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Resilience simulation and optimization of China's crude oil supply chain under geopolitical disruptions

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ABSTRACT

Recurring geopolitical disruptions have intensified uncertainty in international energy supply chains, making supply chain resilience a critical dimension of energy security. Although China is a major crude oil importer, the resilience of its crude oil supply chain (COSC) has received limited attention. This study employs a coupled system dynamics and input-output model to simulate COSC resilience under geopolitical disruptions and identifies priority emergency response strategies for the gasoline, diesel, and kerosene supply chains by evaluating the recovery capacity and cost-effectiveness of alternative emergency measure combinations. Results show that releasing 10% of the strategic petroleum reserve and 10% of refined oil inventories provides a baseline response but cannot fully offset severe import disruptions. Under the Middle East conflict scenario, which causes a 47% crude oil import shortfall lasting 180 days, upstream measures are generally more cost-effective than downstream ones. Full recovery requires upstream measures plus gasoline export reduction and consumption compression for gasoline, upstream measures plus diesel consumption compression and emergency diesel import for diesel, and either kerosene export reduction alone or upstream measures plus emergency kerosene import for kerosene, with the latter showing better cost-effectiveness. Under the Strait of Malacca blockade scenario, which causes a 73.5% crude oil import shortfall, gasoline and diesel require inventory-release caps of 39% and 27%, respectively, whereas kerosene can be restored through a targeted second-stage combination. These findings suggest that strengthening COSC resilience requires prioritizing upstream supply-support measures, enhancing reserve governance flexibility, adopting differentiated strategies for refined oil products, diversifying import sources and maritime routes, and developing a real-time risk early-warning and emergency decision-support platform.

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1. Introduction

In recent years, global energy supply chains have been exposed to significant shocks, including the COVID-19 pandemic (Katsoras and Georgiadis, 2022), geopolitical conflicts (Wang et al., 2021), and rising protectionism (Wang et al., 2023). These ‘black swan’ events have disrupted and reshaped international energy trade relationships (Liu et al., 2025a), triggering crises related to the

availability, affordability, and accessibility of energy supplies (Aslam et al., 2024). Against this backdrop of disruptions and restructuring, the security of energy supply chains has become a critical concern for governments worldwide.

Crude oil is one of the world's primary energy sources and plays an indispensable role in national economic development (Guo et al., 2024; Zhang et al., 2026). Although crude oil has limited direct utility, it can be refined into various products that meet the energy demands of modern society (Marchese et al., 2020). China is a major crude oil consumer. Between 2012 and 2022, both its net crude oil imports and total consumption increased markedly, and its dependence on imported crude oil exceeded the widely accepted 50% security threshold. Moreover, the Middle East and Africa are the main sources of China's crude oil imports. Persistent instability, terrorism, and armed conflict in these regions amplify

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the geopolitical supply risks facing China's crude oil supply chain (COSC) (Liu et al., 2025b). Nearly 80% of China's imported crude oil is transported by sea, with routes passing through maritime chokepoints such as the Strait of Malacca and the Strait of Hormuz, which further increases the vulnerability of the COSC (Zhang et al., 2013). Given China's high dependence on global crude oil markets, strengthening the resilience of its COSC to geopolitical disruptions has become an urgent priority (Lin and Lin, 2026). Quantifying and enhancing that supply chain's capacity to withstand external shocks is therefore essential for safeguarding energy security, informing policy decisions, and improving systemic resilience.

Resilience theory provides an appropriate conceptual framework for analyzing system behavior under external shocks (Ding et al., 2022; Tortorella et al., 2025). Safeguarding energy security fundamentally requires supply chains to possess sufficient resilience to withstand stresses and maintain continuity of supply (Hoggett, 2014). Existing research on energy system resilience has laid a solid foundation for the study of supply chain resilience; however, several gaps remain. First, current studies on energy supply chain responses to exogenous shocks focus predominantly on qualitative or policy-oriented approaches, while coupled analyses based on the resilience curve and quantitative metrics remain limited. Second, resilience is inherently a dynamic and path-dependent process, and single static indicators are often insufficient to reveal system performance across different stages of recovery. Third, existing studies on energy system resilience have typically emphasized recovery capacity, whereas the socioeconomic losses induced by disruptions and the response costs of emergency measures have often been overlooked. Addressing these gaps will not only contribute to a more comprehensive theoretical framework for energy supply chain resilience but also provide methodological guidance for resilience assessments of other critical supply chains.

Based on the above analysis, this paper investigates the systemic resilience of China's COSC under geopolitical disruptions. Specifically, it establishes a resilience assessment framework by adopting the demand satisfaction rate (DSR), derived from the resilience curve, to quantify recovery capability, and the incremental benefit-cost ratio (IBCR) to evaluate economic efficiency. On this basis, an integrated model coupling system dynamics (SD) and a supply-driven input-output (I-O) model is developed to dynamically simulate the resilience of the COSC under geopolitical disruptions. By comparing the recovery performance and cost-effectiveness of response measures under two disruption scenarios, the study identifies priority response strategies for balancing the supply-demand relationships for three refined oil products: gasoline, diesel and kerosene.

This study makes three contributions. First, it develops a resilience assessment framework that integrates the resilience curve with quantitative indicators. The framework characterizes the supply chain's performance evolution and resilience features across the stages of degradation, recovery, and adaptation, thereby enriching methodological approaches in energy system resilience research. Second, by integrating SD with a supply-driven I-O model, the study captures the dynamic recovery process under complex feedback loops and time delays while quantifying the economic propagation of upstream supply shocks to downstream sectors. Consequently, this coupled framework provides a practical quantitative tool for measuring the socioeconomic losses induced by shocks and evaluating the cost-effectiveness of resilience responses. Third, it identifies priority emergency response sequences for each refined oil product under geopolitical disruptions. These empirical findings provide policy-relevant evidence to support differentiated emergency strategies, improve resource allocation, and strengthen the resilience of the COSC.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the methodology and data. Sections 4 and 5 present the results and discussion, respectively. Finally, Section 6 concludes the paper and discusses the corresponding policy implications.

2. Literature review

2.1. Energy system resilience

The term resilience derives from the Latin *resilire*, meaning 'to return to an original state' (Hosseini et al., 2016). The concept was first introduced into ecology by Holling (1973) to describe an ecosystem's capacity to absorb disturbances while retaining its basic structure and functions. The U.S. National Academy of Sciences (NAS) identified four core elements of resilience: plan/prepare, absorb, recover, and adapt (National Research Council, 2012). Building on these ideas, Linkov et al. (2013) adapted the network-centric operations (NCO) perspective to propose a resilience measurement matrix spanning four domains—physical, information, cognitive, and social—and applied this 4×4 matrix to network systems. Roeger et al. (2014) subsequently extended this 4×4 resilience matrix to the energy domain and proposed a structured, system-level framework of energy resilience indicators. Although there is still no universally accepted definition of energy system resilience (Jesse et al., 2019), the definition advanced by the International Energy Agency (IEA) is widely used: the ability of an energy system and its components to respond to hazards or trends by maintaining essential functions, characteristics, and structure while demonstrating the capacities to adapt, learn, and transform.

The resilience of energy systems is often characterized by the resilience curve, which depicts the temporal evolution of system performance through stages such as degradation, recovery, and adaptation following a disruptive event (Henry and Ramirez-Marquez, 2012; Jasiūnas et al., 2021; Shafiei et al., 2025). At present, the resilience curve and its derived metrics have been widely applied in studies on power systems (Bie et al., 2017; Gholami et al., 2018), fossil energy systems (Bag et al., 2025; Chen et al., 2020; Ding et al., 2022), and integrated energy systems (Chen et al., 2023; Moslehi and Reddy, 2018). For example, Qian et al. (2023) proposed a resilience assessment framework for gas systems based on the resilience curve, incorporating the DSR, economic output loss (EOL), and emergency response costs.

