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Energy Transition's Technical Pathways, Risks, and Equity—Article

Assessing Oil Security and System Resilience under China's Low-carbon Energy Transition

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ABSTRACT

Rising geopolitical tensions present significant risks to national energy security, coinciding with a critical moment in the global energy transition. Securing stable energy availability has thus grown increasingly vital for pursuing nations' climate targets. Deep decarbonization of the energy system remains a cornerstone of China's long-term modernization agenda but is hindered by challenges like mitigating oil supply risks. External oil supply of China is exposed to high risk due to potential interruption in global chokepoints like Strait of Hormuz and Strait of Malacca. This study therefore investigates how the ongoing energy transition will reshape China's long-term oil security landscape and its short-term resilience to such supply disruptions. In this study, we employed our self-developed integrated assessment model (IAM), called IAMET, to quantify future energy development pathways and evaluate China's oil security by integrating IAM with a forward-looking assessment framework. System reliance is used to simulate oil security under oil supply disruptions and the enhancement space of resilience are estimated. Results indicate that: ① By 2060, China's oil demand will be around 200–300 million tons under carbon neutrality constraint, reducing the country's oil import dependency ratio from the current 72% to 41%–60%, while oil security will face acute risks in the next 10–15 years. ② Energy transition will help to enhance oil supply resilience. Under a simulated disruption of 39%–66% of overseas oil imports, oil supply resilience will be "moderate" under carbon neutrality scenario. ③ Strategic petroleum reserves and demand rationing policies have different temporal effects on oil supply resilience enhancement. By adjusting energy demand structure, resilience will rise sharply in the early phase with greater possibility to belong to "good" zone, while current oil strategic stock has larger effects in the later phase as the oil demand shrink. This study underscores the growing role of IAM in evaluating oil security and emphasizes that reducing oil consumption through demand-side strategies can effectively complement supply-side actions to safeguard national energy security.

1. Introduction

1.1. Background

The world eagerly anticipates the next round of Nationally Determined Contributions (NDCs), which aim to commit to and deliver significant reductions in greenhouse gas emissions by 2035 [1]. Achieving these NDCs targets, alongside broader

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long-term climate goals, underscores the urgency of transitioning energy systems [2]. The transition demands rapid expansion of renewable energy and a carefully managed phase-out of fossil fuels, while regional conflicts and wars continue to disrupt supply and heighten geopolitical tensions [3]. Although the low-carbon transition raises new resource dependency issues and expands the notion of energy security, oil security will remain crucial despite its declining share in the energy mix [4]. Managing the transition at realistic and societally acceptable rates is changing, as decision makers must balance competing interests across sectors, users, and the wider energy systems. Addressing this challenge requires systematic observation, modeling, and analysis of global, regional, and national energy systems over the coming decades. Moreover, in the context of escalating geopolitical tensions, there is an urgent need to move beyond static dependency metrics toward dynamic indicators of resilience that can capture the processes of adaptation and recovery during periods of disruption

To achieve global net-zero target by 2050, the share of oil in total energy supply is estimated to decline to 8% [5]. The declining importance of oil and the rise of its replacements would imply rates of change that substantially differ from historical growth rates of global energy systems [6]. Managing both the energy transition and energy security remains one of the key challenges the energy system will confront in the coming years [7]. Ensuring a balance between oil supply and demand will continue to be a crucial challenge in the short to medium term. Moreover, global oil supply and demand mismatch are even evident in the regional or country level. Asia-Pacific has risen as the epicenter of global oil consumption, while the consumption in EU shrinks and United States remains as the largest single consumer. China remains the world's second-largest oil consumer, with demand surpassing that of the entire European Union. In 2023, oil accounts for less than 20% of China's energy mix [8]. Limited domestic resources have long left China heavily reliant on external oil supplies [9,10].

China's new NDCs aims to reduce economy-wide net greenhouse gas emissions by 7%–10% from peak levels targeting on 2035 [11]. Oil security depends on both oil supply and demand side and is impacted by large uncertainties [12] under China's energy transition, which may simultaneously affect the global energy security landscape. Integrating perspectives on oil supply disruption improves traditional assessments of geopolitical risks. While external oil dependency has long served as a simple index of annual or period-specific supply risk, it cannot capture the dynamic process of recovery during disruptions. This underscores the need for advanced indicator to evaluate China's oil security under energy transition and to assess the effectiveness of coping strategies under extreme supply scenario—an issue of growing importance for academic, policymakers, and decision makers.

1.2. Literature review

1.2.1. Assessment of China's oil security requires systemic model

Historically, oil security draws great attention due to the irreplaceable value of oil in the war [13], economics [14], industrial development [15], and politics [16]. In recent decades, the uneven geological distribution of global oil supply and the dominant role of oil in energy consumption still makes oil security the core issue in energy security concerns [17]. Due to high marginal abatement cost and the increase of energy service, the oil consumption of transportation and industry sector is hard to be replaced by low-carbon fuels [18]. In 2023, oil accounts for 32% of global primary energy consumption, while oil supply has played important role in energy security [19]. What role of oil can and will play under a China's low-carbon transition has attracted growing interest within the energy research field [20].

A systemic research framework is essential for monitoring China's oil security, which requires both systemic model and systemic index [21]. Network model can reveal the historic oil security by depicting the historical dynamic of global and national oil trade [22], while it can hardly reflect the oil security in the future. Other macro-level "top–down" models like supply chain analysis method [23], data envelopment analysis (DEA) method [24], and optimization model [25] manifest advantages of reflecting the heterogeneity of risk in oil upper-, middle-, and lower-stream. However, these approaches neglect the impact of energy technologies due to relatively low-resolution of single technology in the model. Advances in energy technologies can fundamentally transform energy systems, enabling a complete shift in reliance from one type of fuel to another. Integrated assessment models (IAMs) generate the energy transition scenario [26], which can be used as a model to explore future oil demand trends under low-carbon constraints. IAMs are useful tools to study complex global or national socioeconomic-energy pathways in long-term perspectives going all the way to 2100 [27], while simultaneously addressing climate change [28]. These models are intended to provide policy-relevant insights into global environmental changes and sustainable development challenges. By quantitatively capturing key processes within human and Earth systems and their interactions, IAMs serve as powerful tools for analyzing and addressing critical global issues. Existing studies have conducted prospective oil security study using IAMs to provide oil demand information at global [29] and national [30] levels. Intergovernmental Panel on Climate Change (IPCC) scenarios database indicates that global oil supply will decline on average by 62% under scenarios limiting warming to 1.5 °C with or limited overshoot [31]. Although IAMs offer clear advantages in representing energy demand and incorporating high-level detail on energy technologies, most existing IAMs do not explicitly model oil supply. Instead, oil supply is typically treated as an exogenous parameter, often calibrated to long-term estimates of recoverable reserves. As a result, only a limited number of IAMs are capable of jointly modeling oil supply and demand, which constrains their applicability for assessing China's oil security. From a temporal perspective, the absence of endogenous oil supply projections has led the literature to focus predominantly on historical analyses of oil security, with relatively few studies examining its potential evolution under future conditions. Such forward-looking assessments require systematic simulation of societal change and energy system transformation. Collectively, these limitations reveal a clear research gap in the use of systemic modeling frameworks, such as IAMs, for the comprehensive assessment of China's oil security.

1.2.2. Oil supply system resilience holds significant potential for analyzing supply interruptions

Typically, oil security indicators are embedded in model-based scenario analyses: The model first project oil supply and demand trends from a system perspective, and the indicator then translate this information into a measure of oil security [32]. External dependency of oil is the mainstream national oil security indicator for its simplicity and straightforward [33]. Different climate targets reflect 70% fluctuation of China's oil import dependence, which mainly took perspective of oil consumption [34]. However, this indicator reflects oil security only as a static condition at a given point in time, failing to capture the dynamic evolution of oil supply in response to supply interruptions. Resilience describes the speed at which a system recovers to equilibrium after a cascading disruption [35], and it has been used in broad sustainability related research disciplines (such as ecology [36], society [37], engineering [38], and disaster studies [39]). In energy system research, resilience reflects the capacity to withstand and adapt to external shocks such as supply disruptions, making it a dynamic indicator of oil security. Under unconventional scenarios shaped by geopolitical risks, energy supply resilience offers a valuable complement to traditional energy security assessments.

