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Navigating the energy trilemma: integrating technological innovation and digitalization transition for sustainable solutions

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HIGHLIGHTS

- A dual approach combining PLS-SEM and fsQCA is employed.
- TI boosts security and sustainability but harms equity while DT enhances all three.
- Industrial structure, resource rents, and energy structure mediated the effects.
- Tailored strategies are identified to address specific energy trilemma challenges.

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ABSTRACT

Understanding how technological innovation (TI) and digitalization transition (DT) independently shape energy security, energy equity, and environmental sustainability is crucial for effectively addressing the energy trilemma. However, existing literature lacks a comprehensive analysis that distinguishes their impacts, complicating efforts by countries to reconcile competing priorities and achieve overall improvements. This study addresses this gap by systematically comparing the influences of TI and DT on each aspect of the energy trilemma. The resulting targeted policy recommendations provide guidance for countries seeking to alleviate these challenges. The empirical analysis is based on panel data from 14 countries (2000−2021) using a dual-method approach that combines Partial Least Squares Structural Equation Modeling and fuzzy-set Qualitative Comparative Analysis (fsQCA). The findings reveal that: (1) TI strengthens energy equity and environmental sustainability but inadvertently undermines energy equity, whereas DT simultaneously enhances all three aspects of energy trilemma. (2) Industrial structure, natural resource rents and energy structure critically mediate the relationships between TI, DT and the energy trilemma, potentially amplifying, dampening, or even reversing their effects. Building on these insights, fsQCA identifies tailored strategies for alleviating the energy trilemma: (1) Resource-endowed countries should enhance environmental sustainability by strategically integrating TI/DT to diversify their energy portfolios; (2) Developing countries should improve energy equity by leveraging DT-driven initiatives to broaden energy accessibility; (3) Rapidly industrializing countries need to enhance environmental sustainability through targeted investments in green technology innovation. By bridging methodological and contextual divides, this research advances a holistic framework that enables policymakers to navigate trade-offs, align global energy goals with local realities, and accelerate progress toward a balanced resolution of the energy trilemma.

1. Introduction

Driven by climate change and geopolitical conflicts, the global energy system is undergoing a low-carbon transformation [1]. However, this transition is confronted with the energy trilemma, which underscores the complex trade-offs among energy security, energy equity, and environmental sustainability [2]. Neglecting any aspect of this trilemma can exacerbate the challenges of the energy transition, leading to intensified competition for limited energy resources, increased inequalities in energy access, and heightened environmental degradation. Therefore, to effectively navigate the energy trilemma, countries must address each aspect individually rather than treating them as a vague,

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overarching concept. This approach allows for the formulation of specific strategies that can mitigate the distinct challenges associated with energy security, energy equity, and environmental sustainability.

A range of factors including economic, social, environmental, and technological elements can contribute to alleviating the energy trilemma [3]. Among these factors, technological innovation (TI)—an innovation-driven strategy—is particularly effective in addressing these challenges, and its significance has grown with the advent of Industry 4.0 [4]. TI involves the development of new technologies or the enhancement of existing ones to create new products, services or processes that effectively address energy-related challenges. Given its potential benefits, governmental investments in TI have increased significantly. For instance, Finland allocated approximately USD 280 million between 2000 and 2012, with a particular emphasis on hydrogen programs [5]. Despite global recognition of TI's potential to address the energy trilemma, the effects of these efforts remain unclear [6]. One reason for this uncertainty, as noted by Samour et al. [7], is that the impact of TI on each aspect of energy trilemma and the associated mechanisms has not been thoroughly investigated in existing literature. This knowledge gap complicates the interpretation of results and leads to less effective strategies, thus hindering efforts to address the energy trilemma. To overcome this challenge, it is crucial to examine the extent of TI's impact and the mechanisms through which TI affects each aspect of the energy trilemma. By clarifying the underlying transmission channels, TI-drive strategies can be optimized to maximize their benefits.

Moreover, as highlighted by the United Nations Environment Program in its Medium-Term Strategy for 2022–2025 in 2023, digitalization serves as a transformative force in reshaping the monitoring, management, and optimization of energy systems and may also contribute to alleviating the energy trilemma. Unlike TI, digitalization transition (DT) involves converting information into digital formats and emphasizes the use of digital technologies to enhance existing management models within the energy systems. This distinction underscores the complementary roles of TI and DT in addressing the energy trilemma. However, there is ongoing debate within academia regarding the benefits of integrating DT into energy systems. Proponents argue that DT can facilitate the establishment of energy networks [8], which have the potential to improve energy management efficiency and enhance the integration of renewable energy sources, thereby contributing positively to energy security. Conversely, skeptics caution against its environmental impacts, arguing that digital energy infrastructure requires substantial energy consumption and leads to increased carbon emissions [9]. This scenario poses a risk to environmental sustainability. Therefore, it is evident that the impacts of DT on the three aspects of the energy trilemma vary considerably. While existing literature presents diverse perspectives on the effects of DT on the energy trilemma, most studies fail to systematically compare its distinct effects on each aspect. This oversight has resulted in findings that are often inconsistent across different studies. Given the growing prominence of energy digitalization, it is imperative to clarify and explicitly compare its impacts on each aspect of the energy trilemma, as well as the associated transmission channels. Conducting such an analysis is essential for generating actionable insights that promote the responsible application of DT within the energy sector.

Building on the investigation of the transmission channels through which TI and DT affect each aspect of the energy trilemma, it becomes feasible to systematically explore how different configurations of TI and DT interact to produce favorable outcomes for alleviating the energy trilemma. By identifying the optimal combinations of these elements, multifaceted strategies can be developed that leverage the strengths of both domains. Such strategies are better equipped to address the challenges of the energy trilemma across diverse contexts.

Consequently, this study presents two objectives: (1) to investigate and compare the influences of TI and DT on energy security, energy equity and environmental sustainability, while elucidating the mechanisms behind these influences; and (2) to identify the optimal configurations of TI and DT that can effectively alleviate the energy trilemma for different types of countries.

The research follows a "what-how-what-how" logic, as illustrated in Fig. 1. It begins with identifying the research objectives (what), followed by the formulation of hypotheses and the adoption of methodologies to achieve these objectives (how). Subsequently, the findings are presented (what), leading to the development of tailored enhancement pathways (how). The remainder of this paper is organized according to the following framework: Section 2 reviews existing literature on the influences of TI and DT on the energy trilemma. Section 3 develops the research hypotheses. Section 4 presents the research design and methodology. Section 5 details the empirical analysis encompassing 14 countries spanning the period from 2000 to 2021, along with the results. Section 6 provides the policy implications for alleviating the energy trilemma. Finally, Section 7 concludes the study and summarizes the research limitations.

2. Literature review

2.1. The nexus between TI and the energy trilemma

The growing recognition of TI as a sustainable solution to the energy trilemma has spurred numerous research. However, much of the research tends to be scattered across the fields of energy security, energy equity and environmental sustainability. In terms of energy security, Chalvatzis et al. [10] asserted that TI in the energy sector can enhance energy security by increasing the share of renewable energy and diversifying the energy mix in China. This finding is supported by Martinopoulos [11] in the context of EU countries. Regarding the nexus between TI and energy equity, Min et al. [12] illustrated how residential-level innovations, such as rooftop solar panels, exacerbate energy inequality by favoring affluent households capable of bearing high adoption costs. In contrast, Guan et al. [13] found that innovations in energy storage technologies at the community level help mitigate energy inequality by enhancing energy flexibility. Likewise, the impact of TI on environmental sustainability varies significantly with different contextual factors. For example, Deka [14] reported that TI can significantly benefit resource-intensive African countries by facilitating carbon emission reductions. Fatima et al. [15] reaffirmed the positive role of TI in improving environmental sustainability by implementing stringent environmental policies. However, Siripi et al. [16] presented a contrasting perspective, finding that TI in Ghana was associated with increases in carbon emissions but declines in environmental sustainability. The authors noted that these adverse effects of TI can be mitigated when it is combined with foreign direct investment. This divergence in findings underscores the necessity for distinct and tailored strategies for different countries to effectively combat the energy trilemma. However, it should be noted that such studies overlook the unintended consequences of TI. For example, while smart grids or centralized renewable systems may enhance energy security, they can also exacerbate energy equity gaps by displacing marginalized communities or escalating energy prices. This omission is indicative of a broader trend in the literature, which tends to focus on one aspect of the energy trilemma while neglecting its spillover effects on others. As a result, although TI may yield improvements in a specific aspect, achieving overall progress across all aspects of the energy trilemma remains challenging.