Within energy systems, the supply chain is a critical component spanning supply, production, transportation, storage, and consumption. It relies on physical and financial infrastructure, as well as information-sharing and transport networks, to form a complex system (Emenike and Falcone, 2020; Halldórsson and Svanberg, 2013). When energy supply chains are disrupted, the resulting impacts extend beyond the energy sector itself, propagating through inter-industry linkages to other economic sectors and causing substantial socioeconomic losses. Consequently, the ability of energy supply chains to withstand stresses and shocks while maintaining continuity of supply directly affects overall energy security. Existing studies indicate that external security threats to energy supply chains cannot be overlooked (Chester, 2010; Hoggett, 2014). Through multiple case studies, Urciuoli et al. (2014) identified vessel hijacking, terrorism, and armed conflict as major sources of disruption to European oil and gas flows. Although the European Union has developed relatively comprehensive strategic responses, coordination between these strategies and the operational practices of supply chain enterprises is often lacking. Emenike and Falcone (2020) noted that, in addition to optimization-based resilience enhancements, regional

heterogeneity analysis of energy supply chains can also promote resilience learning and the accumulation of operational experience. [Chrisandina et al. \(2022\)](#) further emphasized that resilience is not only a property of the supply chain as a whole, but also of individual nodes, links, and subsystems, thereby motivating multiscale approaches to strengthening overall energy supply chain resilience.

Overall, although resilience has been incorporated into energy system research, quantitative studies that couple resilience curves with energy supply chain analysis to dynamically evaluate energy supply chain performance under exogenous shocks remain limited. Among the complex array of emergency measures, how to prioritize response strategies so as to achieve a better balance between response speed and cost-effectiveness remains an urgent issue to be addressed ([Hosseini Shekarabi et al., 2025](#)). Therefore, developing coupled quantitative approaches that capture the system-level resilience process and quantify the consequences of risk shocks will not only advance the theoretical understanding of energy system resilience, but also provide valuable practical guidance for strengthening the resilience of energy supply chains.

2.2. SD and the supply-driven I-O model

Although resilience indices are widely regarded as effective tools for assessing system resilience because of their clear definitions and relatively simple and interpretable computations ([Qian et al., 2023](#); [Zhang and Wang, 2023](#)), constructing standardized quantitative methods based on such indices remains challenging due to uncertainties inherent in different systems and their inputs ([Kammouh et al., 2020](#)). SD, a methodology that integrates qualitative and quantitative analyses with holistic reasoning, has proven effective for studying nonlinear complex systems and supporting decision-making ([Jeon et al., 2025](#); [Liu et al., 2021](#); [Liu and Zeng, 2017](#); [Selivanova et al., 2025](#)). This method has been widely applied to socio-ecological systems ([Elsawah et al., 2017](#)), urban systems ([Li et al., 2020](#)), and energy systems ([Zhang et al., 2022](#)). For instance, [Song et al. \(2025\)](#) developed a multi-scenario SD model from a dynamic perspective to analyze changes in the resilience of the natural gas system under LNG import interruptions of 39%, 56%, and 100%. By revealing the causal feedback loops underlying system outcomes, SD models emphasize the dynamic evolution of system behavior and were identified by [Herrera and Kopainsky \(2020\)](#) as powerful tools for understanding system structure and conducting resilience assessments. Moreover, resilience assessment practice highlights the importance of learning about and understanding the dynamics of complex adaptive systems. Forming a system-level consensus on the problem is one of the core objectives of effective resilience evaluation ([Quinlan et al., 2016](#)).

Prior studies have primarily focused on system recovery following external shocks, while the socioeconomic losses triggered by system disruptions have received comparatively less attention. The I-O model, which captures interdependencies among economic sectors and can trace indirect effects beyond direct flows, provides a useful means of assessing how intersectoral interactions translate into changes in output and exchange relations within complex systems ([Wang and Chen, 2016](#)). The supply-driven I-O model, originally developed by [Ghosh \(1958\)](#), is particularly suited for analyzing the direct and indirect impacts that changes in a sector's primary inputs exert on other sectors. [Kerschner and Hubacek \(2009\)](#) applied this model to investigate the sectoral and macroeconomic impacts of crude oil supply shortages in the UK, Japan, and Chile, and found pronounced

effects in electricity generation, transportation, finance and insurance, and wholesale and retail trade. [Wu et al. \(2018\)](#) used a supply-driven I-O model combined with a price model to assess the economic impacts of power shortages in Taiwan, showing that neglecting indirect output effects substantially underestimates the total economic consequences. [Qian et al. \(2023\)](#) treated EOL as a key indicator of gas system resilience and quantified it using a supply-driven I-O approach. Although the supply-driven I-O model has clear advantages in evaluating the economic consequences of constrained energy supply, few studies have applied it to quantify the economic shocks that upstream shortages in energy supply chains impose on downstream consumption sectors and other related industries.

Based on the above analysis, applying a coupled SD and supply-driven I-O model to energy supply chain resilience research enables both the dynamic characterization of resilience evolution and the quantification of disruption-induced economic losses, thereby addressing the limited attention paid in previous studies to the economic efficiency of resilience measures. This coupled approach deepens understanding of the dynamic resilience of energy supply chains by explicitly accounting for the cost-benefit trade-offs of resilience responses.

3. Methodology and data

3.1. Overall methodological framework

To simultaneously evaluate the recovery capacity of the COSC under external shocks and the associated socioeconomic consequences, this study adopts the DSR and the IBCR as resilience assessment indicators, and develops a coupled framework integrating the SD model and the supply-driven I-O model to support their quantification. Specifically, the SD model is employed to characterize the dynamic evolution of crude and refined oil supply-demand relationships, inventory release, emergency response activation, and recovery processes under geopolitical disruptions, thereby capturing the multistage, feedback-driven, time-delayed, and nonlinear nature of the COSC. Meanwhile, external shocks are ultimately manifested as reductions in the supply of gasoline, diesel, and kerosene to downstream sectors, which in turn induce economic output losses and value-added losses in related industries. The supply-driven I-O model is well suited to analyzing the direct and indirect impacts of supply constraints in one sector on the outputs of other sectors, and is therefore used to estimate the economic output loss coefficients and value-added coefficients associated with shortages of gasoline, diesel, and kerosene. Furthermore, the coefficients derived from the supply-driven I-O model are embedded into the SD model and combined with the evolution of refined oil shortages to calculate socioeconomic losses over time.

In this framework, the SD model represents the system recovery process, whereas the supply-driven I-O model provides the conversion parameters required for economic loss estimation, with refined oil shortages serving as the interface linking the two models. This coupled framework not only overcomes the limitation of using the SD model alone, which is insufficient for adequately quantifying macroeconomic consequences, but also avoids the shortcoming of using the supply-driven I-O model alone, which fails to capture the dynamic recovery process and policy-response pathways of the COSC. Therefore, the proposed coupling approach is consistent in terms of variable linkage, functional division, and shock-transmission logic, and offers a coherent analytical framework for linking the physical shortage process of the COSC with its socioeconomic consequences.

3.2. Resilience assessment indicators

3.2.1. Demand satisfaction rate

The DSR is employed to quantify the COSC's recovery capability in response to external disturbances. It is calculated as follows:

$$DSR(t) = \frac{\text{Supply}(t)}{\text{Demand}(t)} \quad (1)$$

where $\text{Supply}(t)$ and $\text{Demand}(t)$ denote the available supply and demand at time t , respectively.