China's oil resilience has attracted large research interests in existing literature. Resilience is considered a critical system index that reducing vulnerability in the context of the energy transition [40], while resilience curve is frequently used to quantify system status (i.e. the system performance declines as cascading event upfold and gradually recovers as disruption subside) [41]. Resilience evolution curve is used to depict the system resilience of oil supply by coupling resilience analysis with system dynamic (SD) simulation model [42], long- and short-term memory network model (LSTM) [43], optimization model [44], and mixed-supply-side dynamic inoperability input–output model (M-SDIIM) [45]. However, traditional system models are typically designed for broad applications in energy and resource management and therefore employ relatively coarse representations of energy hierarchies and energy technologies. As a result, they are unable to capture energy system operations and demand with the same level of comprehensiveness as IAMs. Few studies have linked IAMs with resilience evolution curves, highlighting a research gap in integrating energy system modeling with system-level assessment indicators. Moreover, although the extent of oil supply disruptions has been explored under various scenarios, few studies have constructed long-term oil interruption scenarios, limiting understanding of heterogenous impacts of such disruption across different time periods. This indicates a clear gap in the modeling of oil supply-side disruptions with dynamic representation in analyses of China's oil security.

1.2.3. *China's oil security enhancement benefits from supply- and demand-side strategies*

Though supply and demand side strategies have different impacts on oil security, they are essential to mitigate the impacts of oil supply interruption [46]. From supply side, strategic petroleum reserve (SPR) is the main strategy, which was first adopted in western developed countries as early as the 1925 and was adopted by China since 1993 [47]. The optimal SPR can be determined by using the decision tree model [48], dynamic programming model [49], and game model [50] while conducting scenario analysis. Considering the economics of oil supply, available supply of oil is fixed in the short-term [51], which means that it is costly and even impossible to significantly increase the domestic oil production level in short-term.

On the demand side, replacement and reduction constitute the primary strategies. Existing studies examine the evolution of energy demand mainly focusing on the advancement of emerging low-carbon technologies and the uncertainties associated with technology progress [52]. The deployment of negative emission technologies is widely regarded as a critical solution for achieving net-zero emissions [53], while it points to alternative decarbonization option. Additionally, integrating carbon capture, utilization, and storage (CCUS) can enhance power sector flexibility while keeping CO_2 emissions within acceptable limits [54]. Large-scale deployments of CCUS can both decarbonize end-use energy processes that rely on oil product and improve oil recovery [55]. However, few studies have evaluated China's oil security under optimistic scenarios for future CCUS development.

Electricity and hydrogen are widely recognized as the two primary pillars for achieving a carbon-neutral energy system [5]. Both the end-use ratios of electricity and hydrogen [2], as well as the clean generation of them will determine the extent of decarbonation [56,57]. Compared with electricity, the hydrogen pathway will show larger uncertainties in existing decarbonization scenarios [58]. While green hydrogen fits well for hard-to-electrify sectors, the gap between global ambition and implementation by 2030 is large [59]. Despite being central to the low-carbon transition, few studies have systematically quantified the impacts of electricity, hydrogen, and CCUS on oil security. Existing IAM-coupled oil security assessment frameworks rarely capture both supply- and demand-side dynamics, and the effects large-scale deployment of low-carbon technologies on oil security remain largely unexplored. Furthermore, the role of coping strategies in enhancing the resilience of oil supply systems has received little attention. These findings point to a clear research gap in the effective construction and evaluation of coping strategies for oil supply disruptions. Integrating a dynamic resilience curve with a forward-looking IAM that endogenously captures both oil demand and supply can provide a robust framework for the formulation and assessment of such strategies.

In summary, existing studies on China's oil security reveal several gaps. First, future oil security trends have rarely been explored, highlighting the need for IAM-based analysis of oil supply and demand variations under energy, social, and economic system transformations amid geopolitical risks. Second, the dynamic aspects of oil security remain largely unexamined, necessitating advanced indicators beyond oil external dependency, such as oil supply resilience. Addressing these two gaps requires detailed, consistent modeling of China's energy demand and supply and the integration of IAM with oil supply resilience. Third, the effects of SPRs and demand-rationing policies on the recovery of oil security under supply interruption scenario remain unclear, calling for scenario construction and the simulation of coping strategies.

1.3. *The aim of this study*

The study aims to address the gap in assessing China's oil security within IAM scenarios. Insights from China's oil security are relevant for other Asia-Pacific countries that with high external dependency and have significant implications for the global economy. The paper follows a three-step research roadmap. First, an energy system is constructed within the IAM framework to capture the dynamic trends of China's oil demand and domestic supply under the carbon neutrality target, providing essential data for baseline oil security analysis. Second, a resilience-centered oil security assessment framework is proposed, linking IAM scenarios and allowing scenario combinations to account for potential supply disruptions. This approach complements conventional oil security assessment by incorporating resilience metrics. Third, countermeasures to enhance oil security under supply disruptions are simulated, with large-scale deployment of CCUS, electricity, and hydrogen technologies representing demand-side strategies, and SPR serving as supply-side measure. We aim to answer the following three research questions:

(1) What are the projected trends of China's oil security over the coming decades?
(2) How can the resilience of China's oil supply be assessed under oil supply interruption scenarios?
(3) How do the SPR and demand-rationing policies differ in enhancing oil supply resilience?

2. Method

2.1. *Description of IAMET-Energy model*

The IAM for Energy Transition (IAMET) quantifies and manages the multi-dimensional impacts of global and China's energy transition and societal progress. It combines traditional tools like input–output analysis, material flow analysis, life cycle assessment, SD, and optimization with emerging methods such as artificial intelligence (AI) and data-driven approaches. A prototype of China's

IAM—IAM of energy, environment, and economics in China (IAME3C), has been developed and maintained since 2020 by an interdisciplinary team at China University of Petroleum (Beijing) [60]. IAMET is the extended and updated version of IAME3C. IAMET aims to uncover the complex interrelationship among energy, economic, and environment system under the low-carbon transformation. It consists of three sub-models (i.e. IAMET-Energy model, IAMET-Environment model, and IAMET-Economy model). The extended depiction of IAMET can be found in Appendix A.

The IAMET-Energy model not only designs low-carbon transition pathways towards dual carbon goals but also evaluates future energy security trends. In this study, it is applied to analyze oil security resilience. As shown in Fig. 1, IAMET-Energy comprises three sub-modules—energy demand, energy supply, and energy security assessment—enabling integrated modeling of energy supply and demand.

2.1.1. Energy demand module

The energy demand model requires socio-economic drivers, while the energy supply model relies on reserves and production of fossil fuels or other minerals. A soft-link connects the final energy simulation model and energy conversion optimization model: final energy demand is generated via simulation and then used as input for conversion optimization model. Key outputs include primary energy demand and related CO_2 emissions.

(1) Final energy demand module. In the study, final energy demand is categorized into three sectors: industry, transportation, and buildings. The industry sector is subdivided into steel, cement, copper, aluminum, and others; transportation into highways, urban rail transit, railway, water transport, and aviation; and buildings into residential, public, and central heating. A simulation-based model is used to forecast final energy demand, focusing on four key factors: activity levels, energy intensity, energy structure, and carbon emission factors. Activity levels differ by sectors: in industry, they are measured by production or added value; in transportation, by mileage or freight turnover; and in buildings, by floor area.

The energy demand of a single industry is defined as:

$$\mathrm{ID}_{m,\ i,t} = \mathrm{AD}_{m,t} \times I_{m,t} \times S_{i,t} \tag{1}$$

where $\mathrm{AD}_{m,t}$ represents the demand for products and services in industry m in year t. This is referred to as the activity level. Logistic model is employed to forecast activity levels, utilizing macro-socioeconomic parameters such as population, gross domestic product (GDP), and urbanization rates as independent variables. $I_{m,t}$ indicates energy consumption intensity, which is predicted by combining trend extrapolation model with expert analysis, based on historical trends of energy consumption intensity across industries. The relevant history data is sourced from the wind database. $S_{i,t}$ represents the proportion of energy good i in total final energy consumption (i.e., the final energy consumption structure), which is predicted by Markov model.

The direct demand for primary energy and secondary energy by final sectors are expressed as follows:

$$\mathrm{FD}_{\mathrm{pri},\ t} = \sum_{m} \sum_{i_{\mathrm{pri}}} \mathrm{ID}_{m,\ i_{\mathrm{pri}},t} \tag{2}$$

$$\mathrm{FD}_{\mathrm{sec},\ t} = \sum_{m} \sum_{i_{\mathrm{sec}}} \mathrm{ID}_{m,\ i_{\mathrm{sec}},t} \tag{3}$$

where $\mathrm{ID}_{m,\ i_{\mathrm{pri}},t}$ and $\mathrm{ID}_{m,\ i_{\mathrm{sec}},t}$ represent the demand for primary energy i_{pri} and secondary energy i_{sec} in industry m, respectively.

The total final energy demand is as follows:

$$\mathrm{FD}_{t} = \mathrm{FD}_{\mathrm{pri},t} + \mathrm{FD}_{\mathrm{sec},t} \tag{4}$$

Energy-related carbon emissions in final sectors are calculated by

$$\mathrm{FE}_{t} = \sum_{m} \sum_{i} \mathrm{ID}_{m,\ i,t} \times \mathrm{ef}_{i} \tag{5}$$

where ef_{i} denotes carbon emission factors, which are obtained from Ministry of Ecology and Environmental of China.