To address this challenge, a nascent body of research has begun to examine the energy trilemma in a more holistic manner. Specifically, Li et al. [17] demonstrated the positive effects of TI in alleviating the energy trilemma, highlighting its role in curbing energy consumption, a finding echoed by Yang et al. [18]. On the other hand, Behera et al. [19] observed that TI, especially through R&D efforts, had negligible effects on the energy trilemma. While these studies offer valuable insights into the factors affecting the energy trilemma and suggest holistic strategies

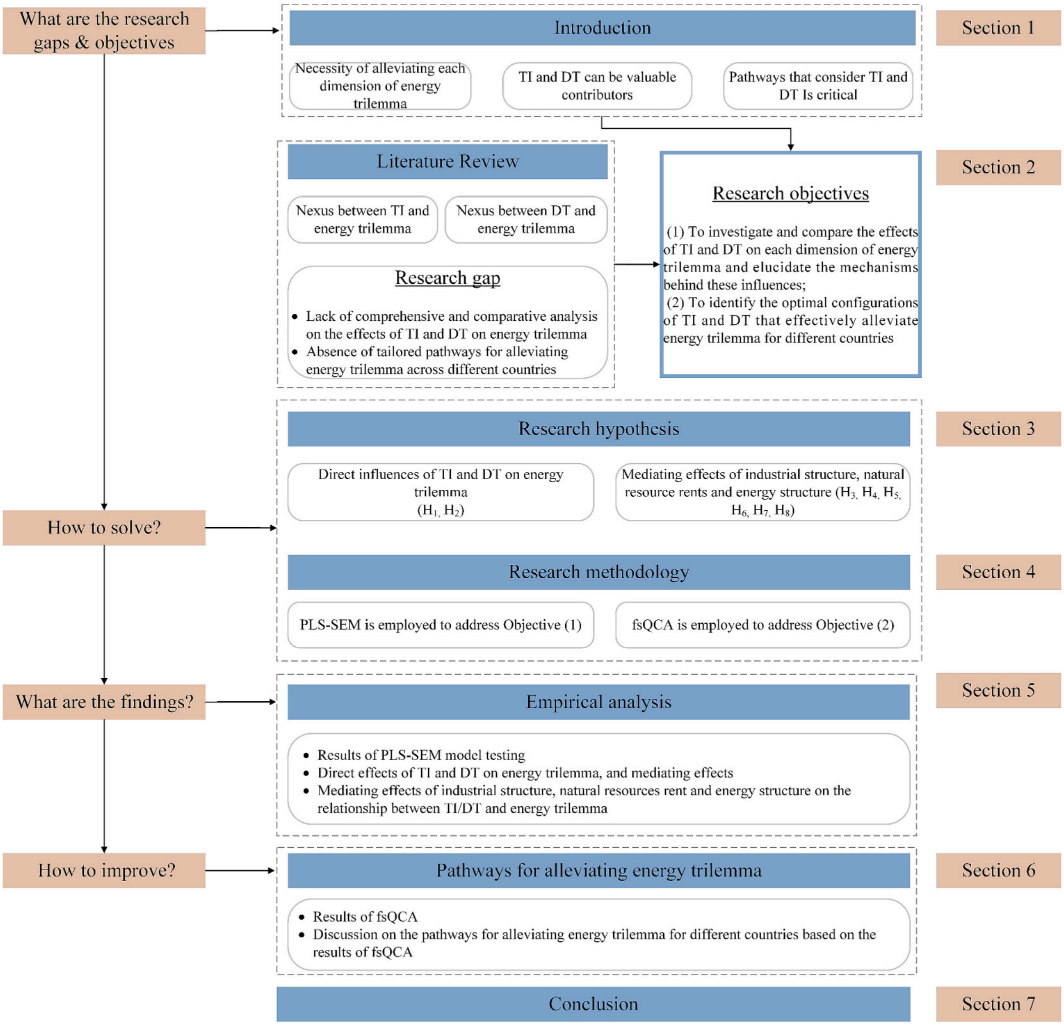

Fig. 1. Research flow.

for improvement, they often fail to identify which aspects of the trilemma are most vulnerable. Therefore, although these strategies are promising in addressing energy challenges, their inability to diagnose and resolve underlying vulnerability risks stalls progress and limits their practical applicability.

The mixed outcomes of both siloed and holistic approaches have raised concerns within academia. Either the unbalanced strategies or the one-size-fits-all conclusions highlight the urgency of a dual imperative: first, to conduct systematic and comparative analysis of TI's effects across each aspect of the trilemma, and second, to develop balanced and targeted strategy frameworks. In this context, studies that compare the influence of identical factors across all aspects are particularly valuable, as they lay the foundation for recognizing the weaknesses and customizing strategies for trilemma improvements. For instance, Parashar et al. [20] found that financial development contributes positively to environmental sustainability and energy equity but adversely affects energy security. This suggests that, when promoting local financial development, it is crucial to place a strong emphasis on measures that protect energy security. However, studies examining the distinct influences of TI on the three aspects of the energy trilemma remain largely unexplored. Addressing this gap could provide deeper insights into how TI can be leveraged to achieve a balanced approach to the energy trilemma.

2.2. The nexus between DT and the energy trilemma

Similarly, research on the effects of DT on the energy trilemma has been increasing; however, it remains fragmented. Firstly, while the influence of DT on energy security has been well investigated, the conclusions are not absolutely positive or negative. For example, Golpîra et al. [21] and Talan et al. [22] demonstrated that DT can enhance energy security by addressing challenges related to energy scheduling, improving energy storage capacity, and facilitating the energy mix. However, the consistency of these positive effects has been questioned. Increased reliance on digitalization may introduce new vulnerabilities into the energy system, such as exposure to cyber threats and increased dependence on complex infrastructure. This concern is further supported by Lee et al. [23], who argue that DT may undermine energy security in high-risk countries where cyber security and infrastructure vulnerabilities are prevalent.

Conversely, the effects of DT on energy equity and environmental sustainability seem to be more consistent. A positive nexus between DT and energy equity was identified by Tao et al. [24]. The authors demonstrated that DT in China can mitigate inequities in energy access by increasing household income and accelerating social capital flows. This finding is further supported by Li et al. [17], who noted that these contributions are facilitated by mediating factors such as upgrading industrial structures, increasing foreign investments, and promoting technological progress. Similarly, in terms of environmental sustainability, Zhang et al. [25] observed that DT can foster carbon emission reduction by promoting the transition to more efficient household appliances and increasing public awareness of energy-saving practices. Lin [26] reached a similar conclusion, noting that DT contributes to enhanced environmental sustainability by reducing the ecological footprint.

In conclusion, while DT has shown promise in addressing energy equity and environmental sustainability, its impact on energy security remains complex. This complexity highlights the risks associated with focusing solely on individual aspects of the energy trilemma, which can lead to one-sided outcomes. To mitigate this bias, some researchers have investigated the performance of the energy trilemma index and explored whether DT contributes to the overall improvements in the index. For example, Zhao et al. [27] found that DT contributed positively to energy security, energy equity and environmental sustainability concurrently. However, despite the growing interest in this area, the number of such studies remains limited. Furthermore, existing research has not thoroughly explored the specific pathways through which DT can enhance each aspect of the energy trilemma. Understanding these pathways is crucial for developing targeted interventions that can effectively balance the competing demands of energy security, energy equity, and environmental sustainability.

The literature reviewed above is summarized in Table 1. While valuable insights have been generated regarding the influence of TI and DT on the energy, several gaps remain. First, most studies that examine the effects of TI and DT focus on individual aspects of the energy trilemma, rather than providing a comprehensive analysis of all three aspects. This fragmented approach results in disparate and incomparable findings, making it challenging for countries to identify their priorities for improving energy systems. Second, while many studies investigate the transmission channels through which TI and DT affect the energy trilemma, they often offer generic recommendations that lack specificity for different national contexts. The absence of targeted pathways for addressing the energy trilemma diminishes the effectiveness of these recommendations, making it difficult for countries to implement meaningful changes. These research gaps motivate the innovations presented in this study: 1) a comprehensive comparison of the effects of TI and DT on energy security, energy equity, and environmental sustainability; and 2) the identification of optimal and targeted pathways for alleviating the energy trilemma across various countries.

3. Development of research hypotheses

3.1. Direct influences of TI and DT on energy trilemma

Disruptive innovation theory posits that disruptive innovations introduce new technologies that fundamentally transform energy systems [28]. Specifically, TI promotes alternative energy sources with lower production costs [29]. This contributes to a more diversified energy mix, which mitigates the risks of supply disruption and enhances energy security. Furthermore, the expansion of renewable energy sources increases access to affordable energy for individuals, addressing energy equity. Additionally, TI can significantly improve energy efficiency, enabling energy systems to achieve greater benefits while simultaneously reducing environmental burdens, contributing to environmental sustainability. Accordingly, the research hypothesis $\mathbf{H_1}$ is proposed as follows:

$\mathbf{H_{1a}}$. TI improves energy security.

