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Do clean energy transitions enhance global energy security? A comparative analysis of trends and tradeoffs across eight major economies, 1990-2020

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ABSTRACT

Energy security has grown increasingly vulnerable in an era of global trade wars, supply shocks, and military conflicts. Against escalating geopolitical tensions and increasing market instability, assessing how clean energy transitions can strengthen resilience has become imperative. Our study examines how clean energy transitions shape the future of energy security under external shocks. We analyze energy security trends from 1990 to 2020 across eight major economies (the United States, Japan, China, India, the United Kingdom, Germany, France, and Brazil) using locally estimated scatterplot smoothing (LOESS) approaches. Multilayer perceptron (MLP) models are then employed to identify key drivers of multidimensional energy security and to generate scenario-based projections through 2050. Although the results reveal diverse national energy security trajectories prior to 2010, a common inflection point occurs around this time. Clean energy transitions are projected to strengthen energy security in most countries and mitigate vulnerability to external disruptions. These findings underscore the strategic urgency of accelerating clean energy deployment to enhance long-term energy resilience and support global net-zero ambitions.

1. Introduction

Ever since the oil shocks of the 1970s, energy security has constituted a fundamental pillar of national security. More recently, it has become an increasingly critical concern for a diverse range of stakeholders, including governments, industries, and households (Gasser, 2020; Ang et al., 2015). Amid increasing energy demand (BP, 2024), and escalating geopolitical uncertainty, achieving a stable and resilient energy system has become more crucial and challenging than ever (Desogus et al., 2023; Szulecki and Overland, 2023).

Academic and public interest in energy security has paralleled with global politics. Originating in the 1970s during the oil crisis (Willrich, 1976), this interest has since evolved alongside geopolitical shifts (Fig. 1 (a)). Over time, energy security has risen rapidly on national and international policy agendas, driven by a convergence of key developments: geopolitical upheavals (Matsumoto and Shiraki, 2018; Shakya et al., 2022), global climate imperatives (McCollum et al., 2018; Cergibozan, 2022), and the rapid advancement of emerging energy technologies (van Greevenbroek et al., 2025; Zhao et al., 2024).

Public concern over energy security has also expanded very recently, with google search trends showing two notable peaks for "energy security" in June 2009 and June 2025 in Fig. 1(b). Related terms like "energy price," "oil security," and "electricity price" have also attracted growing attention, peaking between late 2024 and mid-2025. In response, governments have taken varied actions, for instance, the US has expanded fossil fuel production (Zebang and Yi, 2024), China has accelerated nuclear and hydropower infrastructure projects, including Yarlung Tsangpo River Hydropower Station (Reuters, 2025), the UK has launched Great British Energy to boost clean energy seeking the goal of becoming a "Clean Energy Superpower"(Gov.UK, 2025), and Japan has begun gradually restarting nuclear power after a 14-year hiatus (EIA, 2024).

Accurate measurement is fundamental to energy security research, enabling scholars to assess current conditions, identify key drivers, and inform policy responses (Gasser, 2020; Ang et al., 2015). This study focuses on eight major economies - US, Japan, China, India, UK, Germany, France, Brazil - which together account for about 58% of global greenhouse gas emissions, represent about 59% of global energy

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consumption, and collectively import around 64% of the world's oil (BP, 2024). Examining these typical and illustrative cases provides valuable insights into diverse energy security pathways shaped by varying resource endowments and economic development stages.

In this study, we systematically review 1498 academic publications on energy security, including 245 studies specifically focused on measurement, to trace the field's theoretical and empirical evolution. Building on this foundation, we compile and harmonize data reporting energy security indicators for eight selected economies, constructing national energy security trend lines from 1990 to 2020 based on 2218 observations. Leveraging this consolidated dataset, we apply MLP models to quantify the marginal contribution of individual sub-indicators to observed variations in energy security. We then simulate and forecast the energy security trajectories of these countries from 2021 to 2050 under scenarios involving decarbonization and external shocks.

Our study makes four contributions. First, to the best of our knowledge, it is the first to systematically apply a meta-analysis approach to synthesize quantitative measurement results from existing studies on energy security across eight major economies (Gasser, 2020; Ang et al., 2015). This approach minimizes subjective biases stemming from indicator selection and weighting. Second, departing from conventional methods that construct energy security indicators or indices through weighted aggregation of sub-indicators, this study adopts a results-oriented, reverse identification strategy. This enables the dynamic identification of key drivers over time, addressing the limitations of fixed-weight models in analyzing long-term trends. Third, we develop a multi-country, multi-scenario simulation framework to forecast energy security under decarbonization pathways, fossil fuel policy shifts, and potential external conflicts. While many existing studies have explored the relationship between renewable energy and geopolitical risks (Cergibozan, 2022), this research goes a step further by forecasting how clean energy transitions may reshape energy security in the face of external disruptions. Fourth, focusing on energy security as a multidimensional concept shifts from overly narrow depictions of energy security as security of fuel supplies or appropriately priced energy services, and our study makes it possible to correlate energy security performance with major events such as military conflicts, embargoes, or the introduction of new, transformational energy policies or technologies. Moreover, it helps identify tradeoffs within the different dimensions of energy security as well as reveal energy security vulnerabilities and problems that can motivate regional cooperation by creating an incentive for countries to work together to address common energy security threats.

2. Literature review

Although energy security still lacks a concise or universally accepted definition, decades of research have gradually brought greater convergence in its conceptualization. It is now widely understood as a multidimensional paradigm that extends beyond the stability of energy supply to encompass environmental sustainability, system resilience, and technological adaptability (Gupta, 2008; Sovacool and Brown, 2010; Sovacool et al., 2011; Demski et al., 2018). Building on this conceptual consensus, a substantial body of empirical work has focused on constructing composite energy security indices at national levels. These studies differ markedly in their dimensional coverage, indicator selection, and weighting strategies.

For example, Wang et al. (2024) assessed China's energy security across supply, use, environmental, and economic dimensions at both national and regional scales. More research has expanded the analytical scope from single-country assessments to comparative and global perspectives. Ayaz et al. (2024), for instance, examined 14 non-OECD Asian economies and show that rising dependence on non-renewable energy supply intensifies energy insecurity and constrains economic growth. Zhang and Zhou (2024) proposed a variance-based weighting

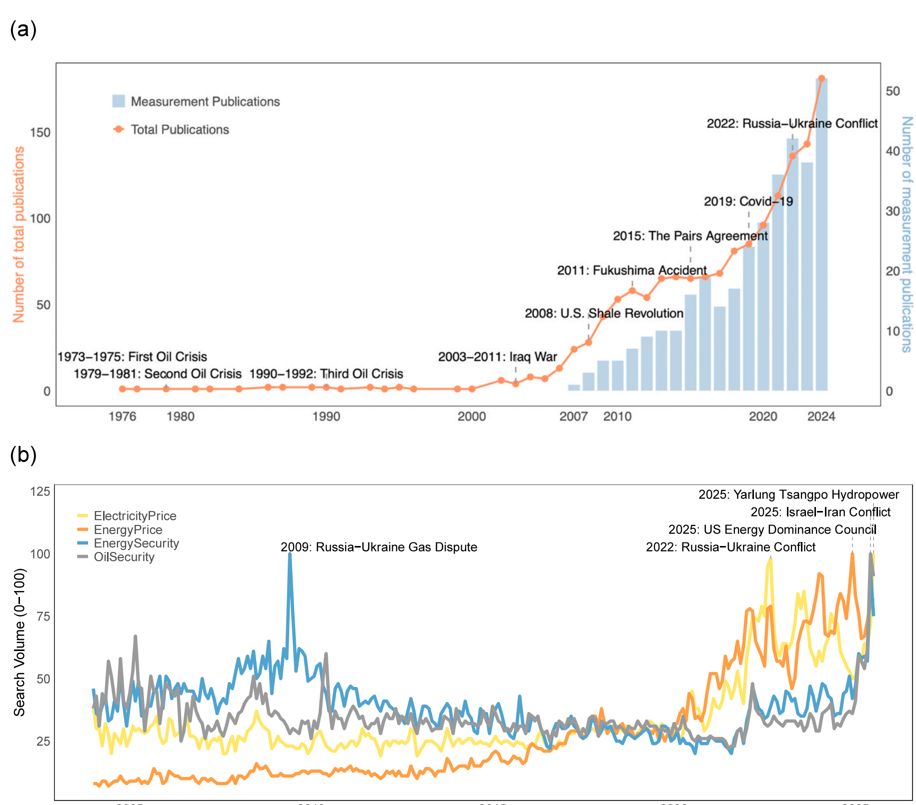

Fig. 1. Academic and Public Attention to Energy Security Published in the Literature Over Time.
(a) Publication trends (1976 - 2024). (b) Google search interest (January 2004 - July 2025).

framework to construct a composite index for 24 countries over the period 1995-2018.