Following an external disturbance, system performance typically follows a four-phase conceptual resilience curve: before, degradation, recovery and after (Ding et al., 2022). This study focuses on the recovery phase of the resilience curve. Fig. 1 illustrates four representative recovery pathways of system resilience under a geopolitical disruption: (1) S_0 : No emergency response measures are implemented. The DSR remains at an impaired level throughout the disruption. (2) S_1 : Limited mitigation measures are adopted, producing a partial improvement in DSR during the disruption. However, owing to constrained response capacity and limited duration of the measures (Poulin and Kane, 2021), the DSR returns to the impaired level after the event. (3) S_2 : More substantial response measures raise the DSR to a new stable level during the disruption, but this level remains below the pre-disturbance baseline. (4) S_3 : Implemented measures completely offset the disruption, so that the DSR is restored to the pre-disturbance level ($DSR = 1$).

3.2.2. Incremental benefit-cost ratio

Incremental analysis is a standard approach in engineering economics for comparing alternatives by examining differences in benefits and costs between different options (Shih, 2008). In this study, the IBCR is used to evaluate the economic performance of alternative emergency response measures relative to the baseline scenario. It is defined as follows:

$$IBCR(S_s) = \frac{TL_0 - TL_s}{TC_s - TC_0}, s = 1, 2, \dots, n \quad (2)$$

where S_s denotes an emergency response scenario, TL represents the total socioeconomic loss, and TC refers to the total emergency response cost. The subscript 0 indicates the baseline scenario.

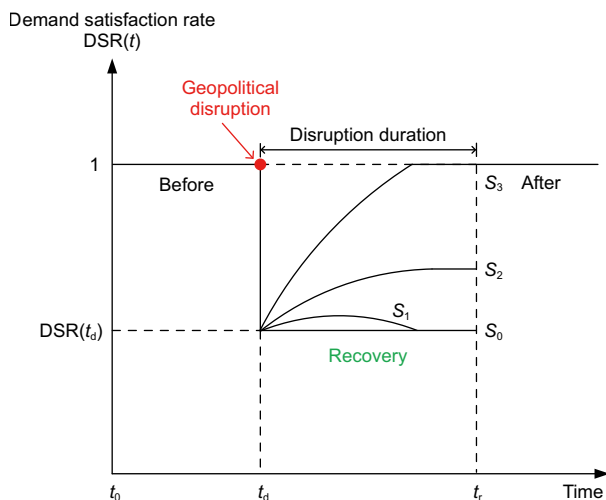


Fig. 1. Recovery pathways of system resilience.

The total emergency response cost is estimated by incorporating both measure-specific additional costs and external price shocks. It is calculated as follows:

$$TC = \int_{t_s}^{t_e} C(t) dt \quad (3)$$

$$C(t) = \sum_{m=1}^n Q_m(t) \times P_m(t) \quad (4)$$

$$P_m(t) = P_m^0 \times (1 + \delta_m) \times (1 + \lambda_m \times \theta_t), 0 \leq \lambda_m \leq 1 \quad (5)$$

$$\theta_t = \begin{cases} 0, & t < t_s \\ \theta_s, & t_s \leq t \leq t_e \\ 0, & t > t_e \end{cases} \quad (6)$$

where $C(t)$ denotes the time-varying emergency response cost; $Q_m(t)$ is the quantity of resources mobilized under measure m at time t ; $P_m(t)$ is the corresponding unit cost at time t ; P_m^0 is the baseline unit cost of measure m ; δ_m is the additional cost coefficient for measure m , capturing dispatching, transportation, coordination, warehousing, insurance, and policy implementation costs; θ_t is the external price shock factor at time t , and θ_s denotes the scenario-specific shock level; λ_m is the pass-through coefficient for measure m , reflecting the extent to which the external price shock is transmitted into the cost of that measure; and t_s and t_e denote the start and end times of the emergency response intervention, respectively.

3.3. Supply-driven I-O model

This study first disaggregates gasoline, kerosene, and diesel from the 2020 input-output table and then aggregates the remaining sectors into six industrial categories according to the *Industrial Classification for National Economic Activities*. The sector disaggregation and classification are presented in Appendix A. In estimating the sectoral economic output loss coefficients and fiscal subsidy intensity coefficients using the supply-driven I-O model, this study assumes that intersectoral production linkages and input structures remain fixed over the simulation period, implying relatively stable input-output coefficients. Under this assumption, the estimated economic losses caused by refined oil shortages should be interpreted as structural approximations under a given production linkage structure rather than precise forecasts of actual macroeconomic outcomes. Nevertheless, this approach remains suitable for comparing the relative socioeconomic consequences of different disruption scenarios and emergency recovery strategies within a unified analytical framework.

3.3.1. Sectoral economic output loss coefficients

In the supply-driven I-O model, the intersectoral input-output relationship among the six aggregated sectors is described as follows:

$$X_j = \sum_i Z_{ij} + v_j \quad (7)$$

where X_j denotes the total input of sector j , Z_{ij} represents the input required from sector i to sector j , and v_j stands for the value added of sector j (e.g., employee compensation, operating surpluses, government taxes, and depreciation).

To account for imports of goods or services in sector i , the ratio of import value M_i to total output X_i is assumed to be constant, and is defined as $m_i = \frac{M_i}{X_i}$. Thus, the total demand of sector i can be expressed as $q_i = X_i + M_i$, or in matrix form as $Q = X + M$. The

corresponding allocation coefficient is defined as $s_{ij} = \frac{Z_{ij}}{q_i}$. Therefore, the input of sector j can be rewritten as:

$$X_j = \sum_i s_{ij} \times q_i + v_j \quad (8)$$

This relationship can be further expressed in matrix form as:

$$X = S' \times Q + V \quad (9)$$

$$V = (I - S' \times (I + m)) \times X \quad (10)$$

$$X = (I - S' \times (I + m))^{-1} \times V = G \times V \quad (11)$$

where S denotes the matrix of allocation coefficients, S' is its transpose, and m is the diagonal matrix of import ratios m_i . Q represents the total demand vector, V is the value-added vector, and G denotes the allocation inverse matrix accounting for imports.

This study focuses on the socioeconomic consequences caused by downstream refined oil supply-demand imbalances within the COSC. Accordingly, the gasoline, kerosene and diesel are treated as exogenous and moved to the value-added term. The model can then be written as:

$$X = (I - S' \times (I + m))_{n-1}^{-1} \times (V + R_e \times X_e) = G_{n-1} \times (V + R_e \times X_e) \quad (12)$$

where the subscript e denotes the refined oil sector and $n-1$ denotes the remaining endogenous sectors after excluding sector e . G_{n-1} is the reduced allocation-inverse matrix, R_e refers to the allocation-coefficient vector of the refined oil supply sector, and X_e represents the output of sector e .

To assess how changes in the refined oil supply affect the outputs of other sectors, the above equation can be rewritten as:

$$\Delta X = G_{n-1} \times (\Delta V + R_e \times \Delta X_e) \quad (13)$$

where ΔX is the vector of output changes in the $n-1$ endogenous sectors, ΔX_e denotes the output change in the refined oil supply sector e , and ΔV is the vector of value-added changes.

Furthermore, the output change induced by a physical reduction in refined oil supply can be expressed as:

$$\Delta X_S = G_{n-1} \times R_e \times \Delta X_e = G_{n-1} \times R_e \times \left(\frac{\Delta X_e}{\rho^e} \right) \times \rho^e = G_{n-1} \times R_e \times (\Delta E_e) \times \rho^e \quad (14)$$

where ρ^e denotes the average price of product e , and ΔE_e represents the physical supply reduction of product e .