$\mathbf{H_{1b}}$. TI contributes to energy equity.

$\mathbf{H_{1c}}$. TI enhances environmental sustainability.

Research indicates that DT has empowered energy management [30]. As noted by Ha [29], energy security involves ensuring a timely energy supply that meets residents' demands. DT facilitates this process by collecting and analyzing extensive data on energy production and consumption. This enables organizations to make more accurate forecasts and ensure adequate real-time supply. As a result, the risks of blackouts are reduced, and overall energy security is improved. Furthermore, DT can help mitigate energy inequity caused by spatial disparities by enhancing access to energy-related information and services through digital platforms [31]. DT also contributes to environmental sustainability through low-carbon business practices, such as e-commerce and online banking [32], as well as by increasing public awareness of energy-retrofitting behaviors. Thus, hypothesis $\mathbf{H_2}$ is proposed.

$\mathbf{H_{2a}}$. DT enhances energy security.

$\mathbf{H_{2b}}$. DT reduces energy equity.

$\mathbf{H_{2c}}$. DT promotes environmental sustainability.

3.2. Mediating effects of industrial structure, natural resource rent and energy structure

3.2.1. Mediating effects of industrial structure

TI and DT can reshape the industrial structure by fostering new industries and transforming existing ones [33], promoting shifts toward energy-efficient and environmentally friendly development patterns [34]. This transformation ensures energy security and supports environmental sustainability. The influence of industrial structure on energy equity can be understood through the principle of “distributional justice,” which emphasizes the fair distribution of energy burdens and benefits to avoid disproportionate impacts on specific groups [35]. In regions dominated by the secondary industry—an industry that consumes significantly more energy than the tertiary or low-carbon industries—a risk of resource shortages and rising energy prices exists. These conditions exacerbate energy inequities, disproportionately affecting individuals and sectors that rely on affordable energy. The hypotheses $\mathbf{H_3}$ and $\mathbf{H_4}$ are as follows:

Hypothesis $\mathbf{H_3}$:

$\mathbf{H_{3a}}$. TI improves energy security when mediated by industrial structure.

$\mathbf{H_{3b}}$. TI reduces energy equity when mediated by industrial structure.

$\mathbf{H_{3c}}$. TI enhances environmental sustainability when mediated by

Table 1
Brief summary of the literature.

Independent variable	Energy security	Energy equity	Environmental sustainability	Energy Trilemma	Reference
TI	–	–	Positive	–	Deka [14], Fatima et al. [15]
	–	–	Negative	–	Siripi et al. [16]
	–	Negative	–	–	Min et al. [12]
	–	Positive	–	–	Guan et al. [13]
	Positive	–	–	–	Chalvatzis et al. [10], Martinopoulos [11]
	–	–	–	Negative	Li et al. [17], Yang et al. [18]
	–	–	–	Insignificant	Behera et al. [19]
DT	–	Positive	–	–	Tao et al. [24]
	Positive	–	–	–	[21], Talan et al. [22]
	Negative	–	–	–	Lee et al. [23]
	–	–	Positive	–	Zhang et al. [25], Lin [26]
	Positive	Positive	Positive	–	Zhao et al. [27]

industrial structure.

Hypothesis $\mathbf{H_4}$:

$\mathbf{H_{4a}}$. DT improves energy security when mediated by industrial structure.

$\mathbf{H_{4b}}$. DT reduces energy equity when mediated by industrial structure.

$\mathbf{H_{4c}}$. DT enhances environmental sustainability when mediated by industrial structure.

3.2.2. Mediating effects of natural resource rent

As discussed in Section 3.1, advancements in TI promote renewable energy alternatives. According to Hussen's hypothesis, rent serves as an indicator of natural resource scarcity [14]. When natural resources are scarce, rents tend to be high; however, the emergence of alternative energy sources reduces this scarcity, thereby reducing natural resource rents. From a macroeconomic perspective, natural resource rents represent a wealth transfer. This transfer flows from energy-importing nations to resource-exporting nations or, from consumers and industrial sectors to the entities controlling energy extraction. Consequently, a decline in these rents could effectively curtail this outflow of capital. In other words, a greater share of national wealth is thereby retained by households, in the form of lower energy bills, and by the industrial sector, through reduced operational costs. This retention of capital can foster overall economic vitality and enhance national competitiveness. It enables the countries to better absorb external shocks, including very energy-related risks, such as price volatility. As a result, we propose the hypothesis that TI enhances energy security through the mediating effects of natural resource rents ($\mathbf{H_{5a}}$). However, natural resource rents are a key source of government revenue. A decline in these rents could lead to higher unemployment [36] and reduced funding for environmental governance. This can undermine energy equity by making energy less affordable and exacerbating challenges to environmental sustainability. Consequently, $\mathbf{H_{5b}}$ and $\mathbf{H_{5c}}$ are proposed in this study.

Hypothesis $\mathbf{H_5}$:

$\mathbf{H_{5a}}$. TI enhances energy security through the mediating effects of natural resource rents.

$\mathbf{H_{5b}}$. TI negatively impacts energy equity through natural resource rents.

$\mathbf{H_{5c}}$. TI impairs environmental sustainability when mediated by natural resource rents.

Conversely, DT can enhance the efficiency of natural resource extraction, potentially inducing energy rebound effects. In other words, improved efficiency leads to increased energy consumption and higher natural resource rents, which results in greater reliance on fossil fuels and, negatively affects energy security. However, in the long term, higher natural resource rents from DT can support energy equity and environmental sustainability. Governments can use the additional revenue to alleviate energy poverty and strengthen environmental governance. Thus, the following hypotheses $\mathbf{H_6}$ are proposed:

Hypothesis $\mathbf{H_6}$:

$\mathbf{H_{6a}}$. DT negatively impacts energy security through the mediating effects of natural resource rents.

$\mathbf{H_{6b}}$. DT positively influences energy equity when mediated by natural resource rents in the long term.

$\mathbf{H_{6c}}$. DT improves environmental sustainability when mediated by natural resource rents in the long term.

3.2.3. Mediating effects of energy structure

The configuration of the energy structure also mediates the relationship between TI, DT and the energy trilemma. According to Chapman et al. [37], advancements in energy structure involve not only technological progress but also changes in social and political structures. Such transformations can reduce the influence of energy producers and their political ties, enhancing opportunities for secure and equitable energy development. Moreover, Apergis et al. [38] found a positive association between energy structure optimization and environmental sustainability. They noted that a 1% increase in renewable energy share correlates with a 0.149% reduction in carbon intensity. Accordingly, the hypotheses $\mathbf{H_7}$ and $\mathbf{H_8}$ are proposed:

Hypothesis $\mathbf{H_7}$:

$\mathbf{H_{7a}}$. TI improves energy security when mediated by energy structure.

$\mathbf{H_{7b}}$. TI advances energy equity when mediated by energy structure.

$\mathbf{H_{7c}}$. TI enhances environmental sustainability when mediated by energy structure.

Hypothesis $\mathbf{H_8}$:

$\mathbf{H_{8a}}$. DT improves energy security when mediated by energy structure.

$\mathbf{H_{8b}}$. DT enhances environmental sustainability when mediated by energy structure.

$\mathbf{H_{8c}}$. DT advances energy equity when mediated by energy structure.

4. Research design and methodology

4.1. Research methodology

4.1.1. Introduction to PLS-SEM

Partial Least Squares Structural Equation Modeling (PLS-SEM) is commonly applied to measure the symmetric nexus between variables. This study employs PLS-SEM for several reasons. First, it does not require large sample size, and reliable results can be obtained even with relatively small datasets [39]. More importantly, PLS-SEM is particularly effective when referring to composite variables [40], that is, it supports the use of several sub-variables to represent a typical variable. This ensures the comprehensiveness of the variables. Owing to these advantages, PLS-SEM has been widely employed, and its effectiveness has been validated by previous research, including those by Hossain et al. [41] and Wang et al. [42].

PLS-SEM comprises two constructs: (1) the measurement model, and (2) the structural model (refer to Fig. 1). The measurement model is used to describe the nexus between latent variables (X_i) and observed variables (x_{im}). Latent variables are abstract concepts that cannot be measured directly, whereas observed variables are specific, measurable indicators that can be collected through various means, such as official releases. Each latent variable typically has multiple associated observed variables, as illustrated in Fig. 1. The structural model is applied to measure the relationships among latent variables, typically illustrated using a path diagram. In this model, the path relationship (β_i) indicates the direct or indirect effects between latent variables. The direction of the paths (arrows) signifies the direction of causality. It is important to note that these relationships can be mediated by mediating variables (M_j), which can also be represented by observed variables, as shown in Fig. 2.

