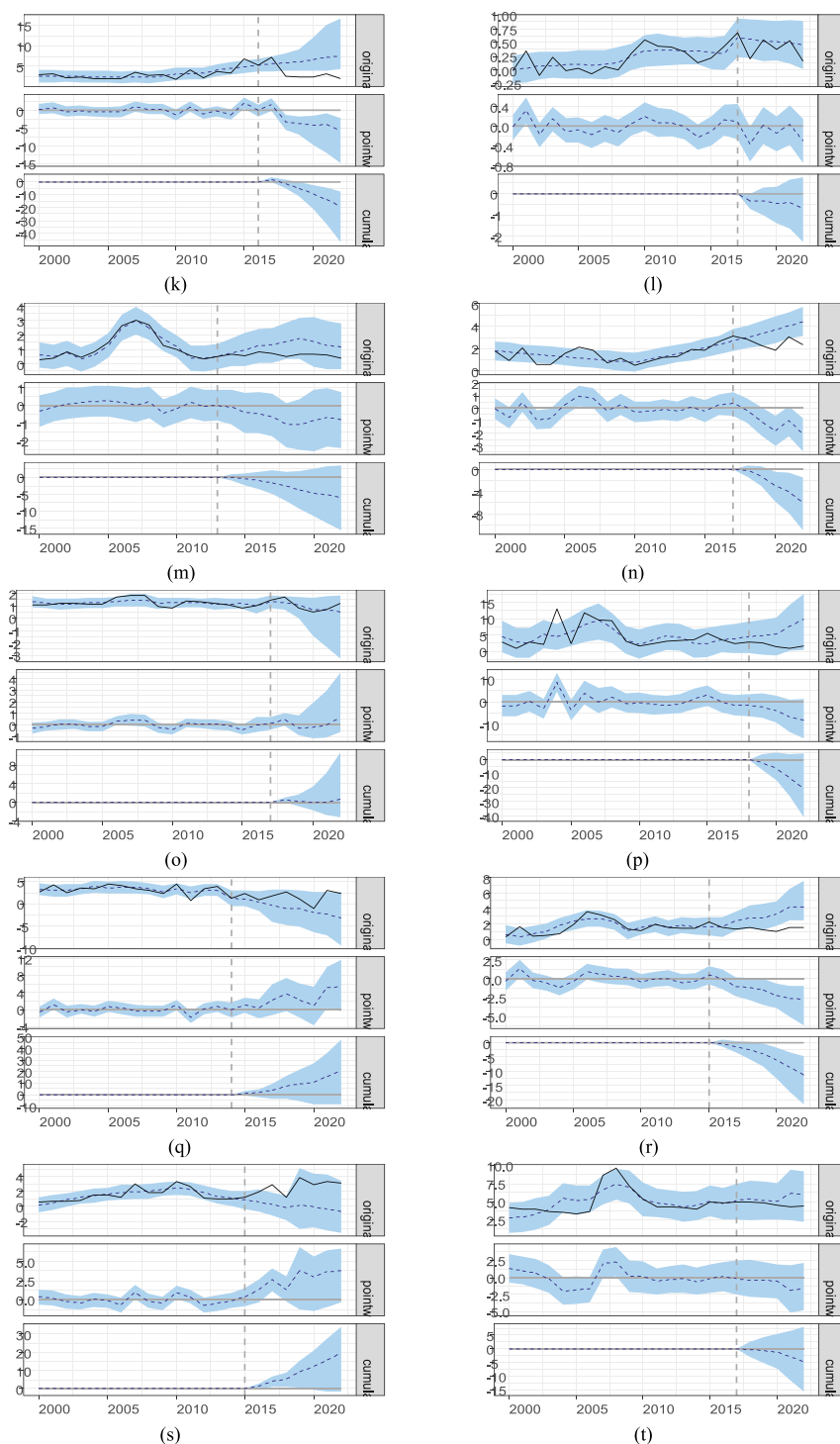


FIGURE 3

(Continued). Causal Impact of BRI initiatives on ESI. (a) Afghanistan; (b) Bangladesh; (c) Cambodia; (d) Indonesia; (e) Kazakhstan; (f) Kyrgyz Republic; (g) Lao PDR; (h) Malaysia; (i) Maldives; (j) Mongolia; (k) Myanmar; (l) Nepal; (m) Pakistan; (n) Philippines; (o) Sri Lanka; (p) Tajikistan; (q) Thailand; (r) Turkey; (s) Uzbekistan; (t) Vietnam.

also evidences a correspondingly significant positive effect on energy sustainability. This result underlines how education, skills, and health conditions can promote sustainable energy use. On the contrary, urbanization exerts a negative effect on energy sustainability at most quantiles. This negative relationship means

that increased urbanization is related to higher energy consumption, since greater energy is needed for transportation.

Causal impact analysis clearly confirms that BRI initiatives have different impacts on energy sustainability in Asian countries, especially through MoUs. For instance in Maldives and Uzbekistan,

the immense change in energy sustainability after the signing of the MoU proves the efficiency in regard to BRI investment for the betterment of energy infrastructure and its efficiency. On the other hand, this issue remains a challenge for most of the countries, meaning thereby that the impact of the BRI initiative is not homogeneous and depends on the context and implementation strategies put into place by each country.

For policymakers and stakeholders, the findings provide valuable insights into how BRI initiatives can be managed to maximize their positive impact on energy sustainability. The study suggests that targeted investments in human capital and infrastructure are crucial for enhancing energy sustainability. Policymakers should focus on creating a conducive environment for economic growth and trade, which can provide the resources needed for sustainable energy investments. Additionally, the negative impact of urbanization highlights the need for urban planning and policies that promote energy efficiency and the adoption of sustainable energy technologies.

Furthermore, countries like Afghanistan, Maldives and Uzbekistan showed positive causal impacts, should continue to encourage and expand investments in energy projects by attracting FDI for energy infrastructure. In nations such as Bangladesh and Pakistan, where the initial impacts are modest or slightly negative, it is crucial to manage short-term disruptions by stabilizing energy policies and infrastructures post-MoU signing. Cambodia, Indonesia, and Turkey, which experienced significant negative impacts, need policies that balance rapid industrialization and urbanization with sustainable energy practices, including implementing energy efficiency measures and promoting cleaner technologies. Thailand's positive outcomes suggest the importance of integrating BRI projects with existing energy infrastructure, a strategy that other countries should adopt for better planning and coordination.

Lastly, in the gradual implementation of BRI projects, Kazakhstan and the Kyrgyz Republic should also be backed with positive but not significant impacts, and support by regular monitoring to ensure that benefits materialize fully. Other countries should take a lead from Uzbekistan and give primacy to investing in human resources and R&D through education, training programs, and incentives for innovation in the energy sector. In the short run, for countries like Myanmar and Tajikistan, which face some of the most negative impacts of large infrastructure, stringent mitigation measures for the environment and green construction methods become necessary.

Despite its contributions, this study has limitations. The scope of countries analyzed and potential data constraints may limit the generalizability of the findings. Future research could expand the analysis to include more countries and longer time frames, and explore additional variables that may influence energy

sustainability. Moreover, further studies could investigate the specific mechanisms through which BRI initiatives impact energy sustainability, providing a more detailed understanding of the causal relationships involved.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://data.worldbank.org>; <https://data.imf.org/>.

Author contributions

AO: Writing – original draft, Conceptualization, Supervision. GZ: Funding acquisition, Methodology, Validation, Writing – review and editing. LS: Funding acquisition, Resources, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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