Accordingly, the sectoral economic output loss (SEOL) can be expressed as:

$$SEOL = \sum \Delta X_S = \sum_{i=1}^{n-1} \Delta X_{S,i} = \sum_{i=1}^{n-1} k_i \times \Delta E_e \quad (15)$$

$$K_{n-1} = G_{n-1} \times R_e \times \rho^e = \begin{pmatrix} k_1 \\ \vdots \\ k_{n-1} \end{pmatrix} \quad (16)$$

$$\Delta E_e = (E_1 \quad \cdots \quad E_{n-1}) \quad (17)$$

where $k_1, \dots, k_{n-1}$ represent the sectoral economic output loss coefficients associated with refined oil sector e , and $E_1, \dots, E_{n-1}$ denote the supply reductions transmitted from sector e to other sectors.

3.3.2. Subsidy intensity coefficients

To prevent broader market risks and secondary effects caused by refined oil shortages, this study assumes that the value-added losses in different sectors resulting from refined oil supply disruptions are fully offset by fiscal compensation. Under this assumption, the fiscal subsidy can be estimated based on the value-added losses in each sector:

$$FS = \sum_{j=1}^{n-1} \Delta L_j^V = \sum_{j=1}^{n-1} \eta_j \times \Delta X_{S,j} \quad (18)$$

where FS represents the fiscal subsidy, ΔL_j^V denotes the fiscal compensation required to maintain the value added of sector j , and $\eta_j = \frac{L_j^V}{X_j}$ denotes the value-added ratio of sector j . Accordingly, η_j can be interpreted as the fiscal subsidy intensity coefficient for sector j .

Based on the coefficients estimated above, the time-varying total socioeconomic loss is dynamically calculated within the SD model as follows:

$$TL = \int_{t_1}^{t_2} [SEOL(t) + FS(t)] dt \quad (19)$$

where TL denotes the total socioeconomic loss induced by downstream refined oil supply-demand shortfalls, consisting of sectoral economic output loss and the fiscal subsidy required to offset value-added losses; t_1 and t_2 represent the start and end times of the refined oil supply-demand imbalance, respectively.

3.4. The SD model of the COSC

3.4.1. System boundary

From a life-cycle perspective, the COSC can be divided into three stages: upstream supply, midstream application, and downstream consumption (Liu et al., 2025b). The upstream supply subsystem comprises domestic production and international imports. The midstream application subsystem consists of refinery processing and the strategic petroleum reserve (SPR). The downstream consumption subsystem involves refined oil inventories, domestic consumption, and trade. However, because this study focuses on the resilience performance of the COSC, an emergency response subsystem is incorporated into the system from both supply-side and demand-side perspectives. Upstream emergency measures include emergency crude oil production, emergency crude oil import, coal-to-liquids supply, and crude oil export reduction. Downstream emergency measures include emergency refined oil import, refined oil export reduction, and refined oil consumption compression. The system boundary of China's COSC is shown in Fig. 2.

3.4.2. Causality analysis

Based on the system boundary of the COSC, a causal loop diagram is constructed, as shown in Fig. 3. This diagram illustrates the main feedback relationships within the supply chain and shows how emergency response measures operate. The nine principal causal loops are summarized as follows: (1) Crude oil gap $\rightarrow (+)$ Strategic reserves release $\rightarrow (+)$ Actual crude oil supply $\rightarrow (-)$ Crude oil gap. (2) Crude oil gap $\rightarrow (+)$ Emergency crude oil production $\rightarrow (+)$ Actual crude oil supply $\rightarrow (-)$ Crude oil gap. (3) Crude oil gap $\rightarrow (+)$ Emergency crude oil import $\rightarrow (+)$ Actual crude oil supply $\rightarrow (-)$ Crude oil gap. (4) Crude oil gap $\rightarrow (+)$ Coal-to-liquids $\rightarrow (+)$ Actual crude oil supply $\rightarrow (-)$ Crude oil gap. (5) Crude oil gap $\rightarrow (+)$ Export crude oil reduction $\rightarrow (+)$ Actual crude oil supply $\rightarrow (-)$ Crude oil gap. (6) Refined oil gap $\rightarrow (+)$ Refined oil

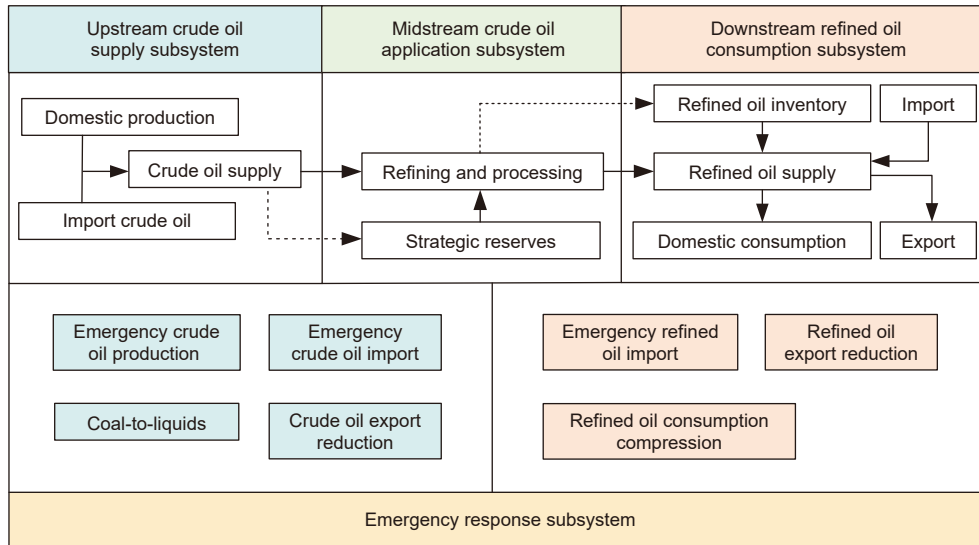


Fig. 2. System boundary of China's COSC.

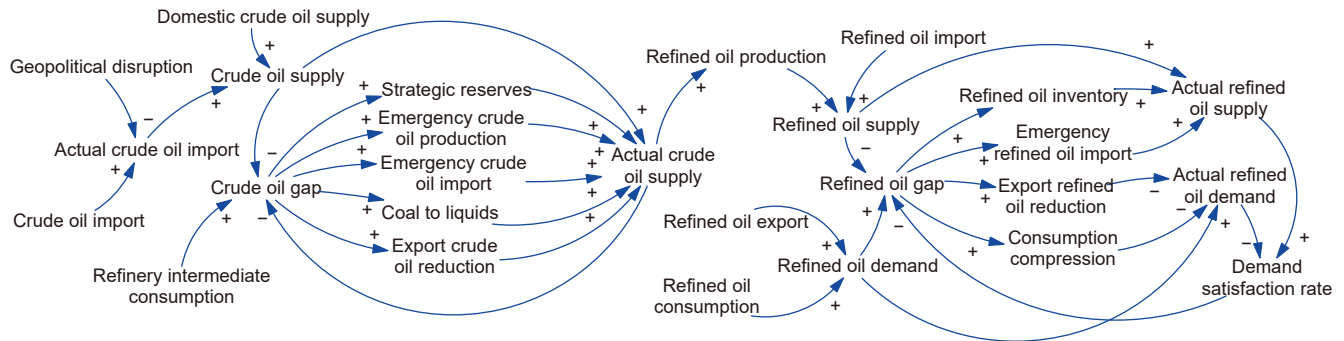


Fig. 3. Causal loop diagram of COSC. Note: In the causal loops, arrows with '+' indicate a positive relationship between two linked components, whereas arrows marked with '-' indicate a negative relationship.

inventory release $\rightarrow (+)$ Actual refined oil supply $\rightarrow (+)$ Demand satisfaction rate $\rightarrow (-)$ Refined oil gap. (7) Refined oil gap $\rightarrow (+)$ Emergency refined oil import $\rightarrow (+)$ Actual refined oil supply $\rightarrow (+)$ Demand satisfaction rate $\rightarrow (-)$ Refined oil gap. (8) Refined oil gap $\rightarrow (+)$ Export refined oil reduction $\rightarrow (-)$ Actual refined oil demand $\rightarrow (+)$ Demand satisfaction rate $\rightarrow (-)$ Refined oil gap. (9) Refined oil gap $\rightarrow (+)$ Consumption compression $\rightarrow (-)$ Actual refined oil demand $\rightarrow (+)$ Demand satisfaction rate $\rightarrow (-)$ Refined oil gap.