(2) Energy conversion module. The energy conversion module models technologies for secondary energy including electricity, hydrogen, heating, and oil refining. It covers both conventional and clean energy technologies, such as photovoltaics, wind power, electrolytic hydrogen production, heat pumps, and CCUS. The energy conversion optimization model is formulated to minimize technology costs, with the objective function defined as follows:

$$\begin{aligned} \mathrm{OBJ} = \min \sum_{\mathrm{tec}} \sum_{t} (&\mathrm{inv\_c}_{\mathrm{sec\_tec},t} \times \mathrm{CAP\_N}_{\mathrm{sec\_tec},t} + \mathrm{fix\_c}_{\mathrm{sec\_tce},t} \\ &\times \mathrm{CAP\_T}_{\mathrm{sec\_tec},t} + \mathrm{var\_c}_{\mathrm{sec\_tec},t} \times \mathrm{ACT}_{\mathrm{sec\_tec},t} + p_{\mathrm{sec\_tec},t} \\ &\times \mathrm{ACT}_{\mathrm{sec\_tec},t} \times \mathrm{ce}_{\mathrm{sec\_tec}}) \end{aligned} \tag{6}$$

where $\mathrm{inv\_c}_{\mathrm{sec\_tec},t}$ represents the investment costs whenever a new plant or unit is built. $\mathrm{fix\_c}_{\mathrm{sec\_tce},t}$ denotes the fixed operation and maintenance costs, and $\mathrm{var\_c}_{\mathrm{sec\_tec},t}$ denotes the variable operation and maintenance costs which are associated with the costs of actively running the plant. The development trend of energy conversion technology costs primarily depends on the learning rate (LR) [61]. $p_{\mathrm{sec\_tec},t}$ represents the energy price consumed by conversion technology sec_tec. $\mathrm{CAP\_N}_{\mathrm{sec\_tec},t}$ and $\mathrm{CAP\_T}_{\mathrm{sec\_tec},t}$ represent the new installed capacity and total installed capacity of energy conversion technology in year t, respectively; $\mathrm{ACT}_{\mathrm{tec},t}$ indicates the activity level of energy conversion technologies. $\mathrm{ce}_{\mathrm{sec\_tec}}$ represents conversion efficiency.

Simultaneously, a set of constraints—considering factors such as meeting terminal energy demand and technology development potential—is applied to enhance the reliability of the energy conversion optimization model.

The constraint 1 requires that the secondary energy production of the energy conversion module must meet the final secondary energy demand.

$$\sum_{\mathrm{sec\_tec}} \mathrm{ACT}_{\mathrm{sec\_tec},t} \geq \mathrm{FD}_{\mathrm{sec},t} \tag{7}$$

The constraint 2 provides upper bounds and lower bounds on new capacity installation.

$$\mathrm{CAP\_N}_{\mathrm{sec\_tec},t_{\mathrm{bound\_up}}} \leq \mathrm{CAP\_N}_{\mathrm{sec\_tec},t} \leq \mathrm{CAP\_N}_{\mathrm{sec\_tec},t_{\mathrm{bound\_lo}}} \tag{8}$$

The constraint 3 gives upper bounds and lower bounds on the total installed capacity of a technology in a specific year.

$$\mathrm{CAP\_T}_{\mathrm{sec\_tec},t_{\mathrm{bound\_up}}} \leq \mathrm{CAP\_T}_{\mathrm{sec\_tec},t} \leq \mathrm{CAP\_T}_{\mathrm{sec\_tec},t_{\mathrm{bound\_lo}}} \tag{9}$$

The constraint 4 gives upper bounds and lower bounds on technology penetration rate.

$$\mathrm{sec\_tec}_{\mathrm{share},t_{\mathrm{bound\_lo}}} \leq \mathrm{sec\_tec}_{\mathrm{share},t} \leq \mathrm{sec\_tec}_{\mathrm{share},t_{\mathrm{bound\_lo}}} \tag{9}$$

The constraint 5 enforces upper bounds on carbon emissions.

$$\sum_{t} \mathrm{ef}_{\mathrm{sec\_tec},t} \times \mathrm{ACT}_{\mathrm{sec\_tec},t} + \mathrm{FE}_{t} \leq \mathrm{EMISSION}_{\mathrm{bound},t} \tag{10}$$

where $\mathrm{ef}_{\mathrm{sec\_tec},t}$ represents the carbon emission factors for energy conversion technologies.

Therefore, the total primary energy demand is defined as:

$$\mathrm{TPED}_{t} = \sum_{\mathrm{sec\_tec}} \mathrm{ACT}_{\mathrm{sec\_tec},t} \times \mathrm{ce}_{\mathrm{sec\_tec}} + \mathrm{FD}_{\mathrm{pri},t} \tag{11}$$

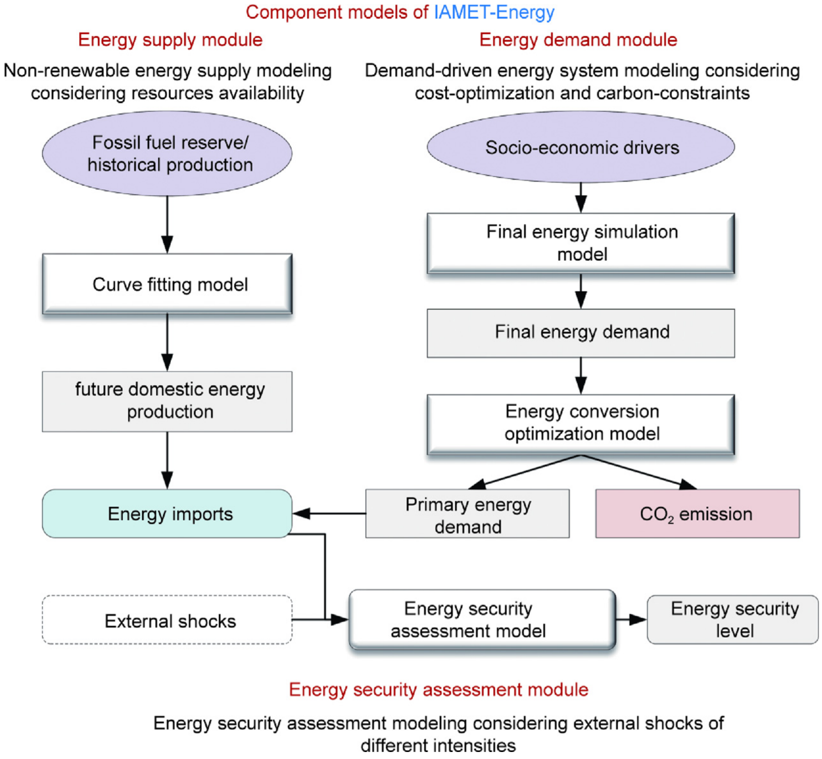


Fig. 1. IAMET-Energy framework.

2.1.2. Energy supply module

In this section, the Generalized Weng's model is applied to predict domestic fossil energy production [62]. It is a curve fitting model that generates the future energy production outlook consider the resources availability from supply side. The reserve and production of fossil energy are required in the energy supply model. Energy supply projection model is a curve fitting model that generate the future energy production outlook consider the resources availability from supply side. The expression is as follows:

$$Q_{k,t} = \frac{\mathrm{URR}_k}{a^{b+1}\Gamma(b+1)} t^b \mathrm{e}^{-\frac{t}{a}} \tag{13}$$

$$\mathrm{URR}_k = \mathrm{RRR}_k + \mathrm{HP}_k \tag{14}$$

where $Q_{k,t}$ represents the future fossil energy k production in year t. URR_k represents the ultimate recoverable reserves of fossil energy k, which is calculated by using the plus between the remaining recoverable reserves (RRR_k) and the history productions (HP_k). Both a and b are parameters. $\Gamma(b+1)$ is the gamma function.

When domestic fossil energy productions cannot meet total fossil energy demand, the fossil energy imports are defined as the gap between fossil energy demand and domestic supply. The expression is as follows:

$$\mathrm{IM}_{k,t} = \mathrm{TPED}_{k,t} - Q_{k,t} \tag{15}$$

where $\mathrm{IM}_{k,t}$ represents the fossil energy k imports in year t. $\mathrm{TPED}_{k,t}$ denotes the total demand for fossil energy k, which is from energy demand model.

2.1.3. Energy security assessment module

This research constructs an energy security assessment model using two approaches based on whether external shocks occur. If there are no interruptions, external dependence is used to assess energy security:$\mathrm{ED}_{k,t} = \frac{\mathrm{IM}_{k,t}}{\mathrm{TPED}_{k,t}}(16)$

where $\mathrm{ED}_{k,t}$ represents the external dependence of fossil energy k in year t.