Synthesizing insights from the existing literature, this study conceptualizes national energy security along four dimensions: energy reliability, economic stability, environmental sustainability, and governance capacity, as shown in Table 1.

Although a broad consensus has gradually emerged on the conceptual dimensions of energy security, existing measurement studies remain highly fragmented as well as uneven in their geographic focus, with a bias still towards economies in the Global North. To address this limitation, this study adopts a meta-analytical framework to systematically synthesize quantitative measurement results across a mix of Global North and Global South countries from the literature and reconstruct comparable energy security trends, thereby enhancing cross-study consistency and comparability.

Building on this growing body of research, we have the opportunity to move beyond measurement and toward explaining the underlying drivers of observed variations in energy security. Prior studies in this area have primarily focused on energy efficiency and energy consumption. For instance, Wang et al. (2018) found that renewable energy significantly contributed to maintaining China's energy independence and mitigating climate change. Similarly, Trotta (2020) employed the Logarithmic Mean Divisia Index I (LMDI-I) method to demonstrate that improvements in energy efficiency played a critical role in reducing Finland's energy consumption between 2005 and 2015. Dao et al. (2025) examined energy security through energy diversification indices, showing that technological innovation and geopolitical risk jointly shape distinct dimensions of energy security.

Table 1
Dimensions and indicators of energy security used in the literature.

Dimensions	Indicators	References
Energy reliability	Production per capita	Sovacool (2013); Li et al. (2016); Li and Zhang (2018); Wang et al. (2021); Wang et al. (2024); Zhang and Zhou (2024); Zhi et al. (2024); Fang et al. (2025)
	Reserve to production ratios	Ang et al. (2015); Song et al. (2019); Wang et al. (2020); Huang et al. (2021); Ziemba (2022); Zhang and Zhou (2024)
	Import dependence	Yao and Chang (2024); Li and Zhang (2018); Song et al. (2019); Le et al. (2019); Wang et al. (2020); Wang et al. (2021); Huang et al. (2021); Fang et al. (2025)
	Consumption per capita	Gong et al. (2021); Brodny and Tutak (2023); Wang et al. (2024); Zhi et al. (2024); Fang et al. (2025)
	Energy intensity	Ang et al. (2015); Li et al. (2016); Li and Zhang (2018); Radovanović et al. (2017); Le et al. (2019); Gong et al. (2021); Brodny and Tutak (2023); Du et al. (2024)
Economic stability	GDP per capita	Li et al. (2016); Le et al. (2019); Wang et al. (2020); Ziemba (2022); Zhang and Zhou (2024); Du et al. (2024)
	Electricity price	Sovacool (2013); Ang et al. (2015); Huang et al. (2021); Gong et al. (2021); Brodny and Tutak (2023)
	Oil price	Yao and Chang (2024); Li and Zhang (2018); Wang et al. (2020); Zhang and Zhou (2024);
Environmental sustainability	Carbon emission intensity	Li et al. (2016); Radovanović et al. (2017); Song et al. (2019); Gong et al. (2021); Zhi et al. (2024)
	Carbon emission per capita	Li and Zhang (2018); Zhi et al. (2024); Wang et al. (2020); Ziemba (2022); Wang et al. (2024); Du et al. (2024)
Governance capacity	Global government index	Sovacool et al. (2011); Huang et al. (2021)

Nevertheless, existing studies often concentrate on a limited set of drivers, thereby underrepresenting the relative importance of multiple dimensions of energy security. Moreover, the temporal evolution of individual indicator contributions remains insufficiently examined, particularly in comparative cross-country analyses. To address these gaps, this study develops a multidimensional, temporally explicit decomposition framework that deciphers the evolving roles of key drivers over three decades.

Energy and geopolitics have long been deeply intertwined, and the ongoing clean energy transition is fundamentally reshaping international energy relations. In an increasingly interconnected world, national energy systems rely heavily on cross-border flows of energy commodities, critical raw materials, and technological capabilities (Van de Graaf et al., 2016; Gasser, 2020; Van de Graaf and Sovacool, 2020; Wang et al., 2024). Simultaneously, intensifying geopolitical volatility has subjected global markets to more frequent and systemic disruptions, characterized by acute price instability and heightened supply-chain fragility. While traditional vulnerabilities, such as the regional concentration of oil trade, remain potent sources of systemic shock (Wei et al., 2022), the decarbonization of energy systems has introduced new risk vectors. The channels through which geopolitical instability propagates have expanded beyond fossil fuel markets to encompass low-carbon supply chains and critical mineral inputs. For instance, recent evidence suggests that geopolitical risk exerts persistent downward pressure on the price stability of clean energy metals (Shao et al., 2026).

Meanwhile, worsening climate conditions and growing concerns over carbon emissions are accelerating the shift toward renewable energy sources such as solar and wind. Clean energy is widely recognized not only as a critical substitute for fossil fuels in mitigating global warming but also as a more evenly distributed resource that may enhance national self-sufficiency and reshape the balance of global energy power (Chen et al., 2024). Against the backdrop of intensifying geopolitical tensions and market instability, scholars have increasingly focused on whether clean energy can strengthen national energy security. For instance, Kartal et al. (2023) found that nuclear power represents a viable option for France to cope with reductions in natural gas supplies, while Su et al. (2024) demonstrated that China's energy system resilience improves significantly under carbon neutrality scenarios.

Despite these insights, existing studies largely treat clean energy transition and geopolitical risk as separate analytical domains, offering limited evidence regarding the dynamic interplay between these two forces. Addressing this gap, this study explicitly examines the moderating role of clean energy transition in the relationship between geopolitical disruptions and national energy security, thereby contributing new evidence to the literature on energy resilience and energy governance.

3. Research design

3.1. Literature screening and evaluation

To systematically construct a comprehensive, multidimensional database of national energy security performance, we conducted a structured literature review integrating peer-reviewed academic studies and institutional reports. The primary data sources were Web of Science and Scopus, using a set of targeted keywords including "energy security," "coal security," "oil security," "gas security," "LNG security," "nuclear security," and "renewable energy security." Inclusion criteria comprised publication type (peer-reviewed journal articles) and language (published in English). As of December 2024, our search yielded 2861 publications from Web of Science and 3133 from Scopus. After removing duplicates and screening for relevance, we retained 1462 unique studies directly related to energy security. An additional 11 publications were identified through backward snowballing. We also included 16 institutional reports from authoritative sources such as the International Energy Agency (IEA, 2024) and the Global Energy Index

(GEI, 2020), resulting in a final pool of 1489 relevant sources.