4.1.2. Introduction to fsQCA

Fuzzy-set qualitative comparative analysis (fsQCA) is designed to identify and analyze the configurations of variables that lead to specific outcomes. This approach complements PLS-SEM by capturing asymmetric relationships among variables [43]. In PLS-SEM, the relationship between dependent and independent latent variables is assumed to be symmetric, such as TI (independent latent variable) and energy security (dependent latent variable). This implies that advancements in TI directly enhance energy security, and vice versa. However, in practice, while innovations such as renewable energy technologies can indeed improve energy security, the reverse is not always guaranteed. This is

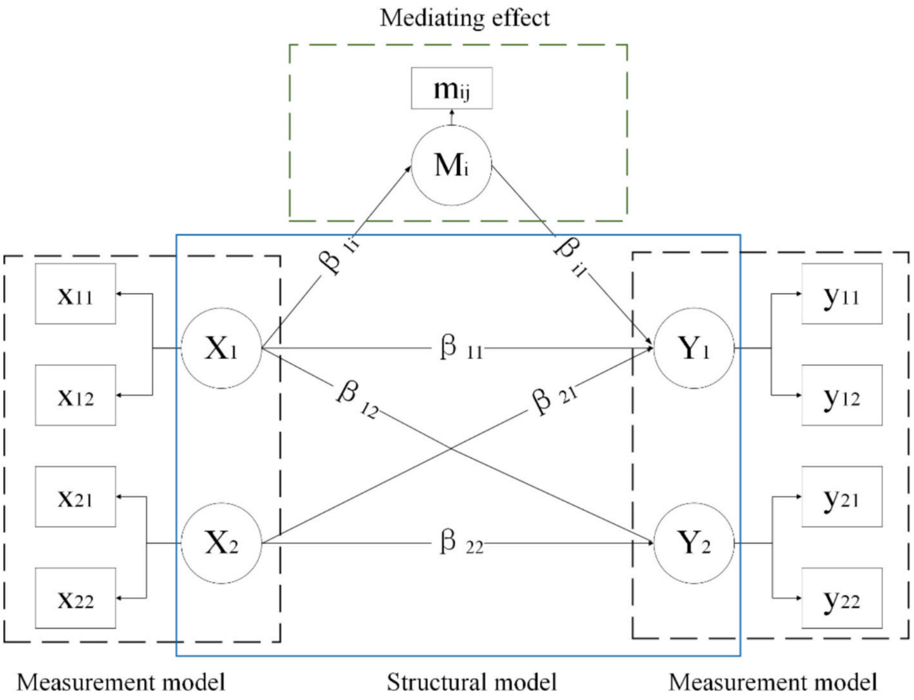

Fig. 2. PLS-SEM model specification.

because, policymakers may fail to support new technologies due to political, economic, or social reasons, even if energy security improves. Thus, enhanced energy security does not always stimulate more TI.

4.2. Variables

In terms of the principles of the PLS-SEM model, the latent and observed variables are identified in Table 2.

"TI (X_1)" results from the collaborative efforts of practice and research. On the practical side, the number of technological patents (x_{11}) provides measurable data indicating the level of innovation, while machinery advancement (x_{12}) captures improvements in production technology [44]. On the academic side, publications related to science and technology (x_{13}) reflect the role of academic institutions in driving technological advancements. "DT (X_2)" typically functions through digital services and associated networks [45]. Therefore, penetration of the internet (x_{21}) and information and communications technology service (x_{22}) are identified as observed variables. The latent variable "Energy security (Y_1)" is associated with a diversified energy mix, which enhances resilience to uncertainties and reduces the likelihood of blackouts caused by unstable energy supplies. Therefore, the diversity of energy sources (y_{11}) is selected as an observed variable for energy security. As for "Energy equity (Y_2)," the Sustainable Energy for All initiative asserts that every individual should have equal access to energy. Thus, energy accessibility (y_{21}) is used as an observed variable for energy equity. Specifically, y_{21} is measured by per capita access to primary energy, a metric whose validity has been empirically confirmed by Huang et al. [46]. A relatively low per capita access to primary energy indicates that the region may face challenges in energy access and utilization, highlighting the unequal distribution of energy resources and revealing issues of energy equity. However, owing to data availability constraints, only coal is considered in this study. In terms of "Environmental sustainability (Y_3)", evidence indicates that approximately 90% of carbon emissions originate from fossil fuel combustion [47]. Therefore, the observed variable "per capita carbon emissions (y_{31})" is considered an appropriate observed variable for environmental sustainability. The mediating variable "Industrial structure (M_1)" is represented by the degree of industrial upgradation (m_{11}), which is measured as the ratio of value added in the secondary industry to GDP [48]. A

Table 2
Description of variables.

Latent variable	Observed variable	Description
X_1: TI	***x_{11}:*** Technological patents	The number of patent applications from non-residents
	x_{12}: Machinery advancement	Machinery and transport equipment (% of value added in manufacturing) The percentage of the value of machinery and transport equipment relative to the overall value added
	x_{13}: Academia efforts to TI	The number of journal articles regarding scientific and technical fields
X_2: DT	***x_{21}:*** Penetration of the internet	The proportion of imports of computer, communications, and other services relative to total service imports
	x_{22}: Information and communications technology service	ICT service exports
Y_1: Energy security	***y_{11}:*** Diversity of energy sources	The ratio of the number of applied energy types to the total number of energy types
Y_2: Energy equity	***y_{21}:*** Energy accessibility	Per capital access to coal
Y_3: Environmental sustainability	***y_{31}:*** Per capita carbon emissions	The proportion of total carbon emissions to permanent residents
M_1: Industrial structure	***m_{11}:*** The degree of industrial upgradation	The ratio between the value added in secondary industry to GDP
M_2: Natural resource rent	***m_{21}:*** Coal rent	Denote the economic profit that can be derived from the extraction and sale of coal/oil, above and beyond the costs of production
	m_{22}: Oil rent	
M_3: Energy structure	***m_{31}:*** Renewable alternatives production	Share of renewable alternatives to total energy production
	m_{32}: Renewable alternatives consumption	Share of renewable alternatives to total energy consumption

higher ratio indicates a less advanced industrial structure. “Natural resources rent (M_2)” is represented by the observed variables “coal rent” (m_{21}) and “oil rent” (m_{22}). These economic measurements reflect fluctuations in energy prices, providing insights into energy market dynamics. “Energy structure (M_3)” is indicated by the shares of renewable energy production and consumption (m_{31} and m_{32}).

The data used in this study are obtained from the World Development Indicators, a comprehensive database developed by the World Bank (Source: https://databank.worldbank.org/). The dataset covers the period from 2000 to 2021. Owing to data availability constraints, 14 countries were selected as cases for this research: specifically, three from North America (Canada, United States, and Mexico), two from South America (Brazil and Colombia), two from Europe (Romania and United Kingdom), and eight from Asia (Kazakhstan, Russia, Uzbekistan, China, India, Indonesia, and Thailand), as shown in Fig. 3. The sample data for the year 2021 are provided in Appendix Table 1.

The descriptive statistics for the variables were analyzed to ensure data reliability (see Table 3). The standard deviation indicates that the data dispersion is within an acceptable range. Notably, the skewness value exceeds 1, suggesting a highly skewed distribution of the data. Additionally, the kurtosis values for some variables (such as m_{32}, m_{21}, x_{22}) fall outside the ±2 range [49], indicating the presence of outliers or extreme cases. However, considering that 79% of the surveyed countries are developing countries and 21% are developed countries, the disparities in the performance of these variables are understandable. For example, regarding x_{22} (Information and communications technology), developed countries generally have access to ample capital, advanced technologies, skilled talent, and robust infrastructure, all of which support their growth in this field. In contrast, developing countries often face constraints due to limited resources, resulting in lower performance for variable x_{22}. Subjectively removing these data points could result in the loss of critical information, ultimately undermining the reliability of the results. Consequently, these potential outliers are retained for future analysis. To address the impact of extreme values and enhance the interpretability of the data, a logarithmic transformation was applied.

Table 3
Descriptive analysis.