However, in the event of external shocks, this study applies the widely accepted resilience framework to assess energy security [63,64]. Under external shocks, the system can be represented by a conceptual resilience curve illustrating four stages of performance (Fig. 2), which are before, degradation, recovery, and after. The original system performance is $P_k(t_0)$ before the disruption. When the external shocks occur, the system performance $P_k(t)$ degrades to $P_k(t_e)$ and then recovers back to $P_k(t_0)$, forming a shadow area, which is named the resilience triangle (RT) [64].

In this research, system performance $P_k(t)$ is defined as the extent to which energy demand is satisfied during disruptions. Therefore, we chose the demand satisfaction rate (DSR) as the function of system performance, which is practical as well as consistent with relative research [65]. System performance function $P_k(t)$ can be calculated by

$$P_k(t) = \frac{Q_{k,t} + \mathrm{IM}_{k,t} \times (1 - \mathrm{IR}_{k,t})}{\mathrm{TPED}_{k,t}} \tag{17}$$

where, the maximum value of $P_k(t)$ is 1 (i.e., original system performance $P_k(t_0) = 1$), indicating the system performance of supply–demand balance. $\mathrm{IR}_{k,t}$ represents the interruption ratio under the external shocks.

The RT represents the system performance loss, so the smaller the triangle, the better the resilience. The RT can be calculated by

$$\mathrm{RT}_{k,t} = \frac{\int_{t_e}^{t_f} (P_k(t_0) - P_k(t))\mathrm{d}t}{\int_{t_e}^{t_f} P_k(t_0)\mathrm{d}t} \tag{18}$$

where t_e is the time disruption occurs and t_f is the time that system performance recovers to normal.

During supply disruptions, a system's resilience is defined by its ability to its initial performance. Resilience captures the full evolution of system performance under external shocks: the higher the resilience, the stronger the energy security. Mathematically, energy system resilience is expressed as the ratio of the area of remaining system performance to that of the original system performance

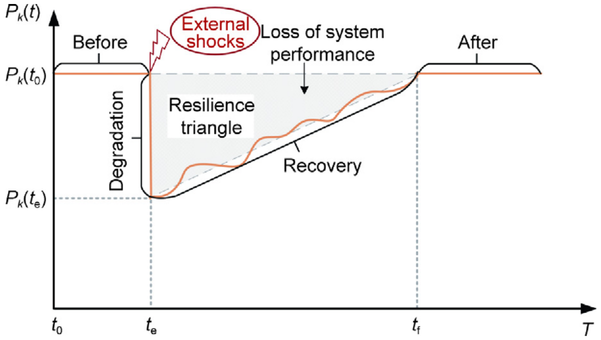


Fig. 2. Four basic stages of system performance in the resilience curve.

$$R_{k,t} = \frac{\int_{t_e}^{t_f} P_k(t)\mathrm{d}t}{\int_{t_e}^{t_f} P_k(t_0)\mathrm{d}t} \tag{19}$$

where $R_{k,t}$ represents the system resilience of fossil energy k in year t.

For a more detailed resilience assessment, resilience can be categorized into three zones: good, moderate, and poor. Two reference curves define these zones: one indicates the resilience level required basic system functions under external shocks, ensuring basic energy demand is met; the other represents the resilience needed to maintain bottom-line functions, ensuring minimum energy demand. Resilience above the basic-demand curve falls into the good zone, resilience between the bottom-line and basic-demand curve falls into the moderate zone, and resilience below bottom-line curve falls into the poor zone.

In this study, China's basic oil demand includes the oil demand from agriculture, all industrial sectors, and the transportation sector, excluding private car transportation. Bottom-line oil demand includes the oil demand from agriculture, freight transportation, public transportation, and the chemical industry—representing the minimum oil demand required to ensure the normal running of China's economy and society [66,67].

2.2. The oil security assessment roadmap using IAMET-Energy

Using IAMET as core model, we have developed the following assessment roadmap to analyze oil security and the need for countermeasures. The roadmap consists of three main steps as shown in Fig. 3.

In Step 1, the IAMET model is used to collect data on oil end-use in key sectors, total oil demand, and domestic supply, enabling a forward-looking analysis of oil supply and demand. In Step 2, the scale of imported oil is calculated as the gap between demand and domestic supply. Oil security is then quantified considering potential disruptions in overseas oil supply due to geopolitical conflicts. If no interruptions occur (interruption ratio = 0), external oil dependence is used; if interruptions occur (interruption ratio > 0), oil supply resilience becomes the metric. Step 3 develops countermeasure scenarios from both demand- and supply-side perspectives. Oil security is reassessed under these scenarios using Steps 1 and 2, and the results are compared with Step 2 to evaluate the effectiveness of the countermeasures.

3. Scenario settings

In this study, a set of scenarios was developed to explore alternative future developments in China's energy system, with a primary focus on oil security. These scenarios integrate both oil demand and supply information, as detailed in Table 1. On the energy demand side, we constructed one reference scenario and one CO_2 mitigation scenarios. These scenarios are based on a consistent set of socio-economic assumptions, including GDP, population, and urbanization (details in Appendix A), ensuring alignment with China's long-term development goals, including the target of quadrupling GDP by 2060 compared to 2020 levels. The reference scenario, business as usual (BAU), represents energy development under current policies without additional CO_2 constraints. The CO_2 emission mitigation scenario, carbon neutrality scenario (CNS), depicts China's transition pathways towards deep decarbonization target. It is assumed that China's carbon sink will reach ~2 Gt by the mid-century, thus capping maximum CO_2 emissions at this level. The CNS further explores energy transition pathways with a moderate deployment of various low-carbon technologies. Detailed socio-economic assumptions and carbon sink estimates are provided in Appendix A.

To account for energy demand-side countermeasures, three additional scenarios are developed each emphasizing the large-scale deployment of a specific low-carbon technologies: ① CNS with extensive CCUS development (CNS-CCUS), ② CNS with large-scale hydrogen technology development (CNS-H), ③ CNS with accelerate electrification (CNS-E). Using the IAMET-Energy framework, the deployment scale of low-carbon technologies is linked to their intrinsic cost dynamics. Thus, the study investigates large-scale development potentials by adjusting their LRs. Specifically, the LR of low-carbon technology costs are increased by approximately 20% in CNS-CCUS, 15%–20% in CNS-H, and 20%–30% in CNS-E compared with the baseline CNS.

On the supply side, the analysis primarily considers two key sources of oil supply: domestic oil production and overseas oil imports. The ultimate recoverable resources (URRs) are critical for forecasting domestic oil productions. According to data published by the Ministry of Natural Resources of China [68], the remaining recoverable reserves (RRRs) are estimated at 3.85 billion tons. In this study, the URRs are calculated as the sum of the RRRs and the cumulative historical productions, as detailed in Appendix A.

The interruption ratio serves as a key parameter for simulating the impacts of oil supply disruptions. To evaluate variations in oil security, this study adopts the control variate method, in which only overseas oil imports are adjusted across the scenarios to reflect potential geopolitical disruptions. According to existing research, the Strait of Hormuz and the Strait of Malacca represent critical chokepoints in China's oil import network. Disruptions in these two straits would result in approximately 39% and 66% of oil imports being interrupted [69]. Therefore, based on varying levels of import interruptions—0, 39%, and 66%—three oil supply scenarios are designed: the normal supply scenario (NS), the medium interruption supply scenario (MIS), and the severe interruption supply scenario (SIS). These scenarios capture the potential range of external shock intensities that may result from geopolitical disruptions to major maritime oil transport routes.

Considering energy supply-side strategies, strategic oil reserves scenarios (SOR) is developed. In this study, it is assumed that China's SPRs remain at their current level, approximately 90 million tons [70]. For comparison, another scenario excluding the use of strategic oil reserve is also explored. When oil imports are disrupted, the strategic oil reserves are assumed to have a supply capacity of 0.5 million tons per day [43], providing an essential buffer to stabilize oil availability and enhance system resilience.