Of these, 245 studies explicitly reported energy security metrics. We further narrowed the scope to those providing quantitative measures for eight major economies – US, Japan, China, India, UK, Germany, France and Brazil, resulting in 72 studies. These countries were selected because they offer sufficient data coverage over the 1990-2020 period, enabling the construction of complete and reliable energy security trajectories and ensuring that long-term trends are not biased by missing observations. From these studies, we extract a total of 2218 energy security observations, which formed the empirical foundation for the analysis conducted in this study.

We employ a meta-analytical framework to construct national energy security trajectories by aggregating quantitative estimates from the literature. This approach mitigates the influence of study-specific modeling and weighting choices by allowing multiple independent evaluations to jointly inform the inferred trajectories, thereby reducing subjective bias while preserving heterogeneity in expert assessments. Moreover, the collected studies predominantly adopt multi-country and multi-dimensional energy security frameworks, with broadly comparable conceptual dimensions and indicator coverage. The resulting trajectories are consistent with those reported in comparative cross-national energy security assessments, supporting the cross-country comparability of our results.

To ensure cross-study comparability and facilitate integration across diverse methodological frameworks, all extracted energy security scores were standardized onto a common 0-100 scale using min-max normalization. This transformation aligns disparate scoring systems - often based on different conceptual definitions, scales, or measurement intervals - into a unified metric space, as the following equation:

$$y_i^{norm} = \frac{y_i - \min(y)}{\max(y) - \min(y)} \times 100 \tag{1}$$

This linear transformation preserves the relative positioning and interpretability of scores across studies, while enabling robust comparative and meta-analytical assessments.

3.2. Estimating energy security by the LOESS approach

To capture the nonlinear and potentially nonstationary evolution of the energy security indicators over time, we apply LOESS - a flexible, non-parametric regression technique that fits local polynomials to subsets of the data through distance-based weighting (Cleveland, 1979). LOESS approach estimates the smoothed value $\hat{y}(x)$ at a given point x as a weighted average of observed responses.

$$\hat{y}(x) = \sum_{i=1}^{n} w_i(x) y_i^{norm} \tag{2}$$

where y_i is the observed value at location x_i, and $w_i(x)$ is the weight assigned to y_i based on its proximity to x. The weights are typically computed using a tricube kernel function:

$$w_i(x) = \left(1 - \left|\frac{x - x_i}{d(x)}\right|^3\right)^3 \cdot I\left(\left|\frac{x - x_i}{d(x)}\right| \le 1\right) \tag{3}$$

where $d(x)$ defines the local neighborhood radius (determined by a user-specified span parameter), and $I(\cdot)$ is an indicator function that restricts the fit to nearby points. The tricube kernel ensures a smooth weighting scheme, giving greater influence to points closer to the focal year while down-weighting more distant observations.

In this study, we specify a smoothing span of 0.5, a commonly used and empirically accepted choice in LOESS-based trend estimation (Cleveland, 1979; Cleveland and Devlin, 1988). This value balances the need to capture short-term variability with the objective of preserving long-term structural trends in national energy security trajectories. We further conducted a sensitivity analysis using alternative smoothing spans of 0.4 and 0.6 (as shown in Appendix A Figure A1). The overall temporal patterns and cross-country comparisons remain qualitatively consistent across alternative specifications, indicating that our findings are not driven by a particular choice of the smoothing parameter. Within each neighborhood, a first-degree polynomial (linear model) was fitted via weighted least squares. The resulting smoothed energy security trajectories offers an interpretable and data-driven representation of evolving energy security landscape.

3.3. MLP model for driver and forecasting analysis

To uncover the nonlinear relationships between energy security and its underlying determinants, and to forecast future trajectories under policy and shock scenarios, we employ MLP models. The term MLP here refers to a neural network model and should not be confused with the Multi-Level Perspective framework, also commonly abbreviated as MLP, in the sustainability transitions literature. This architecture is well suited for regression tasks involving high-dimensional and heterogeneous input features (Park and Lek, 2016). The MLP consists of an input layer, one or more hidden layers with nonlinear activation functions, and an output layer. Each layer performs a weighted linear transformation of the input, followed by a nonlinear activation, allowing the network to capture complex interactions among variables. Prior to model training, all input variables and the target energy security indicator were standardized to ensure comparability across features. Specifically, each variable was transformed using z-score normalization:

$$x_i' = \frac{x_i - \mu_x}{\sigma_x}, y_i' = \frac{y_i - \mu_y}{\sigma_y} \tag{4}$$

where μ and σ denote the sample mean and standard deviation of the corresponding variable. This preprocessing step prevents features with larger numerical scales from disproportionately influencing model training.

Our MLP model consists of an input layer (vector $x \in \mathbb{R}^d$, $d = 26$), two hidden layers ($\boldsymbol{h}^{(1)}$, $\boldsymbol{h}^{(2)}$), and an output layer ($\hat{y}_t$) to predict the normalized energy security indicators:

$$\boldsymbol{h}^{(1)} = \sigma\left(\boldsymbol{W}^{(1)} x_t + \boldsymbol{b}^{(1)}\right) \tag{5}$$

$$\boldsymbol{h}^{(2)} = \sigma\left(\boldsymbol{W}^{(2)} \boldsymbol{h}^{(1)} + \boldsymbol{b}^{(2)}\right) \tag{6}$$

$$\hat{y}_t = \boldsymbol{W}^{(3)} \boldsymbol{h}^{(2)} + \boldsymbol{b}^{(3)} \tag{7}$$

Here, $\sigma(\cdot)$ is the ReLU activation function, and $\boldsymbol{W}^{(l)}$, $\boldsymbol{b}^{(l)}$ are weight matrix and bias vector for layer$l$. Dropout layers are applied between hidden layers to mitigate overfitting.

The model is trained by minimizing the mean squared error (MSE) loss:

$$\mathscr{L}(\theta) = \frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2 \tag{8}$$

To evaluate model performance, we compare predicted and observed energy security values for each country. The fitting results are presented in Appendix A Figure A2, which show that the MLP model provides a good fit to historical energy security trajectories across all countries considered.

3.4. SHAP decomposition for driver attribution

We employed SHAP approach to enhance the interpretability of the MLP model and quantify the marginal impact of each input feature on energy security (Lundberg and Lee, 2017). The Shapley value ϕ_j for a feature x_j represents its average marginal contribution across all possible feature coalitions:

$$\phi_j(f, x) = \sum_{S \subseteq \mathscr{F} \setminus \{j\}} \frac{|S|!(|\mathscr{F}| - |S| - 1)!}{|\mathscr{F}|!} [f(S \cup \{j\}) - f(S)] \quad (9)$$

where $\mathscr{F}$ is the full set of features, and f(S) denotes the model prediction based on subset S. Specifically, the sum of all SHAP values plus the model's base value (average prediction) equals the final prediction. This additive feature allows for a decomposition of the model's output:

$$f(x) = \phi_0 + \sum_{j=1}^{d} \phi_j \quad (10)$$

where ϕ_0 is the expected prediction over the entire dataset (the baseline), and d is the number of input features. The sum of the SHAP values and the baseline thus provides a transparent, data-driven "weight" for each indicator without imposing arbitrary assumptions. By combining SHAP with the predictive capabilities of the MLP model, this approach offers a dynamic framework for examining the temporal and structural drivers of national energy security.

3.5. Data collection and filtering

We construct a four-dimensional energy security assessment framework based on widely cited academic literature and institutional definitions, covering energy reliability, economic stability, environmental sustainability, and governance capacity. (Appendix A Table A1 provides details of these indicators, including their associated dimensions and calculation methods). A total of 26 representative indicators were selected based on two key criteria: (1) their frequent application in previous empirical studies (as shown in Table 1), and (2) the availability of consistent and continuous data for eight major economies (US, Japan, China, India, UK, Germany, France and Brazil) over the period 1990-2020.