Variables	Mean	Std	Min	Max	Skewness	Kurtosis
x_{11}	0.34	0.67	0.00	3.36	2.96	8.39
x_{12}	0.20	0.09	0.03	0.36	−0.12	−1.01
x_{13}	0.76	1.31	0.00	6.70	2.36	4.84
x_{21}	0.38	0.14	0.03	0.71	−0.25	0.13
x_{22}	1.02	1.89	0.00	11.95	2.76	8.47
m_{11}	0.30	0.08	0.17	0.48	0.31	−0.62
m_{21}	0.51	0.75	0.00	4.95	2.65	9.22
m_{22}	3.30	4.61	0.01	24.70	2.46	6.16
m_{31}	0.61	0.81	0.00	3.91	2.35	5.08
m_{32}	2.18	3.39	0.04	23.51	3.06	12.25
Y_1	0.92	0.11	0.50	1.00	−1.27	0.75
Y_2	1.48	1.59	0.02	6.96	1.57	2.36
Y_3	0.66	0.52	0.09	2.04	0.95	−0.12

4.3. PLS-SEM model construct in this study

Based on the introduction to PLS-SEM and the identified variables listed in Table 2, a PLS-SEM construct was established (see Fig. 4). The

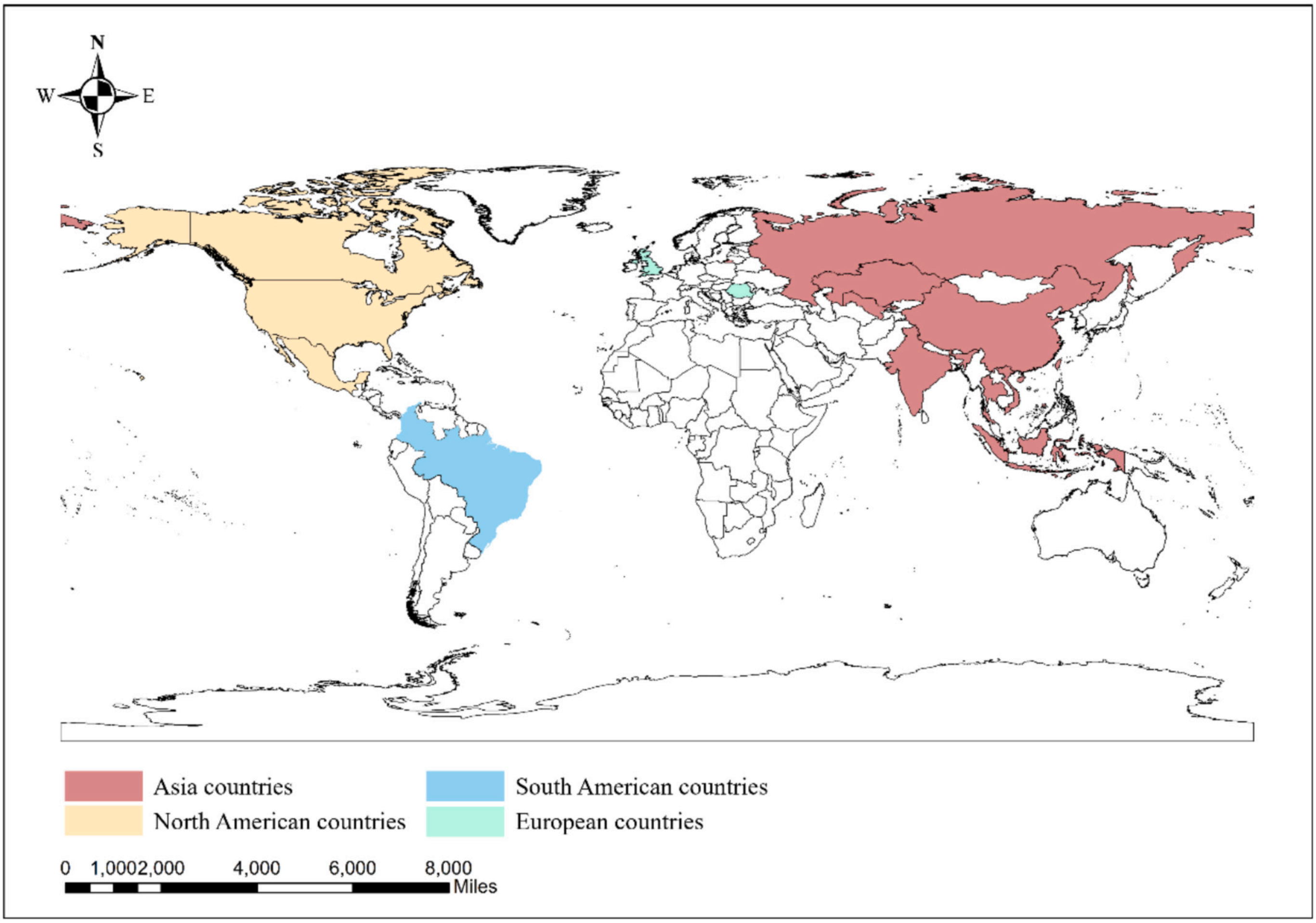

Fig. 3. Distribution of research cases.

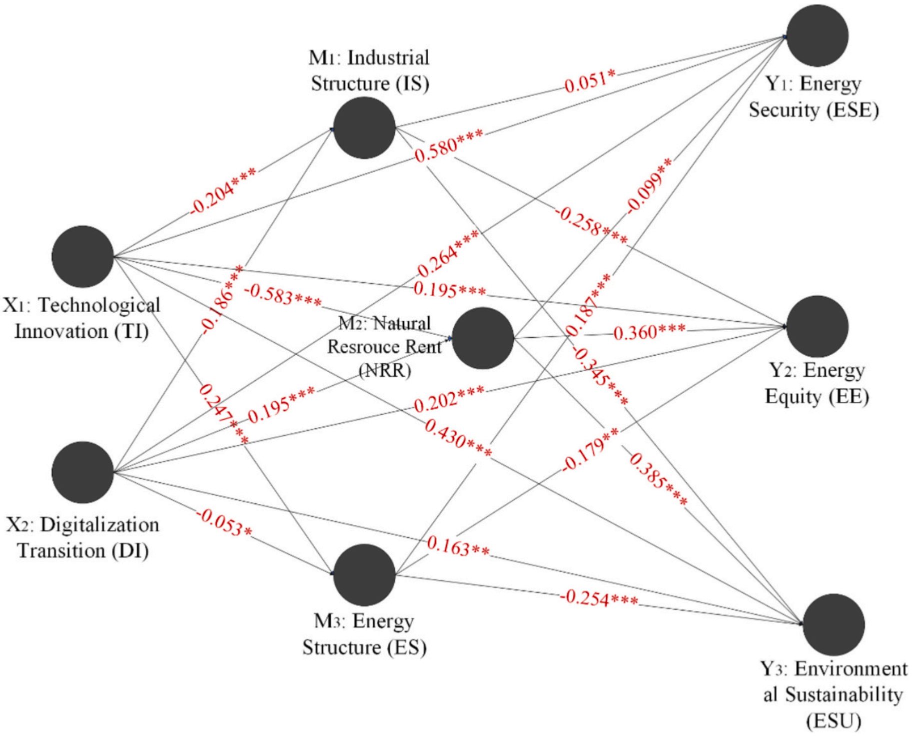

Fig. 4. PLS-SEM model design for this study.

outer loadings are presented in Table 4. An outer loading above 0.7 indicates significant relationships between latent and observed variables, thereby validating the effectiveness of the model. For TI (X_1), represented by observed variables x_{11} to x_{13}, the outer loadings fall between 0.747 and 0.923, suggesting strong associations between X_1 and its observed variables. Similarly, DT (X_2), natural resource rent (M_2), and energy structure(M_3) show outer loadings of 0.898, 0.997 and 0.912 respectively, further reinforcing the robustness of the model. Notably, the latent variables energy security(Y_1), energy equity(Y_2), environmental sustainability(Y_3), and industrial structure (M_1) are each represented by a single observed variable. Consequently, they inherently exhibit strong associations with the latent variables, and their outer loadings are equal to 1. These results collectively imply the effectiveness of the PLS-SEM construct.

5. Empirical analysis

5.1. Results of reliability and validity test

In the PLS-SEM model, convergent validity evaluates how effectively a group of items represents a single underlying concept. This is typically assessed using Cronbach's alpha (CA), composite reliability (CR), and average variance extracted (AVE) [43]. CA assesses the degree to which items in a scale measure the same underlying construct. The minimum threshold of CA is 0.7, with higher values indicating greater reliability. CR similarly assesses the internal consistency of the items associated with a construct and should also exceed 0.70 to indicate acceptable reliability. AVE measures the proportion of variance that a construct captures in relation to measurement error and should be above 0.50. These metrics collectively ensure that the constructs are well-defined and accurately measured. Regarding the discriminant validity, the Heterotrait-Monotrait (HTMT) ratio of correlations is particularly useful because it provides a more stringent test compared to traditional methods such as the Fornell-Larcker criterion [50]. An HTMT ratio less than 0.9 indicates sufficient discriminant validity. All these metrics were measured through SmartPLS 4.0 (see Table 5). The results show that CA and CR values exceed their thresholds of 0.7, suggesting reliability. AVE values exceed the minimum of 0.5, reflecting convergent validity, and the HTMT ratio remains below the upper limit of 0.9, demonstrating discriminant validity.