4. Results

4.1. China's oil demand and supply under different scenarios

Fig. 4 depicts key results output under two scenarios, which include primary energy demand, oil demand and supply. Figs. 4 (a) and (c) illustrate China's primary energy pathways under the two scenarios. The primary energy demand follows a growth–peak–decline trajectory, reaching its maximum around 2035–2040

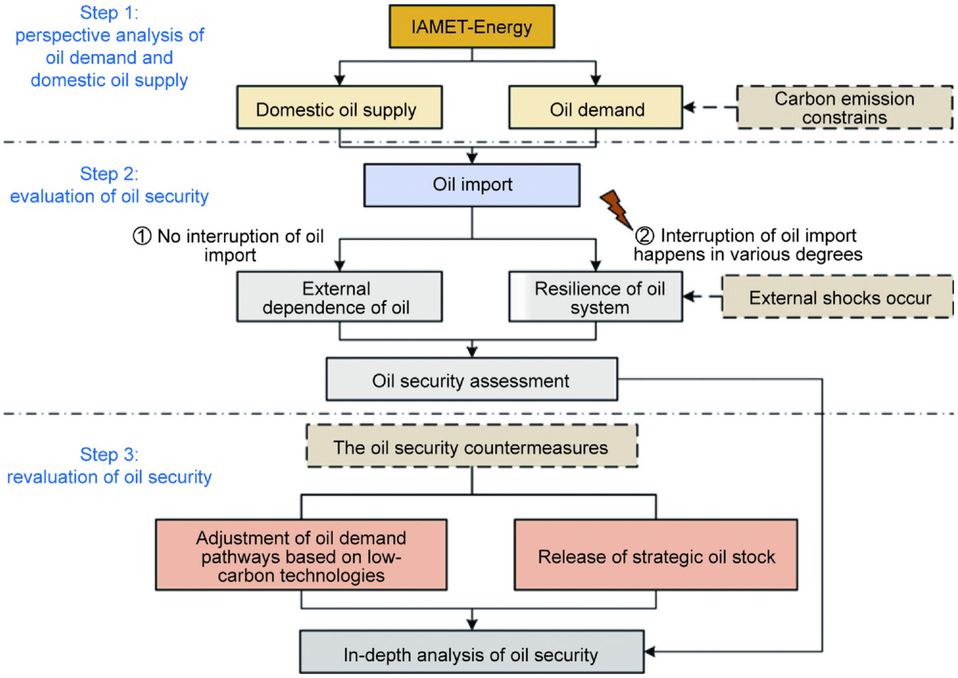


Fig. 3. Oil security assessment roadmap.

Table 1
Scenario settings.

Scenario categories	Descriptions	
	Demand-side	Supply-side
Energy transition scenario		
BAU	Follow the trend of current policies without carbon mitigation target	URR equals the RRR (3.85 billion tons) plus the historical productions
CNS	Reaching deep decarbonization target by the mid-century	URR equals the RRR (3.85 billion tons) plus the historical productions
Countermeasure scenario		
CNS-CCUS	Reaching deep decarbonization target by the mid-century, while assuming a 20% increase in the LR of CCUS technology costs compared with CNS	URR equals the RRR (3.85 billion tons) plus the historical productions
CNS-E	Reaching deep decarbonization target by the mid-century, while assuming a 15%–20% increase in the LR of renewable electricity technology costs compared with CNS	URR equals the RRR (3.85 billion tons) plus the historical productions
CNS-H	Reaching deep decarbonization target by the mid-century, while assuming a 20%–30% increase in the LR of hydrogen energy production technology costs compared with CNS	URR equals the RRR (3.85 billion tons) plus the historical productions
SOR	Reaching deep decarbonization target by the mid-century	Strategic oil reserves remain at 90 million tons Emergency supply of 0.5 million tons per day
Oil interruption scenario		
NS	No interruption of oil supply happens	URR equals the RRR (3.85 billion tons) plus the historical productions
MIS	~39% of oversea oil import is cut off due to the interruption of Strait of Hormuz	URR equals the RRR (3.85 billion tons) plus the historical productions
SIS	~66% of oversea oil import is cut off due to the interruption of Strait of Malacca	URR equals the RRR (3.85 billion tons) plus the historical productions

in both cases. By 2060, total primary energy demand is projected to reach 6.29 billion tonnes of coal equivalent (tce) under the BAU scenario and 5.46 billion tce under the CNS scenario. In the CNS, China's strong policy support for non-fossil energy technologies—including non-fossil power generation and electrolytic hydrogen production—is fully considered. The costs of these technologies are expected to decrease by more than 20% by 2060, enabling their large-scale deployment in the power and hydrogen sectors. As a result, renewable energy gradually replaces fossil fuels to become the dominant source of primary energy consumption, reflecting a clear transition toward decarbonization in CNS.

Figs. 4(b) and (d) present China's mid-to-long-term oil demand projections by end-use across the scenarios. Under the BAU scenario, despite equipment upgrades and energy efficiency improvements, oil consumption is projected to peak at 800 Mt between 2025 and 2030. Following the peak, consumption remains relatively stable for 5–10 years, before gradually declining to 560 Mt by 2060 due to continued advancements in energy utilization technologies. A steeper post-peak decline in oil demand is observed under the CNS compared with the BAU scenario. The contraction of oil demand over the medium to long term reflects reduced exposure to external oil supply risks as the carbon neutrality pledge is achieved.

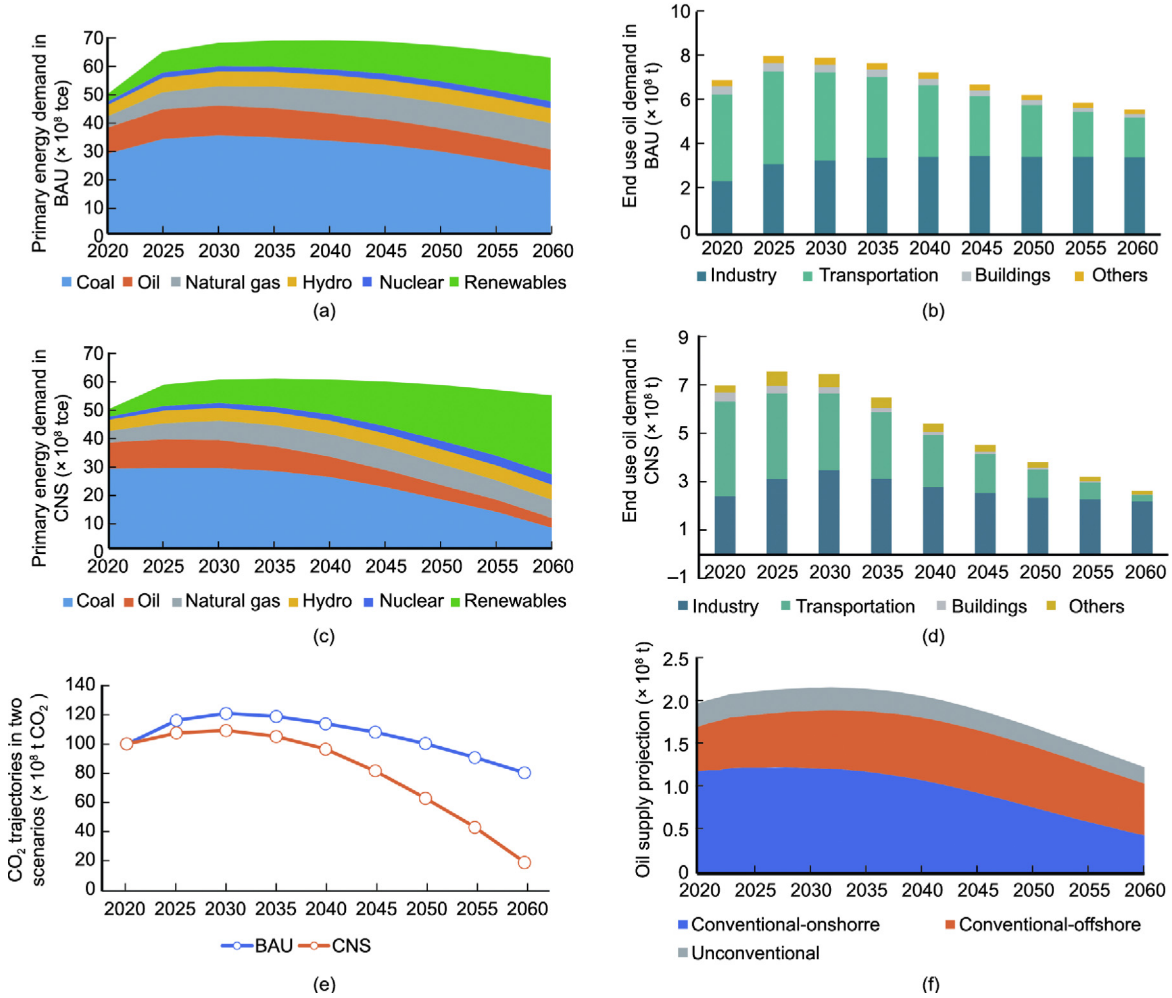


Fig. 4. China's primary energy, oil demand and supply under two scenarios: (a) the primary energy demand under BAU scenario, (b) end-use oil demand under BAU scenario, (c) the primary energy demand under CNS scenario, (d) end-use oil demand under CNS. (e) The CO_2 emission trajectories under two scenarios, (f) China's oil supply under two scenarios.