The energy reliability dimension includes indicators related to energy production, consumption, reserves, and imports, disaggregated by fuel type (coal, oil, gas, and clean energy). The economic stability dimension captures GDP per capita, electricity prices, and international oil prices. The environmental sustainability dimension includes per capita carbon emissions and carbon intensity. Governance capacity is represented by the global government index's rule of law index, which reflects institutional quality and the effectiveness of policy implementation. Compared with existing studies, our framework assigns a relatively larger set of indicators to energy reliability. This reflects both the central role of reliability in energy security (Ang et al., 2015) and our intention to better capture how the transition from coal to clean energy affects supply stability across countries.

Historical data for 1990-2020 were obtained from publicly accessible sources, including US Energy Information Administration for national energy production, consumption, coal reserves, carbon emissions, population, and GDP; Worldometer and Countryeconomy for natural gas and oil reserves; the China Energy Statistical Yearbook for China's national energy reserves; the BP Statistical Review of World Energy for international oil prices; CEIC Data for national electricity prices.

3.6. Clean energy transition and external shocks scenario

To simulate the future evolution of national energy security over the period 2021-2050, we develop a two-dimensional scenario framework defined by clean energy transition pathways and external shock intensity. This framework enables a systematic assessment of how energy transition policies interact dynamically with exogenous disturbances to shape long-term energy security outcomes, as shown in Table 2.

The first dimension captures long-term technological and policy transformations of national energy systems under alternative transition pathways out to midcentury (2050) and is primarily informed by the International Energy Agency's World Energy Outlook (IEA, 2024). Four scenarios are specified within this dimension. The STEPS reflects trajectories shaped by currently implemented policies and officially announced measures, incorporating existing regulatory frameworks, energy market dynamics, and prevailing technology cost trends. The APS assumes that all announced energy and climate commitments are fully and timely implemented. Relative to STEPS, APS implies a substantially faster deployment of clean energy technologies and a more pronounced decline in carbon emissions. Building on APS, the PTS represent a more ambitious policy environment, in which continued technological progress—particularly in energy storage and electrification—enables a significantly greater expansion of clean energy deployment.

Table 2
Two-dimensional prediction scenario.

	No Shock (NS)	Small Shock (SS)	Large Shock (LS)
Stated Policies Scenario (STEPS)	STEPS + NS (business as usual)	STEPS + SS	STEPS + LS
Announced Pledges Scenario (APS)	APS + NS	APS + SS	APS + LS
Policy-Strengthened Transition Scenario (PTS)	PTS + NS	PTS + SS	PTS + LS
Trump Energy Transition Scenario (TET)	TET + NS	TET + SS	TET + LS

To ensure a transparent and quantifiable gradient in policy stringency, we calibrate the difference between PTS and APS to be approximately twice the gap between APS and STEPS. Finally, the TET is constructed exclusively for the United States to capture the continuation of the energy policy orientation observed during the Trump administration, including the relaxation of fossil fuel regulations, the expansion of oil and gas production and exports, and the weakening of climate-related constraints. This scenario is generated using a trend extrapolation approach, assuming that historically observed average annual growth rates persist through 2050.

The second dimension captures the short-term impacts of geopolitical and other external disturbances on energy security. Consistent with real-world supply-side disruption mechanisms, we construct asymmetric shock scenarios in which disturbances initially constrain energy supply and energy price, then subsequently propagate to energy consumption, macroeconomic activity, and carbon emissions. For example, De Santis and Tornese (2025) shows that energy supply shocks generate nonlinear responses in output and prices. Accordingly, external shocks are modeled as temporary, phased disturbances, after which affected variables gradually return to their no-shock baseline trajectories rather than persisting over the entire 2030–2050 period (Jasiūnas et al., 2021). This dimension comprises three disturbance types—no shock (baseline), small shock (moderate), and big shock (severe)—yielding five sub-scenarios in total.

(1) Under the no-shock baseline, all variables remain stable.
(2) Under small shock conditions, two sub-scenarios are defined.

In the first, energy production declines by 10%, while energy consumption, GDP, and carbon emissions fall by 8%, accompanied by 10% and 8% increases in oil and electricity prices, respectively. In the second (as a sensitivity analysis), energy production again declines by 10%, but consumption, GDP, and emissions decrease by 5%, with oil and electricity prices rising by 10% and 5%. These magnitudes are informed by observed energy system responses during the COVID-19 pandemic. The IEA World Energy Review reports a global energy demand contraction of around 5%, alongside substantial declines in energy production and final consumption (IEA, 2020). At the country level, Japan experienced roughly a 9% drop in primary energy production and a 7% reduction in energy consumption (BP, 2024).

Post-shock recovery periods are differentiated by energy system resilience, reflecting cross-country variation in economic adjustment capacity, energy system flexibility, and policy responsiveness. The US, Germany, France, and the UK are classified as relatively high-resilience systems, with recovery periods of 1-2 years (GEI, 2020; Hartvig et al., 2024; Zhang et al., 2025), while Japan, China, India, and Brazil are classified as relatively lower-resilience systems (Matsumoto and Andriosopoulos, 2016; Zhang and Zhou, 2024), with recovery periods of 2-3 years.

(3) Under big shock conditions, two more severe sub-scenarios are considered. In the first, energy production declines by 20%, while energy consumption, GDP, and emissions fall by 15%, and oil and electricity prices increase by 20% and 15%, respectively. In the second (as a sensitivity analysis), energy production again declines by 20%, but consumption, GDP, and emissions decrease by 10%, accompanied by 20% increases in oil prices and 10% increases in electricity prices. These magnitudes are calibrated using evidence from recent major geopolitical disruptions and global energy crises. For instance, BP (2024) reported that in 2022, amid the Russia-Ukraine conflict, France experienced an approximately 20% reduction in energy production and a 9% decline in energy consumption. Recovery periods under big shocks are similarly differentiated: high-resilience countries are assumed to recover within 4-5 years, while lower-resilience countries require 5-7 years.

Projections of population and GDP are drawn from Shared Socio-economic Pathway 2 (SSP2), which represents a "middle-of-the-road" development trajectory characterized by moderate challenges to climate mitigation and adaptation (Riahi et al., 2017). Since key datasets are typically provided in five- or ten-year increments, we employed linear interpolation to convert these into annual time steps.

4. Results and discussion

4.1. Energy security variations across countries

We compiled and visualized the energy security trends of eight major economies from 1990 to 2020, as shown in Fig. 2.

In Fig. 2, the Y-axis represents corresponding energy security values for each country, and the X-axis indicates the applicable year the reported value applies to. The red curve shows the aggregated energy security trajectories for 1990-2020 calculated in this study using the LOESS method, based on 2218 reported values extracted from the academic literature, while the grey shaded area represents the 95% confidence interval of the fitted curve. Colored dots represent annual estimates from individual studies (each color corresponds to a different paper in each country). Boxplots summarize the yearly distribution of reported values (median, interquartile range, and extreme values).

The energy security trajectories of the eight countries can be categorized into four distinct patterns. The US and India exhibit a slight U-shaped trend, China displays an N-shaped pattern, and Japan follows an inverted V-shaped path, while the UK, Germany, France and Brazil demonstrate relatively linear and stable developments. It is worth emphasizing that the period around 2010 marked a critical inflection point in the energy security trajectories of several countries, particularly the US, China, and Japan. This turning point coincides with a series of global structural shocks, including the 2008-2009 global financial crisis, which altered energy demand and investment patterns, the US shale gas revolution, which reshaped global oil and gas markets, and the 2011 Fukushima nuclear accident, which prompted a worldwide reassessment of nuclear energy. Given that these countries are major global energy consumers and oil importers, shifts in their energy security trajectories carry significant implications for the international energy system.