3.4.3. System stock-flow diagram

To further clarify the quantitative relationships among variables, a system stock-flow diagram of the COSC was developed using *Vensim* software based on the system boundary and causal loop diagram, as illustrated in Fig. 4. Fig. 4 highlights the interactions among the upstream crude oil supply subsystem, the midstream application subsystem, the downstream refined oil consumption subsystem, and the emergency response subsystem. In this study, the downstream refined oil consumption subsystem comprises gasoline, diesel, and kerosene. The complete stock-flow diagram, together with the mathematical formulations and parameter values for each subsystem, is provided in Appendix B.

3.4.4. Model test

Model testing constitutes a critical final step in the model construction process. It serves to validate the model's accuracy and robustness, identify potential deficiencies, and support corresponding adjustments and corrections. In this study, the COSC model underwent comprehensive testing for validity, reality, and sensitivity.

(1) Validity test

In the absence of geopolitical disruptions to the COSC system, this study evaluates the DSRs of refined oil products and the associated socioeconomic losses using the model. The results are presented in Fig. 5. When the geopolitical disruption variable is set to zero, the DSRs for gasoline, diesel, and kerosene remain at unity, and the total economic loss is zero. These results indicate that the COSC system operates in a stable state under normal conditions.

(2) Reality test

To further calibrate and validate the model, a reality test is conducted using inventory levels as representative state variables. The results are presented in Fig. 6. Under normal conditions, the supply rates of crude oil, diesel, and kerosene exceed their

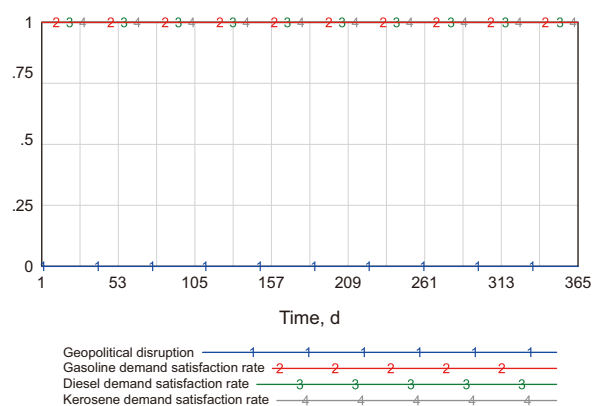


Fig. 5. Validity test under normal conditions.

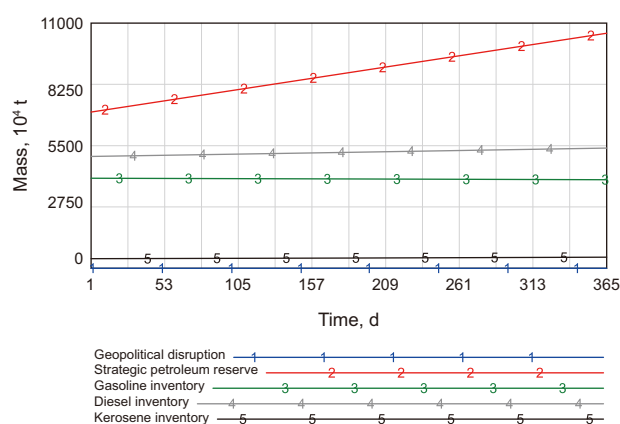


Fig. 6. Reality test under normal conditions.

Table 1
Comparison of simulated and historical inventory changes (Unit: 10⁴ t).

Type	Initial value	Final value	Simulated change	Historical change	APE
Crude oil	7004.40	10538.80	3534.40	3544.10	0.27%
Gasoline	4034.14	3971.93	-62.21	-62.42	0.34%
Diesel	5012.36	5384.89	372.53	373.46	0.25%
Kerosene	424.03	488.96	64.93	65.10	0.26%

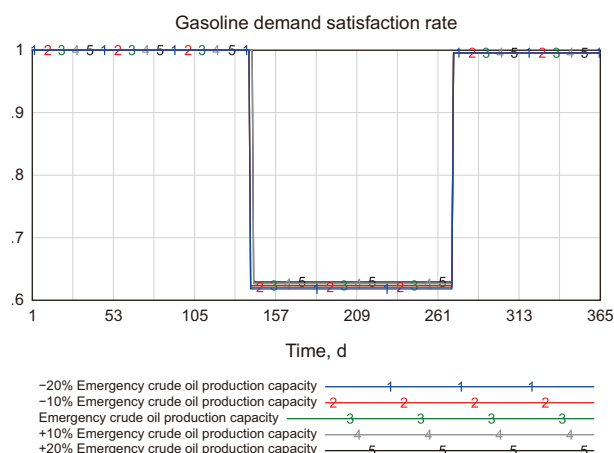


Fig. 7. Sensitivity test results (I).

3.5. Data sources

This study collected reliable statistical data from authoritative sources to parameterize the COSC model. Data on the production, consumption, imports, and exports of crude oil and refined oil were obtained from the *China Energy Statistical Yearbook 2020*, compiled by the Department of Energy Statistics, National Bureau of Statistics. The parameters for geopolitical disruptions were calibrated using China's crude oil import trade data obtained from the United Nations Statistics Division. Initial refined oil inventory levels were estimated based on industry circulation analysis reports published by the Ministry of Commerce of China. Emergency import capacities for refined oil were determined according to the maximum monthly import volumes reported by the General Administration of Customs of China. Price data for crude oil, refined oil, and coal were sourced from the IndexMundi data portal. Coal-to-liquids production capacity was derived from the annual report on coal industry development issued by the China National Coal Association. The 2020 China I-O table was obtained from the National Bureau of Statistics. In addition, official reports issued by the National Energy Administration of China were consulted as supplementary sources.

4. Simulation results under geopolitical disruption scenarios

4.1. Scenario design and parameter settings

4.1.1. Scenario design

This study considers two representative geopolitical disruption scenarios: the Middle East conflict and the Strait of Malacca blockade. In 2020, crude oil imports from the Middle East accounted for 47% of China's total crude oil imports. Accordingly, the disruption parameter for the Middle East scenario is set to 0.470. Similarly, crude oil imports transiting the Strait of Malacca accounted for 73.5% of total crude oil imports, and the disruption parameter for the Strait of Malacca blockade scenario is therefore set to 0.735. In both scenarios, the disruption begins on day 90 and lasts for 180 days. In addition, the sectoral economic output loss coefficients and subsidy intensity coefficients calculated using the I-O model are presented in [Appendix C](#).

In response to the crude oil import shortage caused by geopolitical disruption, this study designs a three-stage emergency recovery strategy, as shown in [Table 2](#). The COSC's emergency response system first activates the baseline response, namely the release of 10% SPR and 10% refined oil inventories. If the baseline response is insufficient to bridge the supply-demand gap, additional single or combined recovery measures are implemented.