Under the CNS, improvements in energy efficiency and rising electrification in final sectors lead oil demand to peak at 750 Mt between 2025 and 2030. After 2030, oil's role as a chemical feedstock gradually overtakes its role as a transportation fuel. Driven by the rapid adoption of electric vehicles and continued improvements in transport fuel efficiency, oil consumption declines at an average annual rate of about 5% between 2030 and 2045. By 2060, oil demand is projected to fall to approximately 261 Mt, as substitution in petrochemical production and aviation remains technically and economically challenging. New energy vehicles are expected to account for around 75% of passenger vehicle ownership, contributing the largest reduction in oil consumption. Meanwhile, the petrochemical sector increasingly relies on oil as a feedstock for high-end manufacturing, new energy applications, and environmental technologies, making feedstock use the dominant driver of oil demand, surpassing transportation. This result is consistent with existing literature [12,71]. Fig. 4(e) presents China's energy-related CO_2 emission trajectories under the two scenarios. The peak CO_2 emissions exceed 12 billion tons under the BAU scenario, compared to 10.9 billion tons under the CNS. By 2060, CO_2 emissions are projected to decline to below 2 billion tons in the CNS, while remaining around 8 billion tons under BAU. The rapid emission reduction in the CNS can be attributed to two main factors. First, the electrification rate in final consumption sectors rises substantially, reaching 50% by 2060. Secondly, non-fossil energy technologies are extensively deployed in energy conversion processes. By 2060, the total installed capacity of non-fossil power generation is expected to reach 6.8 kW, underscoring the pivotal role of renewables in achieving deep decarbonization.

Fig. 4(f) presents the projection of China's domestic oil supply. The peak is expected between 2030 and 2035, with conventional oil continuing to dominate, accounting for 84%–88% of total production. Offshore oil is projected to be the primary driver of conventional oil growth, contributing increasingly until around 2040–2045. By 2060, domestic oil supply is expected to decline from its peak of over 200 Mt to approximately 120 Mt, reflecting the combined effects of resource depletion and production constraints. The declining trend in domestic oil supply indicates that, although shrinking oil demand reduces overall supply risks, continued dependence on oil imports remains a significant challenge even under deep decarbonization pathways. This underscores the need for in-depth analysis capable of capturing temporal and structural variations in oil security.

4.2. Assessment of China's oil security

The energy transition is projected to reduce China's external oil dependence, thereby enhancing overall oil security. Table 2 presents trends in oil imports and the external dependence ratio under the NS. After 2030, oil imports are expected to decline across all scenarios. By 2060, imports are projected at 437.3 Mt under BAU and 137.8 Mt under CNS, reflecting the growing share of

Table 2
Oil security assessment under normal supply scenario.

Scenario	Oil import (Mt)			Ratio of oil external dependence		
	2030	2045	2060	2030	2045	2060
BAU	578.3	482.9	437.3	73%	72%	78%
CNS	525.3	258.5	137.8	71%	58%	53%

non-fossil energy in the energy mix, which strengthens oil security. Despite this declining trend, oil security remains a critical concern. Under the CNS, the external oil dependence ratio is expected to fall to 53% by 2060, compared with 78% under BAU.

Fig. 5 presents the assessment of oil supply resilience over the study period, reflecting oil security under oil supply interruption scenario. Resilience peaks during the middle of study period, and declines toward the end. As shown in Fig. 5(a), under a medium supply interruption, oil supply resilience in the BAU scenario remains in the upper range of the moderate zone (0.70–0.72). In contrast, a severe supply interruption causes a sharp decline in resilience to 0.49–0.53 compared with the medium interruption. By 2060, resilience falls into the poor zone under the severe interruption scenario, highlighting the vulnerability of the BAU system to extreme external shocks.

The energy transition enhances oil supply resilience, with its effects strengthening over time. Compared with BAU, external oil dependence under the CNS scenario is projected to decline to 53% by 2060, reducing the system's vulnerability to external shocks. As shown in Fig. 5(b), resilience under CNS improves by 35 and 14 percentage points under severe (66%) and medium (39%) supply interruptions, respectively, by 2060. Between 2045 and 2060, oil supply resilience remains in the moderate zone even under severe disruptions, and approaches the good zone under mild supply interruption. This indicates that the CNS pathways supported by energy transition measures, can substantially mitigate the impacts of external supply shocks.

4.3. The potential for enhancing oil supply resilience

The potential to enhance oil supply resilience is estimated by comparing outcomes with and without demand- and supply-side countermeasures under the CNS. Several key findings and implications regarding oil supply resilience can be drawn from Fig. 6.

Supply-side countermeasures exhibit varying impacts over the study period, with pronounced effects after 2035 (Fig. 6(a)). Under mild oil interruption, resilience remains in the good zone from 2035 to 2060. A similar trend is observed under severe interruptions, with resilience reaching the good zone only after 2055. Overall, the oil strategic stock contributes to a 9%–23% increase in resilience under mild oil interruptions, and a 12%–28% improvement under severe interruptions, highlighting its long-term importance, especially as oil demand declines.

The CCUS-dominated low-carbon pathway enhances resilience notably in the early phase (Fig. 6(b)), with over 20% improvement from 2030 to 2035 compared to CNS. This is primarily due to a lower oil demand peak in 2025, reducing external dependence. Under mild interruption (39%), resilience remains in the good zone from 2030 to 2055. Under severe interruption (66%), it stays in the moderate zone throughout the study period. After 2035, as CCUS costs decline, deployment in power, steel, and cement sectors increases, with potential CO_2 capture of 2 billion tons by 2060. This expanded application slows the decline in oil demand, resulting in lower resilience relative to CNS from 2035 to 2060.

The electricity-dominated pathway maintains the highest resilience throughout the study period (Fig. 6(c)). By 2060, non-fossil power capacity reaches 6.8 billion kW, 14% higher than CNS, and final sectors' electrification rises to 63%. Oil is largely replaced by electricity, enhancing system resilience. Under mild interruptions, resilience remains in the good zone and reaches its maximum starting in 2030. Even under severe interruptions, resilience stays in the good zone from 2035 to 2060, with improvement of 14%–38% under mild oil and 14%–50% under severe interruption.

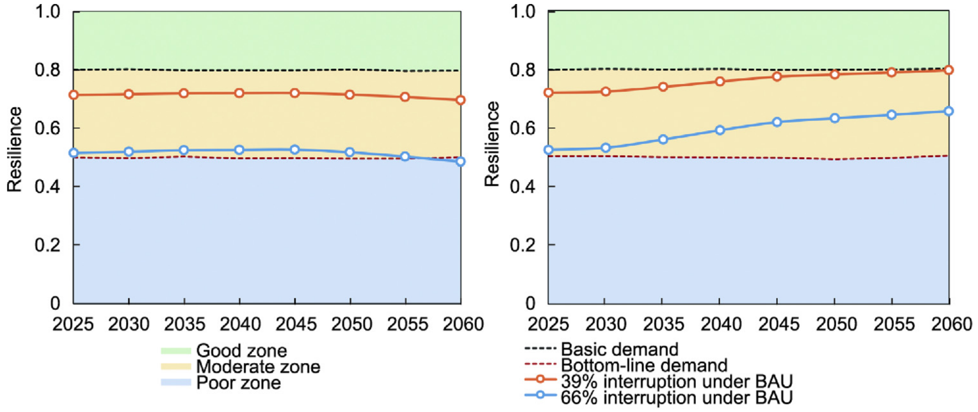
The hydrogen-dominated pathway exhibits a trend similar to the electricity pathway (Fig. 6(d)). By 2060, hydrogen demand reaches 81 Mt, 50% higher than CNS. Large-scale hydrogen deployment in industry and transportation accelerates the decline in oil demand, improving resilience to external shocks. Under mild interruptions, resilience stays in the good zone, peaking between 2035 and 2040. Under severe interruptions, it drops to the moderate zone, peaking at 0.79 in 2040. This pathway rises resilience under severe interruptions to levels comparable to mild interruptions under CNS, with 8%–35% improvement under mild and 10%–38% under severe interruptions.