Table 4
Outer loadings of PLS-SEM model.

Latent variables	Observed variables	Outer loadings
TI (X_1)	x_{11}	0.893
	x_{12}	0.923
	x_{13}	0.747
DT (X_2)	x_{21}	0.898
	x_{22}	0.898
Energy security (Y_1)	y_{11}	1.000
Energy equity (Y_2)	y_{21}	1.000
Environmental sustainability (Y_3)	y_{31}	1.000
Industrial structure (M_1)	m_{11}	1.000
Natural resource rent (M_2)	m_{21}	0.997
	m_{22}	0.997
Energy structure (M_3)	m_{31}	0.912
	m_{32}	0.912

5.2. Results of structural model

The structural model was tested using bootstrap analysis at a 5% confidence level. The results of the hypothesis testing are summarized in Table 6, shedding lights on the direct influences of TI and DT on the energy trilemma, as well as the effects mediated by industrial structure (M_1), natural resource rents (M_2) and energy structure (M_3). It can be observed that Hypotheses 1 and 2—which examine the direct relationships between TI/DT and energy security (Y_1), energy equity (Y_2), and environmental sustainability (Y_3)—are statistically supported. Regarding the mediating effects, nearly all hypotheses are supported, except for the mediating effect of industrial structure on the relationship between TI and energy security, which is not statistically significant. This suggests that industrial structure does not meaningfully mediate this relationship. However, it does play an effective mediating role in

Table 5
Test results for measurement model.

Criteria	M_1	M_2	M_3	X_1	X_2	Y_1	Y_2	Y_3
Cronbach's alpha	1.000	0.995	0.797	0.816	0.760	1.000	1.000	1.000
Composite reliability	1.000	0.997	0.908	0.892	0.893	1.000	1.000	1.000
Average variance extracted	1.000	0.995	0.831	0.736	0.807	1.000	1.000	1.000
Heterotrait-Monotrait Constructs	1	2	3	4	5	6	7	8
M_1: Industrial structure								
M_2: Natural resource rent	0.311							
M_3: Energy structure	0.418	0.295						
X_1: TI	0.280	0.589	0.312					
X_2: DT	0.286	0.284	0.150	0.386				
Y_1: Energy security	0.267	0.433	0.374	0.817	0.501			
Y_2: Energy equity	0.335	0.388	0.358	0.147	0.228	0.011		
Y_3: Environmental sustainability	0.284	0.123	0.138	0.344	0.439	0.287	0.480	

Table 6
Hypotheses testing results.

Hypothesis	Path	Path coefficients	*P* value	Remark
Hypothesis 1	1a: X_1 - > Y_1	0.674	0.000***	Supported
	1b: X_1 − > Y_2	−0.111	0.025**	Supported
	1c: X_1 − > Y_3	0.213	0.000***	Supported
Hypothesis 2	2a: X_2 − > Y_1	0.437	0.000***	Supported
	2b: X_2 − > Y_2	0.198	0.000***	Supported
	2c: X_2 − > Y_3	0.383	0.000***	Supported
Hypothesis 3	3a: X_1 − > M_1 − > Y_1	−0.010	0.100	Not Supported
	3b: X_1 − > M_1 − > Y_2	−0.048	0.000***	Supported
	3c: X_1 − > M_1 − > Y_3	0.070	0.001***	Supported
Hypothesis 4	4a: X_2 − > M_1 − > Y_1	−0.010	0.086*	Supported
	4b: X_2 − > M_1 − > Y_2	−0.048	0.000***	Supported
	4c: X_2 − > M_1 − > Y_3	0.064	0.000***	Supported
Hypothesis 5	5a: X_1 − > M_2 − > Y_1	0.058	0.055*	Supported
	5b: X_1 − > M_2 − > Y_2	−0.210	0.000***	Supported
	5c: X_1 − > M_2 − > Y_3	−0.225	0.000***	Supported
Hypothesis 6	6a: X_2 − > M_2 − > Y_1	−0.019	0.070*	Supported
	6b: X_2 − > M_2 − > Y_2	0.070	0.000***	Supported
	6c: X_2 − > M_2 − > Y_3	0.075	0.001***	Supported
Hypothesis 7	7a: X_1 − > M_3 − > Y_1	0.046	0.000***	Supported
	7b: X_1 − > M_3 − > Y_2	−0.044	0.001***	Supported
	7c: X_1 − > M_3 − > Y_3	−0.063	0.000***	Supported
Hypothesis 8	8a: X_2 − > M_3 − > Y_1	−0.010	0.090*	Supported
	8b: X_2 − > M_3 − > Y_2	0.010	0.097*	Supported
	8c: X_2 − > M_3 − > Y_3	0.014	0.085*	Supported

Note: $p < 0.001$, ***; $p < 0.05$, **; $p < 0.1$, *.

other aspects of the energy trilemma.

5.2.1. *Direct influences of TI and DT on energy trilemma*

Table 3 demonstrates that both TI and DT exhibit positive effects on energy security and environmental sustainability. Specifically, TI has a greater effect on energy security than DT, while DT has a larger impact on environmental sustainability than TI. This is because TI can directly enhance energy production and management, improving overall security, whereas DT's effects often depend on technological advancements, which weakens its contribution to energy security. However, DT excels in integrating data across various sectors, such as energy, transportation, and construction, facilitating cross-sector collaboration for environmental sustainability. In contrast, TI typically targets specific technologies or products and often lack the ability to integrate across fields. Additionally, due to longer development cycles of TI, it often struggles to adapt quickly to environmental changes, which weakens its positive influences on environmental sustainability.

Despite this similarity, the key difference is that TI negatively impacts energy equity, whereas DT has a positive influence. This difference arises primarily from the costs associated with implementing TI and DT. Adopting TI often requires substantial investment and infrastructure changes, which can be challenging for less economically developed countries [35]. As a result, economically advantaged countries may achieve higher energy efficiency and consumption, while less developed countries may continue to experience inefficiencies and lower consumption levels. This disparity contributes to a widening gap in energy equity. On the other hand, DT solutions, such as smart grids and mobile applications, can be more easily integrated into existing systems and may require lower capital investment. This accessibility facilitates broader participation across diverse countries, ultimately helping to mitigate energy inequities.

5.2.2. *Mediating effects of industrial structure on the relationship between TI/DT and energy trilemma*

Notably, when industrial structure is introduced as a mediating variable, the effects of TI and DT on energy security exhibit distinct patterns. Specifically, previously significant positive impact of TI on energy security becomes insignificant. In contrast, DT continues to significantly affect energy security; however, its impact shifts to a negative direction. The change in effect of TI can be attributed to the continued reliance of the industrial sector on fossil fuels. Because industrial structure is measured by the share of the secondary industry, an increase in this share often correlates with higher fossil fuel consumption. For many countries, these fossil fuels are imported, as confirmed by the Energy Institute [51], which reports that international energy trading has increased by over 53% since 2000. This situation leads to two key issues: a lack of diversification in energy sources and constraints on energy consumption imposed by exporting countries. Together, these factors diminish the positive effects of TI on energy security. On the other hand, the negative shift in the effect of DT can be explained by the following reason. DT promotes traditional manufacturing industries to shift toward value-added services. For instance, product servitization—such as maintenance and support services provided through cloud computing— enables companies to diversify their revenue streams beyond product sales and expand into the service sector. This shift leads to a relative decline in the share of the secondary industry and a significant increase in the tertiary industry. However, energy storage, transmission, and conversion are closely intertwined with the secondary industry [52]. As the focus shifts toward the tertiary sector, this may disrupt the energy industrial chain, compromising overall energy security. If this structural change is not properly managed, it could introduce risks to the stability and reliability of the energy supply.

Interestingly, previous analysis indicates that TI can directly exacerbate energy inequity; however, these negative effects are mitigated when industrial structure is considered as a mediator. In other words, as the industrial structure upgrades, the positive effects of TI on energy equity begins to emerge. Additionally, when industrial structure serves as a mediator, its impact on environmental sustainability remains significant though less pronounced. Given that industrial structure is proxied by the ratio of secondary industry value-added to GDP, these attenuated effects suggest that TI's positive influence on environmental sustainability diminishes as the secondary industry expands. Conversely, TI's environmental benefits become more substantial when the secondary industry's share declines. This pattern aligns with findings by Xiang et al. [53], who noted that advancing industrial structures strengthens inter-regional industrial linkages, thereby promoting industrial clusters. These clusters facilitate the sharing of resource and clean energy technologies, enabling less-resourced countries to improve energy efficiency, thereby narrowing energy inequities and improving environmental sustainability. In contrast, DT adversely affects these two aspects. It induces changes in industrial structure that may trigger energy rebound effects and alter energy allocation. Specifically, as industrial structures upgrade, demand for energy-intensive products, such as high-tech items in manufacturing, is likely to increase. Producing these items typically requires substantial energy inputs. Consequently, this increased production concentrates resources like electricity and raw materials in high-energy-consuming sectors while restricting access for low-energy-consuming industries, exacerbating energy inequity [54]. Additionally, this increased production generates substantial carbon emissions, undermining environmental sustainability.