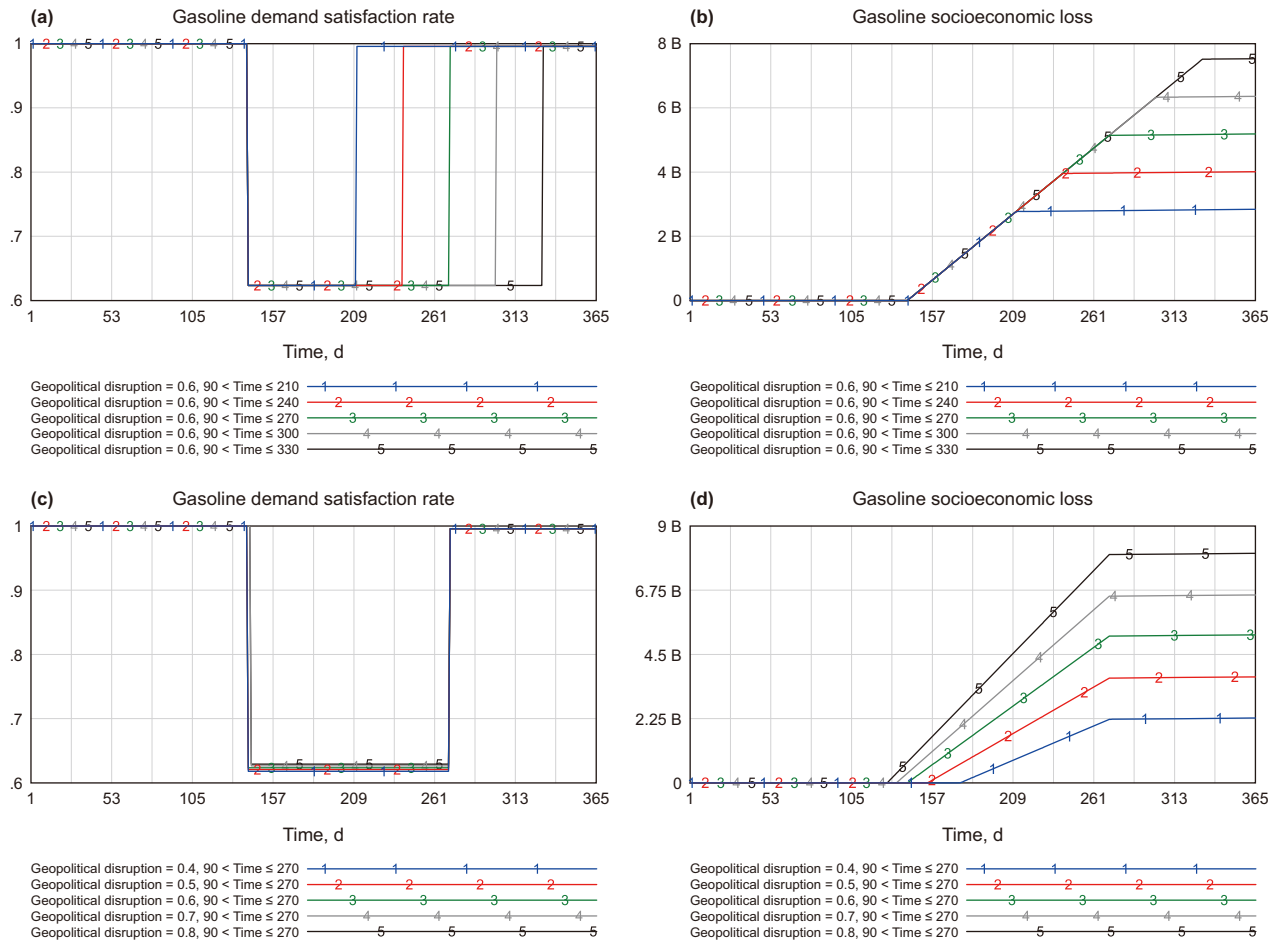


Fig. 8. Sensitivity test results (II).

Table 2

Three-stage emergency recovery strategy under geopolitical disruption scenarios.

Baseline response	Recovery measures	Enhanced response
Release of 10% SPR and 10% refined oil inventories	Emergency crude oil production Emergency crude oil import Coal-to-liquids supply Crude oil export reduction Emergency refined oil import Refined oil export reduction Refined oil consumption compression	Increase the upper bound on refined oil inventory release from 10% to 50%

Upstream recovery measures include emergency crude oil production, emergency crude oil import, coal-to-liquids supply, and crude oil export reduction. Downstream recovery measures include emergency refined oil import, refined oil export reduction, and refined oil consumption compression. If these first two stages still fail to restore the supply-demand balance, an enhanced response is triggered, in which the upper bound on refined oil inventory release is increased from 10% to 50%.

4.1.2. Parameter settings

Under geopolitical disruption scenarios, fluctuations in international crude oil prices may be transmitted to domestic crude oil and refined oil markets (Han et al., 2017; Li et al., 2017), thereby affecting the cost of mobilizing emergency resources. To capture this effect, the scenario-specific external price-shock parameter θ_s is set to 0.25 for the Middle East conflict scenario and 0.35 for the Strait of Malacca blockade scenario. Meanwhile, given the heterogeneity in procurement, transportation, and policy implementation, as well as in

external price sensitivity across different emergency response measures (Balcik et al., 2010), the relevant measures are grouped into four categories: Inventory release, Domestic supply expansion, Import expansion, and Policy adjustment. Accordingly, the additional cost coefficient δ and the price pass-through coefficient λ are specified as category-specific parameters, and the benchmark values along with the assignment criteria are summarized in Table 3. Given the uncertainty associated with the parameters θ_s , λ , and δ , the corresponding sensitivity analysis is presented in Appendix D.

4.2. Geopolitical disruption: the Middle East conflict

4.2.1. Crude oil–gasoline supply chain

Under the Middle East conflict scenario, which results in a 47% crude oil import shortfall lasting 180 days, the baseline response—namely, the release of 10% SPR and 10% gasoline inventory—can delay the onset of gasoline supply-demand imbalance by increasing the amount of crude oil available for refining upstream

Table 3
Benchmark settings for emergency-cost parameters.

Category	Parameter assignment criteria	Emergency measure	δ	λ
Inventory release	Low additional dispatching, storage, coordination, and delivery costs; weak sensitivity to external price shocks.	SPR release; Refined oil inventory release	0.02	0.05
Domestic supply expansion	Moderate additional operating, transportation, and organizational costs; moderate sensitivity to external price shocks.	Emergency crude oil production; Coal-to-liquids supply	0.03	0.10
Import expansion	High exposure to international procurement, shipping, and insurance costs; strong transmission of external price shocks.	Emergency crude oil import; Emergency refined oil import	0.05	0.80
Policy adjustment	Low additional administrative and coordination costs; limited direct price transmission.	Crude oil export reduction; Refined oil export reduction; Refined oil consumption compression	0.01	0.02

and directly supplementing gasoline supply downstream. Specifically, the baseline response postpones the onset of the decline in the gasoline DSR from day 90 to day 154, at an emergency response cost of 1.27×10^9 USD. Although the baseline response can shorten the duration of the supply-demand imbalance in the crude oil–gasoline supply chain, it is insufficient to fully offset the gasoline supply-demand disruption caused by the Middle East conflict scenario, and the resulting gasoline shortage still causes socioeconomic losses of approximately 3.77×10^9 USD. Therefore, second-stage recovery measures need to be implemented on top of the baseline response.