5. Discussion

5.1. IAMs reveal oil security by considering uncertain nature of energy transition

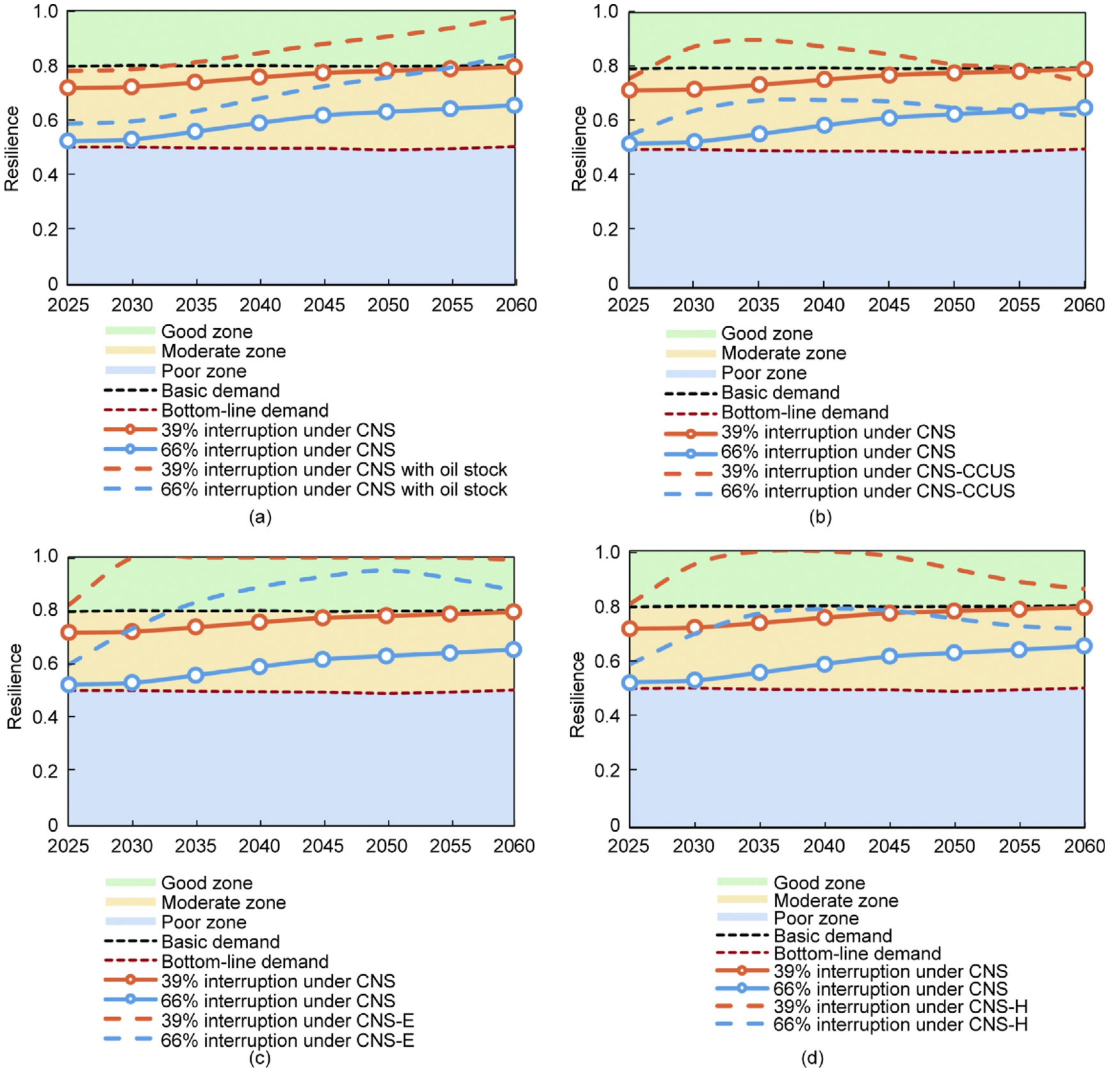
IAMs offer inherent advantages for evaluating resource security in complex systems such as the energy sector. This study examines China's oil security under deep decarbonization IAM scenarios, highlighting the significant uncertainties associated with low-carbon transition pathways driven by the adoption of various technologies. The deployment of CCUS, electricity, and hydrogen technologies influences oil demand while meeting carbon constraints. For example, CCUS can conflicts with other decarbonization strategies, such as end-use electrification and the expansion of non-fossil fuel consumption, whereas electricity and hydrogen technologies primarily replace fossil fuel demand. Moreover, critical trade-offs and co-benefits exists between CCUS and renewable electricity-based electrification. One key challenge is that high renewable penetration can strain grid stability, necessitating careful coordination between technological pathway. Ignoring electricity transmission and comparing the potential of non-fossil energy power generation with electricity demand, China's unmet electricity takes ~18% of total electricity demand [54]. However, combining high renewables penetration with abated fossil power generation using CCUS can significantly enhance the reliability of electricity system. Additionally, the phasing out fossil power generation may result in significant job losses in coal-related industries globally, posing challenges to achieving a just transition. Global job losses in coal industry are estimated at ~1 million by 2050 [72]. Due to the long distance required to access green jobs, only approximately 11%–14% of current coal power workers in China are expected to transition to green employment by 2060 [73].

We emphasize the importance of quantifying oil demand under large-scale deployment of CCUS, electricity, and hydrogen technologies (Fig. 7). Our results show that oil demand under the CNS-CCUS scenario does not exceed that of the CNS until the final decade of the modeling period. This is attributable to two factors: First, the large-scale development of CCUS is partially offset by natural gas to balance other low-carbon measures; second, CCUS tech-



(a) (b)

Fig. 5. Resilience evolutionary under (a) BAU scenario and CNS scenario.



(a) (b) (c) (d)

Fig. 6. The potential of resilience enhancement under strategies: (a) considering the oil strategic stock, (b) considering the large-scale development of CCUS technologies, (c) considering the large-scale development of renewable electricity technologies, and (d) considering the large-scale development of hydrogen technologies.

nologies require longer to mature and achieve economic viability compared to other low-carbon options, becoming cost-competitive only after 10–15 years, delaying their impacts of fossil fuels mitigation.

Furthermore, compared with the CNS, the three technology-dominated pathways lead to a more pronounced reduction in oil demand in the early phase. By 2060, the electricity-dominated pathway exhibits the lowest oil demand, with the uncertainty

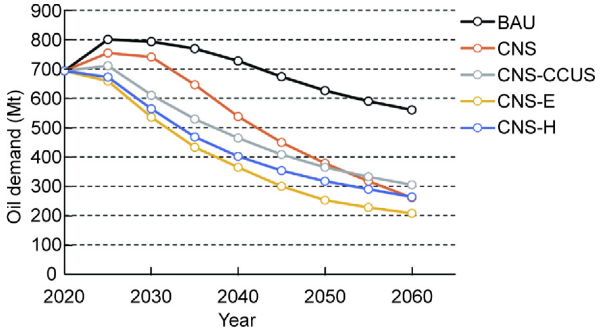


Fig. 7. Comparison of oil demand among scenarios.

range towards carbon neutrality estimated at 200–300 Mt. Table 3 [71,74–77] compares our results with other studies, showing that the CNS outputs are consistent in terms of peak value, peak timing, and the demand in 2050/2060, demonstrating the effectiveness of IAMET-Energy model.

From a supply-side perspective, IAMs have inherent limitations in fully capturing future fossil fuel supply trends. This study quantifies the evolution of China's domestic oil supply over time, incorporating the risk of oil supply interruptions. Ideally, a global oil supply assessment, differentiated by producing regions or countries, would provide valuable insights for evaluating national oil security. However, constructing such a model and integrating it with IAMs is highly complex.

One of the key technical challenges lies in accurately capturing oil trade flows among nations. While the global oil supply-demand balance may eventually be achieved, identifying the specific future supply sources for regional demand remains critical. Another major challenge is selecting appropriate decision-making objectives for prioritizing oil supply. As highlighted in International Energy Agency (IEA)'s special report of oil and gas in net zero transition [4], four illustrative cases are considered: a low-income preference case, an emissions preference case, a cost preference case, and a security preference case.

Our approach seeks to incorporate oil supply-side data into IAMs without introducing unnecessary complexity. Developing a more robust fossil fuel supply model within the IAM framework represents a key avenue for future research. Additionally, the uncertainty surrounding oil supply interruption ratio constitute a limitation of this study. Beyond oil, low-carbon energy transitions create multi-level resource dependencies, including water, metals, land, and biomass. Integrating these dependencies into IAMs would enhance their realism and enable more optimized energy transition pathways, representing a central goal for the future IAM development.

5.2. Constructing systematic coping strategies to enhance oil supply resilience

The oil supply interruption simulation conducted in this study may have broader implications for other fossil energy, which are central to ongoing debates on geopolitical tensions and energy security. In particular, the interruption scenarios settings are closely linked to critical factors, such as the impact of disruptions at maritime chokepoints on the flow of liquefied natural gas (LNG). Rising geopolitical tensions have intensified efforts by Western countries to secure reliable LNG supplies. For instance, the 2021 Suez Canal blockade temporarily halted approximately 8% of global LNG trade, highlighting the vulnerability of energy supply chains to such disruptions. Meza et al. [78] analyzed the effect of chokepoints disruption to the trade of LNG flow under scenarios where the Panama, Suez, and Malacca canals are blocked separately. Major countries like United States, Russia, the EU countries, and China are all big players on LNG industry, which make LNG supply become sensitive to political instability. Optimized LNG transportation routes play a crucial role in supporting a sustainable global energy supply. However, increasing geopolitical antagonism among nations could lead to less energy-efficient routes, resulting in a 13% rise in maritime fuel demand [79]. With the retreat of Arctic Ocean ice, researchers have explored the potential of Arctic Sea corridors for LNG transportation [80]. Previous studies have simulated the impacts of LNG supply interruptions and actively investigated alternative transportation routes [81]. In this context, simulations of disruptions at the Malacca Strait and the Strait of Hormuz validate the approach and findings of our work.