Specifically, energy security in the US initially declined with fluctuations, reaching its lowest point around 2009 (61.965 ± 2.768), before gradually rising to a peak in 2019 (69.068 ± 5.435). This

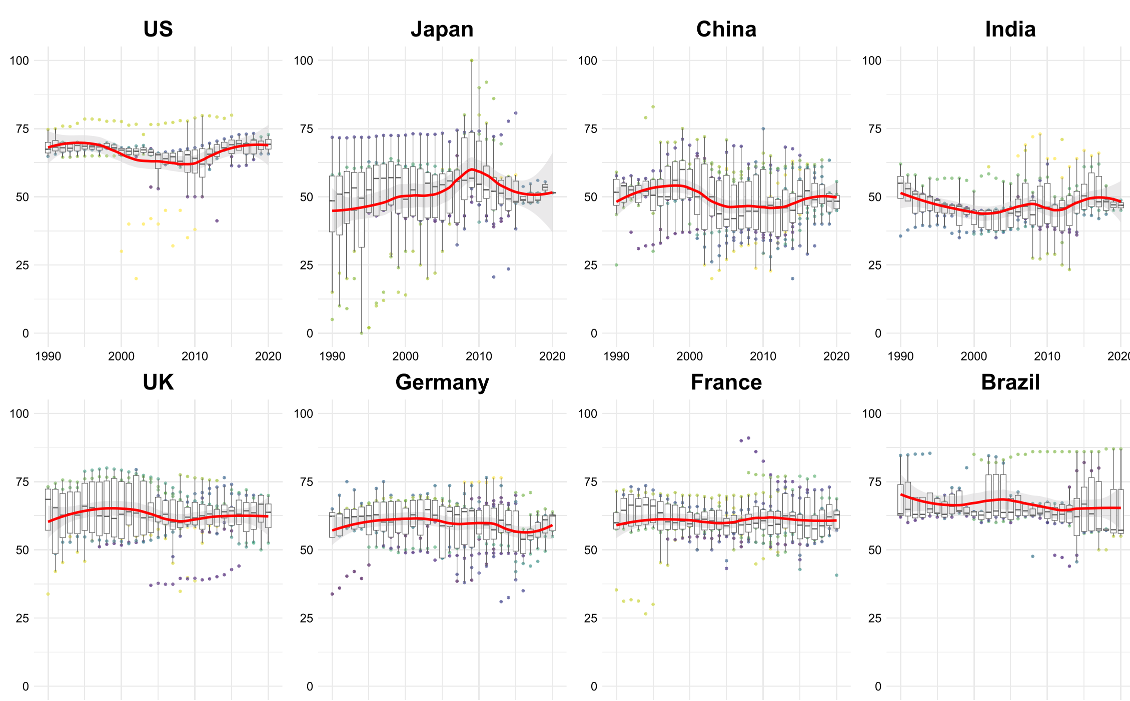

Fig. 2. Energy security trajectories across eight countries derived from reported values in existing studies, 1990-2020.

trajectory aligns with findings from the GEI (2020) and Kosai and Unesaki (2020). The earlier decline is attributed to intensified oil price volatility, including a sharp surge in international oil prices beginning in 2003 and peaking in 2006 (Wang et al., 2020). The subsequent rise is due to the shale revolution, which improved domestic energy self-sufficiency and reinforced the country's leadership in the global energy system (Shakya et al., 2022).

In contrast to the US, Japan's energy security rose in the early period, peaked around 2009 (60.050 ± 4.478), and then declined markedly. The initial improvement was largely driven by Japan's strategy to diversify its primary energy mix by promoting nuclear and alternative energy sources to reduce the risk of import disruptions (Matsumoto and Andriosopoulos, 2016). While following the 2011 Fukushima nuclear disaster, the shut down of most nuclear power plants led to a pronounced short-term decline and major shifts in Japan's institutional and market structure (Valentine et al., 2011).

In China, national energy security rose steadily during the early phase of economic development, peaking around 1998 (54.115 ± 2.533), before entering a prolonged decline and reaching its lowest point around 2011 (45.888 ± 22.386). Wu et al. (2012) attributed the initial

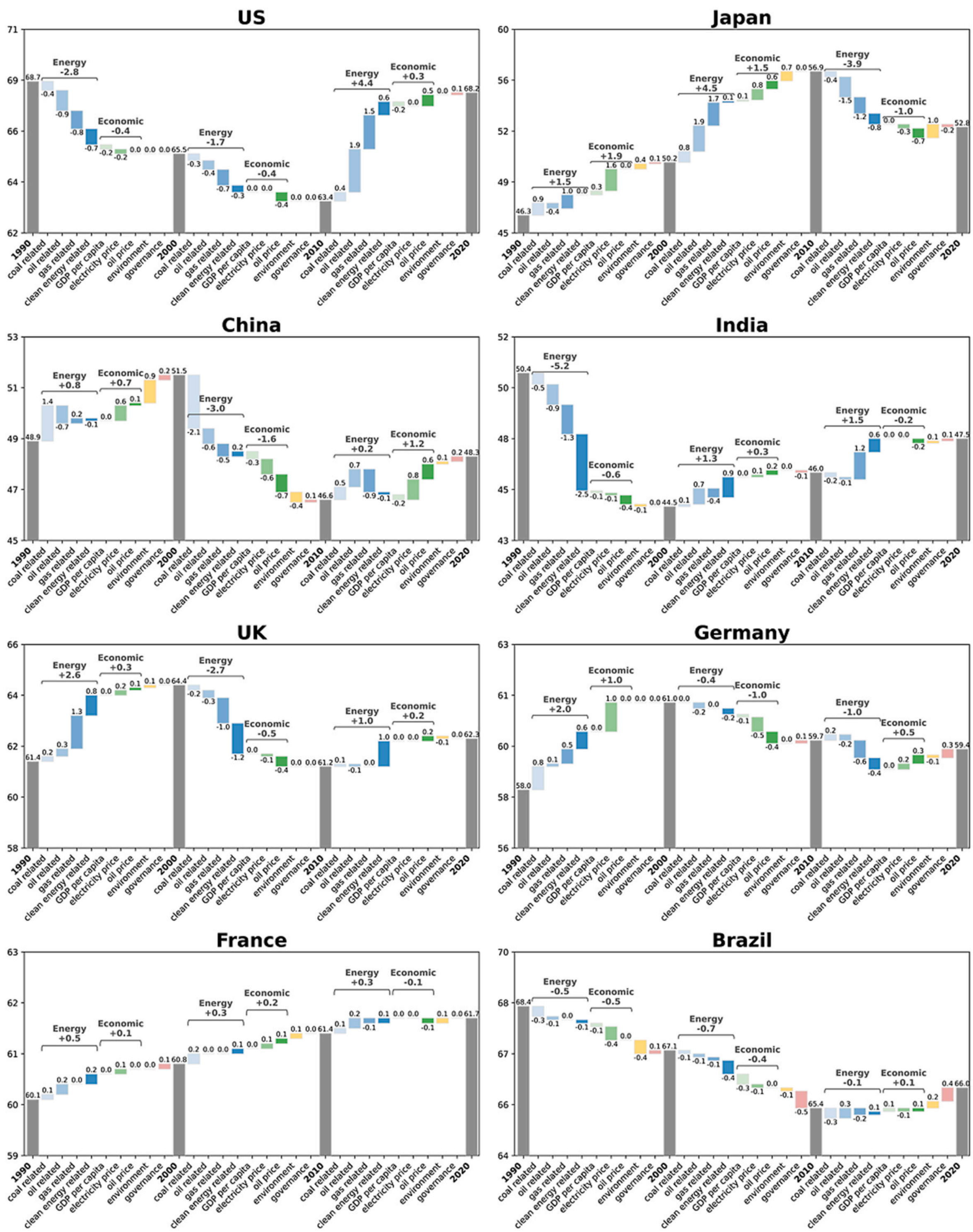

Fig. 3. Key drivers of energy security indicators in the eight major economies, 1990-2020.

improvement to government policies promoting energy efficiency and emission reductions, while the later decline resulted from surging demand and growing dependence on energy imports. Other complicating factors included threats to energy reliability, as well as increasing Chinese dependence on overseas imports of natural gas and oil (Bambawale and Sovacool, 2011a). Song et al. (2019) corroborated this trend, attributing early gains to progress in environmental and economic-technical dimensions, and subsequent losses to a deteriorating energy supply sub-index. In response to rising energy risks, the State Council in 2010 accelerated the phase-out of outdated capacity, ramped up investment in renewable energy, and diversified energy imports and consumption, effectively reversing the downward trend in recent years (Wang et al., 2024).