(1) Individual recovery measures

Based on the baseline response, where the minimum gasoline DSR is 0.696 and the shortage onset is delayed to day 154, the gasoline DSR curves under individual recovery measures are shown in Fig. 9. Among the upstream measures, the recovery performance ranks as follows: emergency crude oil import (minimum DSR = 0.738; shortage onset = day 162) > emergency crude oil production (0.725; day 160) > coal-to-liquids supply (0.710; day 156) > crude oil export reduction (0.700; day 154). Among the downstream measures, the ranking is gasoline export reduction (0.784; day 189) > gasoline consumption compression (0.737; day 164) > emergency gasoline import (0.711; day 156). These results indicate that all individual recovery measures can, to varying degrees, delay the onset of gasoline shortages and alleviate the supply-demand imbalance. However, the differences in recovery

performance reflect the distinct intervention mechanisms of upstream and downstream measures. Upstream measures mainly alleviate gasoline shortages at the source by improving refinery feedstock availability and sustaining refining operations. In contrast, downstream measures primarily act on the refined oil market through direct supply supplementation, demand restraint, or export adjustment, and therefore mitigate shortages more directly at the consumption end.

Table 4 further shows that all four upstream recovery measures are economically viable, with IBCR values ranging from 1.37 to 2.31. Although emergency crude oil import delivers a relatively strong recovery effect among the upstream options, it has the lowest IBCR in this group, indicating that its stronger recovery capability is accompanied by relatively high implementation costs. By contrast, the other three upstream measures produce relatively smaller improvements in DSR but yield higher IBCR values, suggesting a more favorable balance between recovery benefit and incremental cost. The downstream measures exhibit a different cost-benefit pattern. Among them, only gasoline consumption compression has an IBCR greater than 1, indicating that demand-side adjustment can serve as a relatively cost-effective supplement to the baseline response. In comparison, gasoline export reduction and emergency gasoline import show IBCR values of only 0.63 and 0.48, respectively. Although gasoline export reduction achieves the highest DSR among the downstream measures, its high implementation cost substantially weakens its cost-effectiveness. Likewise, emergency gasoline import can directly relieve end-use shortages, but its relatively high cost under

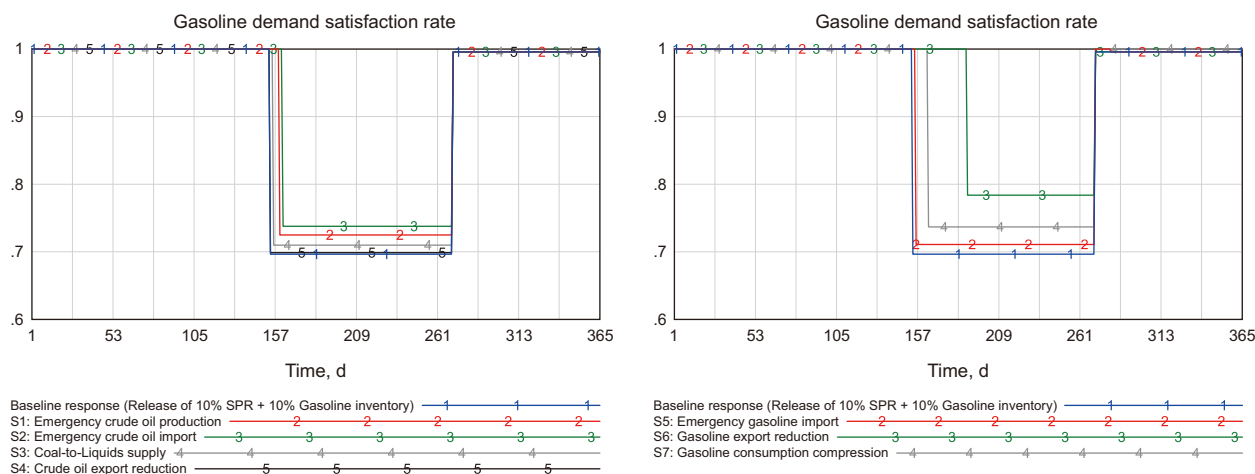


Fig. 9. Gasoline DSR under individual recovery measures.

Table 4
Incremental costs and benefits of individual gasoline recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Gasoline inventory	1.27×10^9	/	3.77×10^9	/	/
S1	Emergency crude oil production	1.57×10^9	3.01×10^8	3.25×10^9	5.23×10^8	1.74
S2	Emergency crude oil import	1.80×10^9	5.31×10^8	3.05×10^9	7.28×10^8	1.37
S3	Coal-to-liquids supply	1.37×10^9	9.75×10^7	3.55×10^9	2.25×10^8	2.31
S4	Crude oil export reduction	1.29×10^9	1.47×10^7	3.75×10^9	2.89×10^7	1.96
S5	Emergency gasoline import	1.78×10^9	5.04×10^8	3.53×10^9	2.43×10^8	0.48
S6	Gasoline export reduction	4.56×10^9	3.29×10^9	1.70×10^9	2.08×10^9	0.63
S7	Gasoline consumption compression	2.04×10^9	7.65×10^8	2.80×10^9	9.79×10^8	1.28

disruption conditions limits its cost-effectiveness. Overall, these results suggest that, under prolonged crude oil import disruptions, upstream recovery measures should be prioritized to ensure gasoline supply security, whereas downstream measures are better regarded as complementary tools for short-term market stabilization.

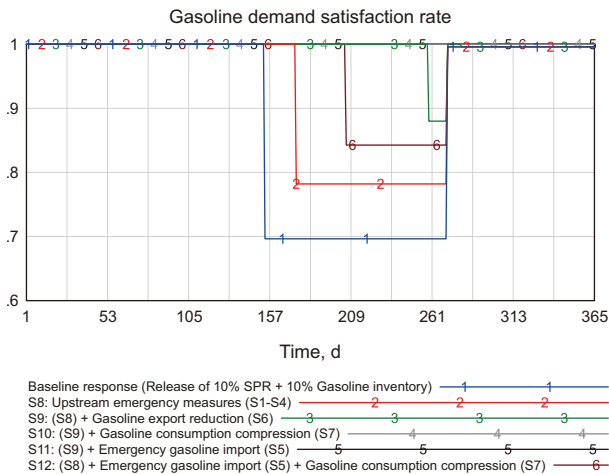
(2) Combined recovery measures

Since no individual recovery measure can fully eliminate the gasoline supply-demand imbalance under a scenario involving a 47% reduction in crude oil imports lasting 180 days, a coordinated response combining upstream and downstream measures across the crude oil–gasoline supply chain is required. Fig. 10 presents the gasoline DSR under different combined recovery measures, and Table 5 reports the corresponding incremental costs, incremental benefits, and IBCRs. Compared with the baseline response, the simultaneous implementation of all upstream recovery measures

raises the minimum gasoline DSR from 0.696 to 0.782 during the crude oil import disruption period and delays the onset of gasoline shortage from day 154 to day 174. Relative to the baseline response, this strategy reduces socioeconomic losses by approximately 1.51×10^9 USD, with an IBCR of 1.58, indicating favorable cost-effectiveness. However, upstream recovery measures alone remain insufficient to fully restore the gasoline supply-demand balance.

When the full set of upstream recovery measures is combined with gasoline export reduction, both the timing and severity of gasoline shortage are further mitigated. This combination postpones the onset of gasoline shortage to day 259. Although it exhibits stronger recovery capability, its IBCR is 0.83, indicating relatively weak cost-effectiveness. When this strategy is further combined with gasoline consumption compression or emergency gasoline import, both resulting combinations can fully eliminate the gasoline supply-demand gap caused by a 47% crude oil import disruption lasting 180 days. However, the IBCRs of both strategies are below 1, suggesting that complete recovery is achieved at the expense of disproportionate incremental costs.