Our study evaluates the impacts of demand- and supply-side measures on oil supply resilience, providing insights beyond static indicators such as external oil dependence. From supply-side perspective, SPRs play a critical role in mitigating supply disruptions, despite their substantial costs. Globally, government-led funding for SPR is common, though exceptions exist in countries such as the United Kingdom and Germany. Given uncertainties surrounding future oil demand and supply risks, dynamic SPR management is essential. In China, direct state management of SPR emphasizes the importance of maximizing the function of state-owned enterprises, as SPR development impacts both oil and national security.

Our findings indicate that maintaining current SPR levels is crucial for enhancing oil supply resilience, though it requires significant investments in infrastructure and replenishment. With China recently renewing its 2035 NDC, incorporating SPR into policy planning under the 15th and 16th Five-Year Plans is vital to ensure the oil security over the next decade. Furthermore, the effectiveness of SPR increases as oil demand declines, underscoring the importance of complementary demand-side measures in strengthening oil security.

The three low-carbon technology-driven pathways demonstrate clear advantages in enhancing short- to mid-term oil supply resilience through proactive optimization of the energy structure. Among these, electrification emerges as the most effective strategy, simultaneously improving oil supply resilience and advancing decarbonization goals. Electrification represents one of the most effective pathways for reducing CO_2 emissions in industrial and manufacturing sectors by replacing traditional coal use with electricity for the provision of steam, heat, and drying processes [82]. The transportation sector can also be substantially decarbonized by shifting from fossil fuel-driven systems to electricity-based

Table 3
Comparison of oil demand in this study with existing literatures.

Source	Time of peak	Peak value (Mt)	Demand in 2050 (Mt)	Demand in 2060 (Mt)
[74]	2025–2030	790	–	260
[71]	2025	770	–	240
[75]	2030	760	270	–
[76]	2025	850	250	–
[77]	2035	730	–	220
CNS in this study	2025	750	380	260

propulsion while meeting transport service demand. The advancement of electrification in China is strongly supported by extensive government policies [83], enabling the country to assume a leading role in the manufacturing of a wide range of power generation and end-use equipment. Thus, electrification in end-use sector accompany with decarbonization in power transformation process is the pillar for achieving China's near-term and long-term carbon mitigation target [84]. As illustrated in Fig. 6, our results show that the large-scale development of electrification leads to the greatest resilience gains, with improvement of 14%–38% compared to the baseline scenario. Large-scale deployment of hydrogen and CCUS also shows substantial potential to enhance oil supply resilience to favorable levels. The temporal characteristics of demand- and supply-side measures indicate that a combined strategy, integrating both approaches, may offer the most effective solution for strengthening oil supply resilience.

5.3. Reducing geopolitical risk impacts of China's oil security

Resilience is a concept with philosophical roots that warrant further clarification in the context of oil security analysis. First, in this study, oil supply resilience reflects the ability of oil system to function under oil supply disruptions, specifically measured as the ratio of oil supply under interruption to total oil demand. Because both oil demand and supply are dynamic over time, this ratio is not constant. It indicates that different from general understanding of resilience as an attribute of an object. Unlike the general notions of resilience as a fixed attribute, oil supply resilience varies across different time periods, which explains why it can increase under the implementation of energy demand rationing and SPR strategy.

Second, the relationship between resilience and scenario requires attention. Oil supply resilience is largely scenario-dependent, meaning it reflects the resilience of a specific decarbonization pathway at different points in time. This scenario-dependent nature underscores the importance of carefully constructing energy demand scenarios and accounting for geopolitical risks when designing oil supply interruption scenarios, thereby ensuring the relevance and robustness of the resilience assessment.

A series of United States/Israel–Iran conflicts in 2026 highlight how extreme scenarios can materialize as "Black Swan" event. In this study, the interruption scenario is analyzed to demonstrate the impact of geopolitical risks on oil security. Given growing tension of oil supply from the middle east, the Belt and Road Initiative (BRI) present a potential opportunity for China to diversify its oil supply sources. With over 150 countries and regions participated in BRI by 2025, the BRI has giant oil supply availability [85]. Excluding the supply of China, total oil production of BRI constitutes ~57% of world oil supply in 2024 [86]. BRI countries are also among the top import sources of China [87]. BRI energy trade has formed a closely linked network, while energy trade volume has increased to 445 billion USD in 2019 [88]. Besides oil import, BRI countries have low investment environment risk for China's oil company due to rich resources, broad cooperation with China, stable political situation, and so forth [89]. This suggests that strategies beyond conventional oil supply- and demand-side measures are essential to manage geopolitical risks. Additionally, leveraging China's unique policy instruments and government tools can further mitigate the impacts of oil supply interruption.

5.4. Limitations of this work

The paper mainly has two limitations:

(1) Coping with extreme oil supply interruptions requires a combination of supply- and demand-side countermeasures, which differs sightly from the approach employed here. In our analysis, we explored the impacts of either supply-side or demand-side measures independently. In real-world decision-making, however, an integrated strategy would likely be necessary. This implies that maintaining current SPR levels while implementing demand-side energy structure adjustment could further optimize the resilience of the oil supply system. Such integrated considerations should be incorporated into future energy security planning.

(2) In this study, we quantified bottom-line and basic oil demand requirements by analyzing the end-use sector demand. However, defining minimum oil demand in practice is challenging. This raises three key questions for future research: ① What is the scale of the minimum oil demand under extreme conditions? ② What is the maximum compression ratio achievable for each end-use sector? ③ How should we measure the spillover effects of oil demand compression on society? The techniques used here provide an initial exploration of minimum oil demand, while the definitions of bottom-line and basic oil demand serve as references for evaluating the effectiveness of oil supply resilience.

Given the limitations, we acknowledge that the applicability of this study may be constrained by inherent uncertainties in oil demand projections. These uncertainties represent a key limitation and warrant further investigation in future research. There is a need for retrospectives analyses comparing past oil demand projections with actual outcomes to evaluate forecast errors and associate uncertainty intervals over time [90,91]. Moreover, although this study focuses exclusively on China's oil security, the discussion of countermeasures offers a potential template for other high-import-dependent economics, such as India. Expanding future research to a broader geography scope would provide the literature with deeper and more generalizable insights int oil security and resilience strategies.

6. Conclusions

This study assesses China's oil security under energy transition by integrating IAMs with a prospective assessment framework. The energy module of the proposed IAMs captures both oil supply and demand, projecting future energy pathways and CO_2 trajectories. In addition to the BAU and CNS, we develop three additional scenarios—CNS-CCUS, CNS-E, and CNS-H—to explore variations in oil demand under large-scale deployment of CCUS, electricity, and hydrogen technologies, while aiming to achieve deep decarbonization target. Following the projection of future domestic oil supply, oil import interruptions are simulated under two representative scenarios. The impacts of supply- and demand-side countermeasures on oil supply resilience are then analyzed under these interruption scenarios. The main findings are as follow:

(1) Energy transition reduces the oil demand, import and external dependence. Oil import is projected to decline from nearly 500 million tons in 2020 to 440 million tons under BAU and 140 million tons under CNS by 2060, demonstrating the positive contribution of clean energy transition to overall energy security.

(2) Oil reliance cannot be fully eliminated. Despite declining domestic oil supply, the ratio of external oil dependence under the CNS is expected to reach 53% by 2060, indicating that oil security will remain a challenge in China's future energy system.

(3) Energy transition enhances oil supply resilience under interruptions. Without SPRs, oil supply resilience remains in the moderate zone under both BAU and CNS scenarios. Compared with BAU, resilience in the CNS improves by 35 and 14 percentage points under severe and medium supply interruption assumption, respectively, by 2060.

(4) Supply- and demand-side countermeasures are essential for strengthening oil security. SPRs primarily enhances resilience in the later phase, while energy structure decarbonization drives resilience gain in the early phase. Under the CNS-E scenario, resilience reaches the good zone after 2030–2035.

The study investigates the system characteristics of oil security by integrating system model modeling with a systematic resilience-based index, enabling the evaluation of both near-term oil supply risk triggered by emergencies and the long-term risks arising from dynamic changes in oil supply and demand during the energy transition. We provide a novel perspective for quantifying oil supply resilience. The findings offer valuable insights not only for China but also for other national, regional, and global studies focused on enhancing oil security and reducing oil supply dependence.

CRediT authorship contribution statement

Xu Tang: Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Kaipeng Ren:** Writing – original draft, Software, Methodology, Funding acquisition, Data curation. **Jianliang Wang:** Supervision, Methodology, Funding acquisition, Conceptualization. **Laibin Zhang:** Validation, Supervision, Conceptualization. **Yu Ding:** Writing – original draft, Methodology, Data curation, Conceptualization. **Yuqing Jiang:** Writing – original draft, Methodology, Funding acquisition, Formal analysis. **Zhida Ma:** Visualization, Methodology, Data curation. **Haichen Ji:** Visualization, Investigation. **Cuiyang Feng:** Writing – review & editing, Validation. **Mikael Höök:** 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2026.04.005.

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