5.2.3. *Mediating effects of natural resource rents and energy structure on the relationship between TI/DT and energy trilemma*

When natural resource rents and energy structure are introduced as a mediating variable, the influences of TI and DT on the energy trilemma reveal opposing patterns. Specifically, TI positively impacts energy security but negatively affects energy equity and environmental sustainability. Conversely, DT exhibits opposing pattern across these three aspects. It should be noted that while the results supported the proposed hypothesis H_5 and H_6, the positive influence of TI on energy security was found to be diminished when mediated by natural resource rents and energy structure. This diminished effect can be understood through a two-fold process. On one hand, as mentioned in Section 3, TI enhances energy structure. This, in turn, reduces a nation's reliance on traditional fossil fuels, thereby decreasing the natural resource rents and potentially leading to underinvestment in their production capacity. On the other hand, the real-world replacement of fossil fuels with renewables is hampered by the slow progress and high costs associated with developing and deploying new technologies and infrastructure. These two concurrent factors—a potential decline in fossil fuel production capacity and the sluggish adoption of renewables—combine to reduce the overall elasticity of the energy supply. This creates a precarious transition period, posing a potential threat to energy security. Therefore, even though TI is ultimately beneficial for energy security, it is necessary to pay attention to the transitional risks involved. Policymakers must strategically manage the pace of this transition, ensuring that investment in reliable renewable infrastructure keeps pace with the phasing out of traditional energy sources to maintain a stable and secure energy supply. Similarly, the positive effects of DT on energy equity and environmental sustainability diminish when we take natural resource rents and energy structure into account. This indicates that the benefits of DT are not inherently universal but are instead contingent on a set of enabling preconditions. For example, when a country relies heavily on natural resource rents, its energy structure is likely to stagnate or regress. While revenue from these rents can be used to tackle issues of energy equity and environmental governance (mentioned in Section 3), the negative consequences may outweigh the benefits. Therefore, it is essential to recognize that, although natural resource rents and a primary energy-dominated structure can generate revenue, unchecked expansion of these resources can undermine the advantages of DT in promoting energy equity and environmental sustainability.

5.3. *Discussion of findings in context*

The findings of this study provide important insights into the interplay between TI, DT, and the energy trilemma—energy security, energy equity, and environmental sustainability. Based on the results above, we further compare the research differences with existing literature. This comparison enhances the understanding of the broader implications and contextual relevance, reinforcing the reliability of our study.

Regarding the studies on the effects of TI and DT on energy security, several findings from our research align with previous research. For example, Ghazouani [55], Lee et al. [56] and Wang et al. [57] discovered that TI consistently foster energy security in the contexts of the United States, China and EU countries respectively, most of which are also sample countries in our study. Likewise, we found that DT negatively influences energy security when mediated by industrial structure. However, these negative effects can be reduced if structural changes are effectively managed. This observation is consistent with the findings from Jin et al. [58], who observed that DT has U-shaped effects on energy security. Specifically, while DT initially negatively impacts energy security, these negative effects may be mitigated as the industrial structure becomes more rational and integrated.

In terms of the literature related to energy equity, some findings diverge from previous research. Notably, we found that TI negatively impacts energy equity. This argument contrasts with the findings of Yang et al. [18], which assert that renewable TI promote energy equity. This disparity may arise from different policy frameworks across countries. Yang et al. [18] focused on China, which has a unique policy environment. For instance, China' "Leader Plan" under the photovoltaic poverty alleviation project promotes the establishment of solar power stations in impoverished areas and mandates that State Grid and China Southern Power Grid unconditionally absorb all power generated by these stations. This ensures a stable electricity supply and generates income for impoverished areas from electricity sales, reducing energy inequity. In a similar vein, some in-depth case studies focused on specific regions have reached conclusions that also diverge from those of the present study. For instance, research by Min et al. [59] demonstrates a positive correlation between TI—specifically in solar programs—and enhanced energy equity across several Pacific Northwest cities, including Bellevue, Seattle, and Portland. The selection of these cities as a point of comparison is strategic: they serve as an ideal-type benchmark due to their unique combination of strong local governance, high social consensus on environmental goals, and, most importantly, technology programs that are intentionally designed with dedicated equity provisions [60]. Min et al. [59]'s positive findings therefore highlight what is achievable under the most favorable conditions. In stark contrast, our study analyzes a diverse set of 14 countries with varying policy backgrounds, economic development and governance capacity. Our findings reveal that in the absence of the robust, equity-oriented policy frameworks seen in the Pacific Northwest, TI do not automatically lead to greater equity. For example, in Brazil, where market-based pricing mechanisms prevail, the implementation of TIs may result in a "green premium," leading to higher costs for consumers and exacerbating energy inequities. Regarding the effects of DT on energy equity, Zhong et al. [61] concluded from their empirical study of over 50 developing and developed countries that DT can promote energy equity. This finding aligns with the results related to direct influences. Although Zhong et al. [61] used energy poverty as the metric for measuring energy equity, it shares significant similarities with the definition of energy equity in this study.

Regarding the effects of TI and DT on environmental sustainability, Jarijari et al. [62] discovered that TI potentially worsens environmental sustainability, as an increase of one unit in TI could lead to approximately a 10% rise in the ecological footprint in Sub-Saharan Africa. This finding contrasts with our assertion that TI has a positive impact on environmental sustainability. Saharan African countries, primarily developing economies, are experiencing slow industrialization, and access to electricity remains limited. It is projected that by 2030, 42% of the population will still lack adequate electricity [63]. Consequently, while these nations receive international development assistance, the majority of funding is prioritized for expanding energy infrastructure rather than advancing clean energy solutions. This development trajectory inevitably exacerbates environmental challenges. However, our study further reveals that advancing industrial structures can amplify the positive effects of TI, aligning with findings from Ma et al. [33]. Therefore, for Saharan African countries, it is recommended to allocate funding strategically. While building energy infrastructure is essential for improving access to energy for residents, it is equally important to support the advancement of local industrial structures. This dual approach has the potential to significantly promote environmental sustainability. Similarly, we found that DT negatively impacts environmental sustainability through industrial structure. This finding is supported by several studies, such as Zhu et al. [64]. However, Ge et al. [65] present a contrasting perspective. While they also argue that DT may induce energy rebound effects mentioned in Section 3, they further noted that a critical threshold could be reached where the gains in energy efficiency from DT exceed the potential harm caused by increased energy consumption on environmental sustainability. In other words, at this juncture, even with higher energy consumption, overall carbon emissions may decrease as digital technologies enhance the marginal efficiency of energy use. These contrasting findings highlight the necessity for a long-term examination of the effects of DT on environmental sustainability, particularly considering the mediating role of industrial structure.

In conclusion, comparing this study's findings with previous research either reinforces its validity or offers additional possibilities and explanations for the results, providing complementary perspectives.

6. Analysis of enhancing paths

6.1. Data calibration and necessity analysis

The scores of the latent variables obtained from PLS-SEM were used for fsQCA analysis, which involves three steps: data calibration, necessity analysis, and sufficiency analysis. For data calibration, the 95%, 50%, and 5% quantiles of the variable distribution were set as the calibration values for "fully in," "crossover," and "fully out," respectively. In the necessity analysis, a consistency value above 0.9 indicates a necessary condition. However, as shown in Table 7, all variables exhibit consistency levels below 0.9, indicating that no single condition is necessary for affecting the energy trilemma. Thus, the analysis proceeded to examine sufficient condition analysis.

6.2. Sufficient analysis of configurations for energy trilemma improvements

For the sufficiency analysis, the upper threshold for consistency was set at 0.8, and the frequency cut-off was established at two cases. Thus, three configuration paths were identified for energy security, three for energy equity, and four for environmental sustainability (see Table 8). The cases relevant to each path are further summarized in Table 9.

Table 7
Necessity analysis for energy trilemma.