As with other developing economies, India's energy security exhibits an initial decline followed by a recovery, with 2011 marking a relative low point (45.080 $\pm$ 2.584). By contrast, Brazil's energy security index declines steadily before stabilizing after 2012 (64.510 $\pm$ 3.510). Despite shared development-stage characteristics, the underlying drivers and constraints differ. Like China, India faces rapidly rising energy demand alongside the need to accelerate a large-scale transition toward cleaner energy sources (Le et al., 2019; Bambawale and Sovacool, 2011b). Brazil, by contrast, is constrained by hydropower dependence and climate-related supply variability, although expanding wind and solar capacity and developing pre-salt offshore oil fields have helped stabilize its energy security trajectory (Ciotta et al., 2023).

Among the eight countries, Japan exhibits the greatest fluctuation in energy security ($\Delta = 15.217$), while France shows the smallest ($\Delta = 2.857$). Germany ($\Delta = 4.962$) and the UK ($\Delta = 5.072$) also experiencing relatively modest changes, due to their proactive promotion of clean energy transitions, diversification of energy supplies, and expansion of energy storage capacity (Cergibozan, 2022; Van Greevenbroek et al., 2025).

4.2. Key drivers of energy security variation

This study identifies the key drivers of national energy security changes across three periods (1990-2000, 2000-2010, and 2010-2020) for each country, based on four commonly used dimensions, as shown in Fig. 3.

In Fig. 3, the Y-axis represents our agglomeration of energy security indicators, while the X-axis shows the contributing factors, categorized into energy, economic, environment, and governance dimensions. Grey bars indicate the energy security values for selected years (1990, 2000, 2010, and 2020), while the colored bars represent the changes in factor contributions across these years (i.e., the same color bar represents the changes in the energy security values of the same factor across different time points).

Among the various factors influencing changes in energy security, energy-related variables consistently emerge as the most influential drivers, closely tied to energy transition patterns. Economic factors (particularly international oil and electricity prices) and environmental considerations have also exerted significant influence across all eight countries analyzed.

Over the past three decades, energy transitions have remained the most prominent dimension in shaping energy security trajectories. The shift from coal to cleaner energy significantly influences energy security pathways of Japan and Germany. In Japan, energy security is driven by coal and natural gas from 1990 to 2000, oil and gas from 2000 to 2010, and a significant rise in clean energy after 2010, enabled by stable and integrated renewable expansions (e.g., the Feed-in Tariff (FiT) scheme and rapid solar photovoltaic (PV) expansion, Wen et al., 2021). Germany follows a similar path, initially relying on abundant domestic lignite and hard coal reserves, then expanding its use of natural gas from the early 2000s and accelerating wind and solar deployment, especially after the 2011 Energiewende policy (Löschel et al., 2021).

In UK, energy security evolves from reliance on North Sea gas and early-stage renewables (1990-2010) to a strong post-2010 emphasis on clean energy, supported by enduring low-carbon policies (HM Government, 2023). In US, oil and gas remain the dominant factors throughout (GEI, 2020). France, by contrast, maintains a stable energy security profile due to its long-standing nuclear-based energy system (Kartal et al., 2023).

For developing countries, China and India experience a gradual shift from coal dominance (1990–2010) toward greater reliance on oil and gas (2010–2020), while the clean energy transition is not yet reflected (Song et al., 2019). Coal continues to have a significant impact on Brazil's energy security.

Economic stability also plays a crucial role. Between 1990 and 2000, countries show notable energy security improvements, with electricity pricing playing a particularly positive role (Brown et al., 2014). In China, the implementation of the “electricity pricing unification” reform and rural electrification initiatives improve equity in energy access (Chen et al., 2022). In Japan, following the collapse of the economic bubble, maintaining stable electricity prices is a strategic measure to support economic recovery (Gasparatos and Gadda, 2009). In Germany, the 1991 Electricity Feed-in Act introduces feed-in tariffs for renewable energy, enabling investors to receive above-market returns and promoting the country's energy transition (Löschel et al., 2021). However, from 2000 to 2010, energy security declines, largely due to surging international oil prices and associated shocks (Wang et al., 2024).

Environmental sustainability also shapes energy security outcomes. In China, escalating pollution problems prompt the adoption of stronger energy conservation and emission reduction policies, such as the Renewable Energy Law (Wu et al., 2012). In Japan, environmental performance improves through nuclear expansion and alternative energy promotion, especially after the Kyoto Protocol (Matsumoto and Shiraki, 2018). France benefits consistently from its nuclear-heavy energy mix, which supports long-term environmental goals (Kartal et al., 2023).

Government capability plays an important role in Brazil's energy security and has exerted a positive influence in recent years through policies such as initiatives to diversify the energy mix and support for domestic resource development (Werner and Lazaro, 2023).

4.3. Energy security prediction in multiple scenarios

To examine how clean energy transitions and external shocks influence future national energy security, we forecast each country's energy security trajectories from 2021 to 2050, as shown in Fig. 4.

In Fig. 4, the X-axis represents the years from 2021 to 2050, while the Y-axis shows the national energy security values. Twenty scenarios are illustrated for US, and fifteen scenarios are shown for each of the other five countries. These red points (Matsumoto, 2015; Matsumoto and Shiraki, 2018; GEI, 2020) do not reflect the actual energy security values reported in those studies, rather, they assume the 2020 baseline energy security values match that of this study, allowing for a visual comparison of projected trends across different sources.

Decarbonization scenarios (APS/PTS), characterized by clean energy transition efforts, are associated with higher energy security across most countries, with the notable exception of the United States, consistent with previous findings (Gökgöz and Güvercin, 2018; Zhang et al., 2023). Even under external shocks, energy security levels remain higher in clean energy-oriented pathways than under the current policy baseline (STEPS), reinforcing the role of renewable energy development in enhancing energy security (Cergibozan, 2022; Aslam et al., 2024; Bashir et al., 2025).

However, the magnitude and timing of these effects vary substantially across national countries. Among the countries analyzed, Japan records the most significant improvement in energy security under the PTS-NS scenario, with its energy security values rising by about 4 points compared to the BAU case in 2050. This result may be attributed to the model, trained on data from 1990 to 2020, capturing the substantial

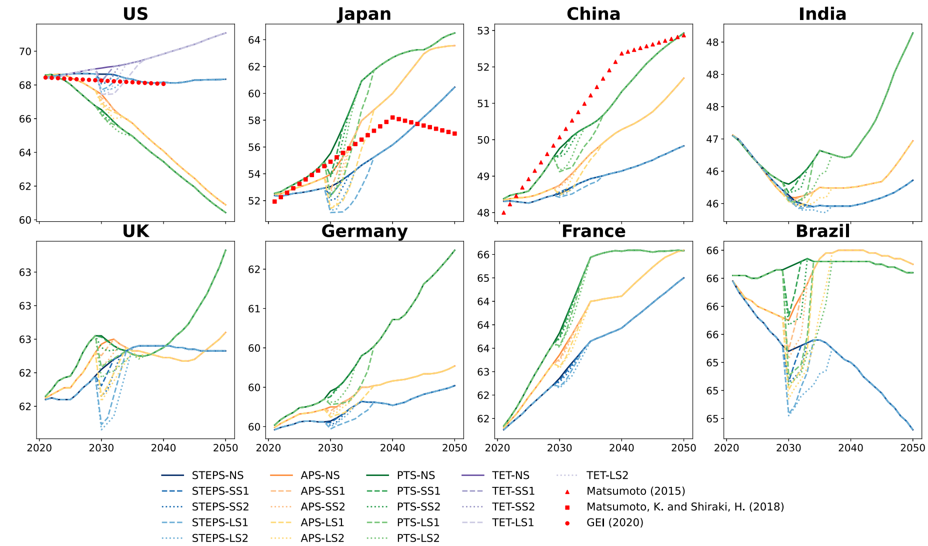

Fig. 4. Energy Security trajectories under multiple decarbonization pathways and external shocks in eight major economics, 2021-2050.

volatility in Japan's energy security and leading to a more pronounced projected rebound (Kartal et al., 2023; Matsumoto and Andriosopoulos, 2016). China ranks second with a 3.1-point increase in energy security values under the same scenario (Zhang et al., 2023; Aslam et al., 2024). From 2021 to 2050, both Japan and China are expected to experience declining populations alongside continued economic growth (Lundberg and Lee, 2017), accompanied by reduced fossil fuel consumption, lower energy imports, and decreased total primary energy demand (IEA, 2024). These structural changes contribute to greater energy efficiency and security, while accelerated clean energy deployment amplifies these benefits (Riahi et al., 2017). In contrast, Germany, UK, and France see more modest gains, reflecting their historically stable energy security levels and longstanding clean energy commitments (Mišík, 2022; Huang et al., 2021). US shows a divergent trend, likely due to recent improvements from increased oil and gas production, and a sharp pivot away from fossil fuels could weaken its strategic position in global energy markets (GEI, 2020). These heterogeneous responses underscore that the energy security implications of clean energy transitions are highly context-dependent, shaped by initial energy system structures, import dependence, domestic resource endowments, and the pace of technological deployment.

Rather than exhibiting a uniformly positive linear relationship, the results reveal nonlinear and country-specific dynamics, with energy security gains often materializing only after the clean energy transition reaches sufficient scale or maturity. Under the IEA scenarios, India's and Brazil's energy security follows a decline-recovery trajectory, initially driven by continued growth in fossil fuel and clean energy production and consumption, and later by reduced fossil fuel use alongside rapid renewable energy expansion. By contrast, in countries where clean energy deployment is already relatively advanced, further transitions do not necessarily translate into proportional improvements in energy security. In France, energy security gains appear to plateau once the PTS scenario reaches 2035-year level, suggesting diminishing marginal returns to additional decarbonization efforts. These patterns provide indirect evidence of nonlinear responses, whereby short-term transitional pressures may precede longer-term security gains and, in some cases, be followed by saturation effects.

Importantly, long-term improvements in energy security do not preclude short-term trade-offs across multiple dimensions of the energy system (Sovacool and Brown, 2010; Jasiūnas et al., 2021). On the supply side, rapid early-stage deployment of variable renewables can strain system flexibility, requiring additional investment in grids, storage, and backup capacity. On the demand side, electrification and structural adjustments in end-use sectors may temporarily increase energy demand or alter consumption patterns. Economically, clean energy transitions often involve substantial upfront capital costs, placing short-term pressure on public budgets, electricity prices, and investment allocation. At the same time, increased reliance on renewable and storage technologies may shift energy security risks from fuel imports to dependencies on critical minerals and globally concentrated supply chains. Evidence from India and Brazil nevertheless suggests that as clean energy deployment deepens and system integration improves, these transitional costs and vulnerabilities are outweighed by longer-term gains. This underscores the need to view clean energy transitions as a dynamic process involving short-term trade-offs and sustained improvements in energy security, rather than as an instantaneous or uniformly positive shift.

This advantage of clean energy pathways persists even under external shocks. Japan and China again benefit most, with their 2030 energy security values under the PTS-LS2 scenario exceeding the STEPS-LS2 scenario by 1.2and 0.7points, respectively. Similarly, Su et al. (2024) found that a carbon-neutral energy system could improve China's energy resilience by 7.73% between 2020 and 2060. Other countries also benefit, albeit to a lesser extent. Although US does not exhibit absolute gains in energy security under decarbonization scenarios, the negative impact of external shocks is smaller under APS and PTS than under STEPS and TET. As Esmaeili et al. (2024) noted, sharp increases in oil prices often accelerate renewable energy consumption, enabling countries to better navigate energy crises. Similarly, Yang et al. (2025) found that under war-related scenarios (e.g. the Russia-Ukraine conflict), the share of renewable energy in Europe's total energy mix rises significantly compared to non-war scenarios. In this sense, clean energy transitions not only reduce external dependence, thereby mitigating the impact of external shocks on energy security, but also benefit from shocks themselves, which can act as catalysts for accelerating the transition. These findings underscore the dual role of clean energy transitions - as both a strategic pathway to a secure energy future and a critical buffer against the growing risks of global instability.

5. Conclusions and policy implications

Our results yield several key insights. First, while the energy security trajectories differ markedly across countries, all eight countries examined experienced a notable inflection point around 2010, suggesting both national heterogeneity and broader global convergence. Second, energy security is consistently shaped by energy reliability, economic stability, and environmental sustainability, with energy transitions playing a particularly pivotal role, while oil and electricity price volatility continues to pose notable risks. Third, our scenario-based predictions indicate that clean energy transitions generally enhance energy security in most countries. These transitions not only improve overall performance but also strengthen resilience to external shocks, underscoring their long-term strategic value.

Amid stalled global climate governance, our findings identify clean energy investment as a strategic pathway that delivers win–win—and potentially multi-win—outcomes by simultaneously advancing climate objectives and strengthening domestic energy security. Against this backdrop, our findings offer three policy implications to enhance and stabilize energy security. First, accelerating the clean energy transition is fundamental to improving national energy security. Beyond its environmental benefits, clean energy development significantly enhances resilience to external shocks by reducing exposure to fossil fuel price volatility and supply disruptions. Rather than implying a complete withdrawal from fossil fuels or global energy trade, clean energy expansion should be understood as a strategic pathway to diversify energy supply chains, strengthen domestic renewable capacity, and increase system flexibility and autonomy (Cheng et al., 2025; Lin and Liu, 2025). As countries advance toward net-zero targets, traditional fossil fuel–related trade risks are gradually replaced by growing dependence on critical minerals and low-carbon technologies. In this context, improving energy security requires diversifying trade partnerships, promoting technology-driven and circular-economy solutions, and investing in infrastructure tailored to clean energy systems.

Second, clean energy transition strategies should be aligned with countries' transition stages and energy system characteristics. Uniform transition targets may obscure important cross-country differences. For fossil fuel–dependent and emerging economies, accelerating renewable deployment and electrification can substantially enhance energy security by reducing import dependence and vulnerability to external price shocks. Policy priorities in these contexts should include large-scale renewable investment incentives, grid expansion, and concessional financing to ease early-stage transition constraints. By contrast, in countries where clean energy penetration is already high, further capacity expansion alone may yield diminishing energy security returns. Policy emphasis should instead shift toward improving system flexibility, managing critical material dependencies, and strengthening cross-sector integration.