	High performance of energy security		Low performance of energy security		High performance of energy equity		Low performance of energy equity		High performance of environmental sustainability		Low performance of environmental sustainability	
	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage
TI	0.681	0.603	0.252	0.176	0.635	0.640	0.625	0.654	0.689	0.725	0.556	0.558
~TI	0.394	0.507	0.894	0.589	0.656	0.628	0.657	0.651	0.580	0.578	0.726	0.690
DT	0.678	0.619	0.506	0.305	0.776	0.640	0.669	0.608	0.792	0.723	0.650	0.566
~ DT	0.411	0.619	0.668	0.515	0.552	0.616	0.646	0.749	0.524	0.610	0.682	0.758
Industrial structure	0.449	0.818	0.745	0.512	0.689	0.686	0.596	0.616	0.576	0.599	0.673	0.667
~Industrial structure	0.636	0.830	0.422	0.282	0.615	0.595	0.700	0.699	0.679	0.685	0.595	0.573
Natural resource rent	0.409	0.926	0.650	0.503	0.633	0.711	0.543	0.633	0.549	0.643	0.600	0.671
~ Natural resource rent	0.678	0.789	0.509	0.306	0.673	0.587	0.752	0.681	0.719	0.654	0.680	0.590
Energy structure	0.572	0.800	0.391	0.286	0.627	0.666	0.615	0.677	0.565	0.625	0.613	0.648
~ Energy structure	0.501	0.617	0.751	0.473	0.696	0.635	0.697	0.660	0.682	0.649	0.645	0.586

Note: "~" denotes the condition is not satisfied.

According to Table 9, energy security issues should be addressed in the majority of cases (53%). These cases are typically countries with abundant natural resources and exhibit a degree of autonomy in energy production, indicating that a significant portion of their income is derived from natural resource rents. For these cases, Paths ESE1 and ESE3 are the most frequently recommended for enhancing energy

Table 8

Configurations for energy trilemma improvement.

Path	Energy security			Energy equity			Environmental sustainability			
	ESE1	ESE2	ESE3	EE1	EE2	EE3	ESU1	ESU 2	ESU 3	ESU 4
TI		▯	▯	▯		⊗	▯	▯	▯	▯
DT	▯	⊗	▯	⊗	▯	▯	⊗	⊗	⊗	▯
Industrial structure		▯	⊗	⊗		▯			▯	⊗
Natural resource rent	⊗			⊗	▯			⊗		
Energy structure	▯			⊗	⊗	⊗	▯			⊗
Raw coverage	0.456	0.285	0.480	0.253	0.478	0.452	0.334	0.380	0.353	0.355
Consistency	0.946	0.851	0.992	0.820	0.851	0.843	0.832	0.791	0.815	0.859

Note: "▯" denotes the existence of condition, while "⊗" indicates its absence.

Table 9

Paths for each research case.

	ESE1	ESE2	ESE3	EE1	EE2	EE3	ESU1	ESU 2	ESU 3	ESU 4
Canada	√		√							
Mexico		√		√			√	√	√	
United States	√		√	√				√		
Brazil	√		√				√	√		
Colombia										
Romania	√									
United Kingdom	√		√							
Kazakhstan					√	√				
Russia Federal			√		√	√				√
Uzbekistan										
China	√	√			√	√	√	√	√	
India	√		√		√	√	√			√
Indonesia	√									
Thailand		√					√	√	√	
Vietnam							√	√	√	

security. When effectively leveraging their natural resource endowments, these cases are advised to employ a combination of TI and DT to reduce reliance on natural resources while optimizing their energy structure, thereby improving energy security. Approximately 26% of the cases should prioritize energy equity issues. These cases are predominantly found in developing countries, where resources are unevenly distributed [66]. Paths EE2 and EE3 are the most frequently recommended in these contexts, advocating for the effective use of DT to optimize their energy structures and ensure universal access to energy. Environmental sustainability should be prioritized by approximately 33% of the cases. These cases belong to emerging economies, characterized by rapid economic development and industrialization. This growth has led to environmental pressures and increased resource consumption. Therefore, Paths ESU1 and ESU2 are recommended, focusing on leveraging TI to develop more environmentally friendly technologies that support sustainable development.

7. Conclusion

This research employed the PLS-SEM model to examine and compare the effects of TI and DT on energy security, energy equity, and environmental sustainability across 14 countries, while also uncovering the underlying mechanism through which these effects occur. Furthermore, it investigated targeted pathways to alleviate the energy trilemma in different national contexts.

The PLS-SEM analysis confirmed that the constructs used in this study demonstrate strong reliability and validity. Three key findings emerge from the analysis. First, both TI and DT have direct positive effects on energy security, but their contributions are significantly mediated by industrial structure. Second, TI negatively affects energy equity, especially in regions dominated by the secondary industry, whereas DT generally enhances energy equity. Notably, natural resource rents exacerbate the negative impacts of TI, while industrial structure mitigates the positive impacts of DT. Third, regarding environmental sustainability, the positive effects of TI are amplified when mediated by industrial structure, while DT consistently promotes sustainability, although its benefits are less pronounced in areas with a high concentration of secondary industry. To address the energy trilemma, we recommend three distinct pathways, each tailored to the specific priorities identified through fsQCA results for different countries. Firstly, 53% of the cases—typically those with abundant natural resources—should focus on reducing reliance on fossil fuels and diversifying their energy mix to enhance energy security. Secondly, in 26% of the cases, generally found in developing countries, prioritizing DT can improve energy access and thereby advance energy equity. Lastly, approximately 33% of the cases—characterized by rapid industrialization—would benefit from enhancing TI to develop environmentally friendly technologies, thereby reducing pollution and promoting environmental sustainability.

From a theoretical perspective, this study deepens the understanding of the roles of TI and DT in achieving a balanced and sustainable energy future. From a practical perspective, it contributes to the understanding of how TI and DT can be integrated into energy policy frameworks by providing empirical evidence and actionable pathways for policymakers.

Despite these contributions, this study has the following limitation: the limited number of sample countries included in the analysis due to data unavailability. This constraint restricts the generalizability of the findings on a global scale. Therefore, future research should combine traditional statistics with alternative data sources—such as satellite imagery, machine learning-generated estimates, or crowd-sourced datasets—to establish reliable proxy indicators for missing variables, thereby enabling broader and more inclusive cross-country analyses. Second, while the study uses data from 14 countries for PLS-SEM, it does not account for heterogeneity among these nations—such as differences in economic development, institutional frameworks, or resource endowments. Future research should incorporate these variations through stratified analyses or country-specific case studies to better understand how TI and DT impact energy trilemmas across diverse contexts.

CRediT authorship contribution statement

Jiayu Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **C.P. Sing Michael:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Mingming Guan:** Writing – review & editing, Conceptualization.

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.

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Appendix A. Appendix

Appendix Table 1
Sample data for 2021.

Country	x_{11}	x_{12}	x_{13}	x_{21}	x_{22}	m_{11}	m_{21}	m_{22}	m_{31}	m_{32}	Y_1	Y_2	Y_3
Canada	0.32	0.22	0.70	0.60	1.62	0.24	0.07	2.83	1.08	4.22	1.00	1.24	1.33
Mexico	0.15	0.31	0.19	0.32	0.10	0.31	0.02	2.07	0.70	0.78	1.00	0.04	0.35
United States	3.29	0.24	4.71	0.49	5.86	0.18	0.17	0.61	0.77	9.81	1.00	1.54	1.40
Brazil	0.20	0.14	0.71	0.53	0.33	0.20	0.01	2.60	2.76	5.77	1.00	0.04	0.22
Colombia	0.02	0.03	0.08	0.30	0.07	0.25	0.73	3.42	0.58	0.64	0.83	1.16	0.19
Romania	0.00	0.35	0.12	0.53	0.83	0.27	0.02	0.38	1.27	0.27	1.00	0.92	0.49
United Kingdom	0.07	0.29	1.08	0.69	4.27	0.17	0.00	0.42	2.25	1.30	1.00	0.02	0.50
Kazakhstan	0.00	0.08	0.02	0.50	0.02	0.35	0.85	14.84	0.06	0.12	0.83	5.89	1.12
Russian Federation	0.11	0.15	0.73	0.58	0.72	0.32	0.61	9.67	0.26	2.09	1.00	2.98	1.04
Uzbekistan	0.00	0.08	0.01	0.12	0.02	0.31	0.05	0.87	0.09	0.05	0.83	0.15	0.34
China	1.59	0.27	6.13	0.36	5.07	0.39	0.61	0.31	0.63	23.51	1.00	2.89	0.74
India	0.35	0.21	1.39	0.62	11.95	0.26	1.28	0.33	0.43	3.27	1.00	0.57	0.17
Indonesia	0.07	0.13	0.19	0.56	0.17	0.40	1.22	0.77	0.08	0.86	0.83	2.22	0.19
Thailand	0.07	0.31	0.13	0.40	0.03	0.35	0.03	0.48	0.44	0.36	0.83	0.20	0.38

Data availability

Data will be made available on request.

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