Third, energy security should be embedded within broader economic, environmental, and social policy frameworks and objectives. Clean energy transitions often constitute a system-wide transformation rather than a narrowly defined energy policy agenda. Energy security outcomes are closely intertwined with fiscal capacity, industrial competitiveness, environmental sustainability, and social stability. Coordinated electricity pricing mechanisms, investment in enabling technologies such as energy storage, carbon capture and storage, and green hydrogen, as well as workforce transition programs, can jointly enhance energy security while mitigating short-term economic and social adjustment costs. An integrated governance framework that aligns energy, industrial, environmental, and social policies is therefore essential to ensure that short-term transition pressures do not undermine long-term energy security gains, particularly under heightened uncertainty and external shocks.

As with all empirical research, this study has several limitations. Firstly, although we made considerable efforts to compile and harmonize energy security assessments across multiple dimensions, the final results are still influenced by evolving conceptualizations, cross-country differences, and subjective preferences. Consequently, the constructed energy security indicators may retain certain methodological and contextual biases, despite our attempts to ensure comparability and objectivity. Secondly, data availability constraints the country scope of the empirical analysis. The analysis focuses on eight major economies derived from existing peer-reviewed studies remain scarce for many emerging and developing countries. Expanding the framework to a broader set of countries and indicators as data availability improves represents an important avenue for future research. Thirdly, while the MLP-based framework effectively captures nonlinear patterns in historical energy security trajectories and supports scenario-based projections. But the MLP approach does not provide conventional 95% confidence intervals or establish causal relationships among explanatory variables, limiting the assessment of projection uncertainty and causal inference. In addition, the model does not endogenously simulate the dynamic, event-specific impacts of discrete disruptive shocks, such as wars, pandemics, or trade sanctions. Future research could address these limitations by integrating dynamic, probabilistic, or hybrid modeling approaches that combine scenario analysis with structural or agent-based frameworks.

CRediT authorship contribution statement

Shan Zhang: Writing – original draft, Visualization, Software, Methodology, Data curation. **Benjamin K. Sovacool:** Writing – review & editing, Formal analysis. **Chu Wei:** Writing – review & editing, Supervision, Funding acquisition.

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

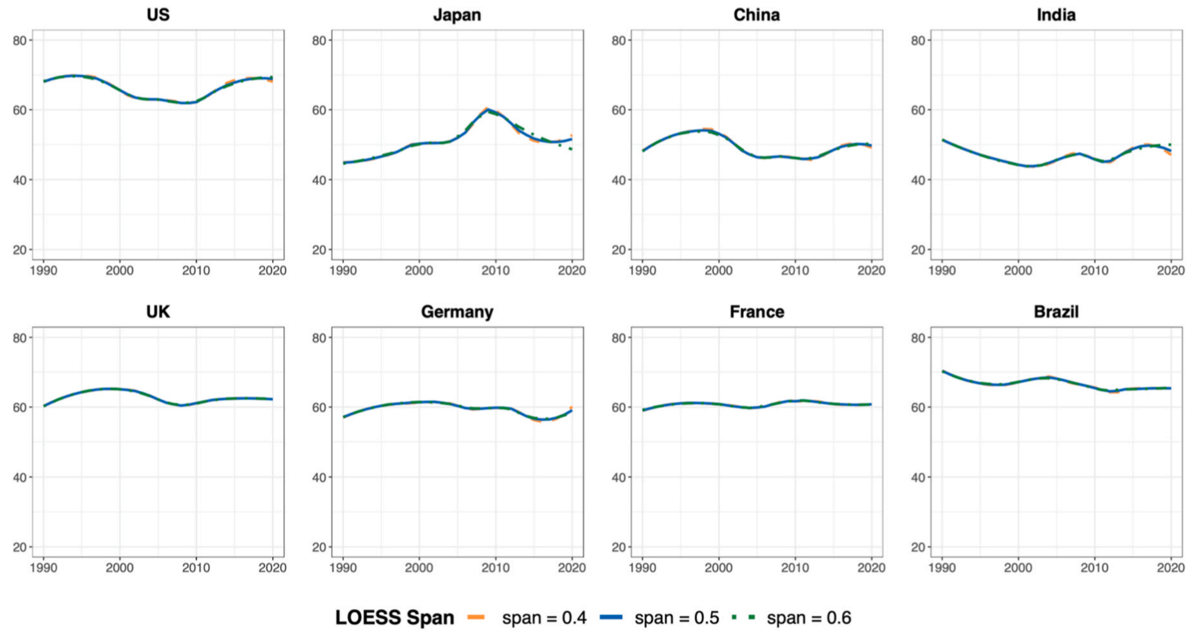

Fig. A1. Sensitivity analysis of national energy security trajectories under alternative spans.

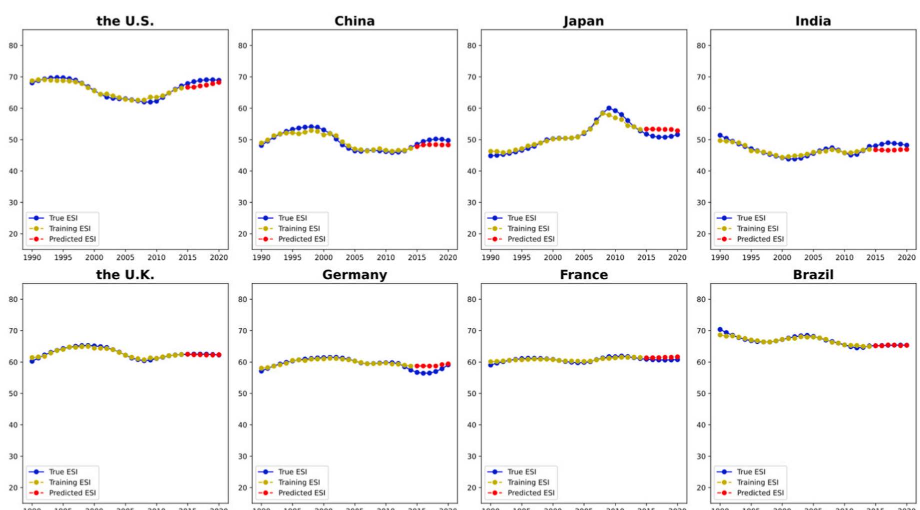

Fig. A2. Predicted ESI trajectories for eight countries using the MLP model.

Table A1
Energy security dimensions and their corresponding indicators

Dimensions	Indicators	Calculation formula
Energy reliability	Coal production per capita	Coal production/total population
	Coal reserve to production ratio	Coal reserve/coal production
	Oil production per capita	Oil production/total population
	Oil reserve to production ratio	Oil reserve/oil production
	Gas production per capita	Gas production/total population
	Gas reserve to production ratio	Gas reserve/gas production
	Coal import dependence	Coal import/coal consumption
	Oil import dependence	Oil import/oil consumption
	Gas import dependence	Gas import/gas consumption
	Electricity share from clean energy production	electricity from clean energy production/electricity from total energy production
	Clean energy production per capita	Clean energy production/total population
	Clean energy share in total energy production	Clean energy production/total energy production
	Coal consumption per capita	Coal consumption/total population
	Coal intensity	Coal consumption/GDP
	Oil consumption per capita	Oil consumption/total population
	Oil intensity	Oil consumption/GDP
	Gas consumption per capita	Gas consumption/total population

(continued on next page)

Table A1 (*continued*)

Dimensions	Indicators	Calculation formula
	Gas intensity	Gas consumption/GDP
	Clean energy intensity	Clean energy consumption/GDP
	Clean energy share in total energy consumption	Clean energy consumption/total energy consumption
Economic stability	GDP per capita	GDP/total population
	Electricity price	-
	Oil price	-
Environmental sustainability	CO2 intensity	CO2/GDP
	CO2 per capita	CO2/total population
Governance capacity	Regulatory quality	-

Data availability

Data will be made available on request.

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