Given that emergency gasoline import exhibits weaker stand-alone recovery performance than gasoline consumption compression and gasoline export reduction, an additional combination was examined by adding emergency gasoline import to the upstream recovery measures and gasoline consumption compression. Compared with the baseline response, this combined strategy reduces socioeconomic losses by approximately 2.76×10^9 USD, with an incremental response cost of about 2.30×10^9 USD, resulting in an IBCR of 1.20. However, its recovery capability remains limited, with a minimum gasoline DSR of 0.843 and the onset of gasoline shortage delayed only to day 206. Overall, both the combination of upstream recovery measures with gasoline export reduction and gasoline consumption compression and the combination of upstream recovery measures with gasoline export reduction and emergency gasoline import can fully eliminate the gasoline supply-demand imbalance under the Middle East conflict scenario. However, the former exhibits better cost-effectiveness and should therefore be prioritized when complete recovery is required.

**Fig. 10.** Gasoline DSR under combined recovery measures.**Table 5**
Incremental costs and benefits of combined gasoline recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Gasoline inventory	1.27×10^9	/	3.77×10^9	/	/
S8	Upstream emergency measures (S1-S4)	2.23×10^9	9.54×10^8	2.27×10^9	1.51×10^9	1.58
S9	(S8) + Gasoline export reduction (S6)	5.60×10^9	4.33×10^9	1.73×10^8	3.60×10^9	0.83
S10	(S9) + Gasoline consumption compression (S7)	5.78×10^9	4.51×10^9	0	3.77×10^9	0.84
S11	(S9) + Emergency gasoline import (S5)	6.07×10^9	4.80×10^9	0	3.77×10^9	0.79
S12	(S8) + Gasoline consumption compression (S7) + Emergency gasoline import (S5)	3.57×10^9	2.30×10^9	1.02×10^9	2.76×10^9	1.20

4.2.2. Crude oil–diesel supply chain

Under the Middle East conflict scenario, a 47% crude oil import shortfall lasting 180 days also disrupts the crude oil–diesel supply chain. The baseline response, consisting of the release of 10% SPR and 10% diesel inventory, postpones the onset of diesel shortage from day 90 to day 171, with an associated emergency response cost of 2.26×10^9 USD. Despite this delaying effect, the baseline response does not fully restore the diesel supply–demand balance under the disruption scenario. Diesel shortage therefore persists and results in socioeconomic losses of approximately 4.16×10^9 USD. These results indicate that the baseline response can only partially buffer the disruption, making the implementation of second-stage recovery measures necessary.

(1) Individual recovery measures

Fig. 11 presents the diesel DSR under individual recovery measures in the Middle East conflict scenario, based on the baseline response, where the minimum DSR is 0.717 and the shortage onset is delayed to day 171. Among the upstream individual recovery measures, the recovery performance ranks as follows: emergency crude oil import (minimum DSR = 0.759; shortage onset = day 183) > emergency crude oil production (0.746; day 180) > coal-to-liquids supply (0.731; day 174) > crude oil export reduction (0.719; day 171). Compared with the minimum diesel DSR of 0.717 under the baseline response, all of these measures improve diesel supply security to varying degrees. Given China's relatively limited crude oil exports, crude oil export reduction exhibits only a modest recovery effect. By contrast, measures that expand crude oil supply can provide additional feedstock for refineries and

therefore play a more significant role in alleviating the downstream diesel supply–demand imbalance. The ranking of downstream recovery performance is as follows: diesel export reduction (0.818; day 231) > diesel consumption compression (0.764; day 189) > emergency diesel import (0.737; day 176). This ranking is closely related to China's position as a major producer, consumer, and exporter of diesel. Accordingly, policy-based regulation of diesel exports and domestic consumption can serve as an effective means of mitigating diesel shortages caused by crude oil import disruptions.

Table 6 summarizes the costs, incremental costs, socioeconomic losses, incremental benefits, and IBCRs of these individual recovery measures relative to the baseline response. Among the upstream recovery measures, emergency crude oil production, coal-to-liquids supply, and crude oil export reduction all have IBCR values greater than 2, indicating that, although their contributions to improving diesel supply–demand balance are relatively limited, they outperform emergency crude oil import in terms of cost–benefit performance, as the latter has an IBCR of 1.66. By contrast, all downstream individual recovery measures have IBCR values below 1, indicating relatively high response costs but limited loss reduction. Among them, emergency diesel import has an IBCR of 0.66, showing relatively weak performance in both recovery capability and economic efficiency. The IBCR values of diesel consumption compression and diesel export reduction are 0.97 and 0.83, respectively. These results suggest that, under prolonged crude oil import disruptions, upstream recovery measures should be prioritized. Meanwhile, among the downstream options, diesel consumption compression and diesel export reduction should be given priority over emergency diesel import.

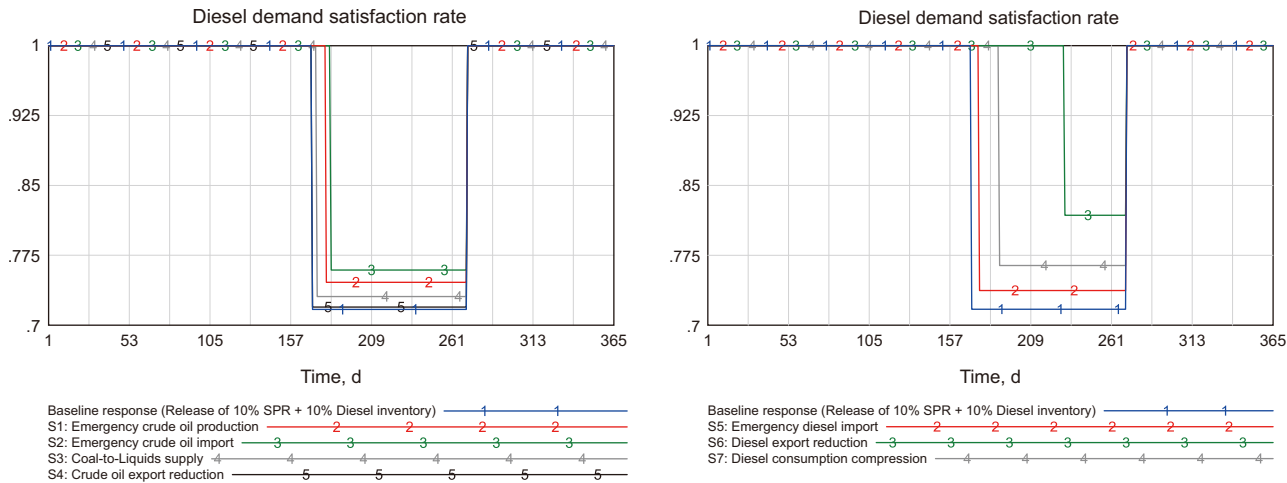


Fig. 11. Diesel DSR under individual recovery measures.

Table 6
Incremental costs and benefits of individual diesel recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Diesel inventory	2.26×10^9	/	4.16×10^9	/	/
S1	Emergency crude oil production	2.63×10^9	3.70×10^8	3.40×10^9	7.63×10^8	2.06
S2	Emergency crude oil import	2.89×10^9	6.30×10^8	3.11×10^9	1.04×10^9	1.66
S3	Coal-to-liquids supply	2.37×10^9	1.10×10^8	3.84×10^9	3.20×10^8	2.90
S4	Crude oil export reduction	2.27×10^9	9.85×10^6	4.12×10^9	3.54×10^7	3.59
S5	Emergency diesel import	3.01×10^9	7.46×10^8	3.67×10^9	4.90×10^8	0.66
S6	Diesel export reduction	6.14×10^9	3.88×10^9	9.38×10^8	3.22×10^9	0.83
S7	Diesel consumption compression	3.80×10^9	1.54×10^9	2.67×10^9	1.49×10^9	0.97

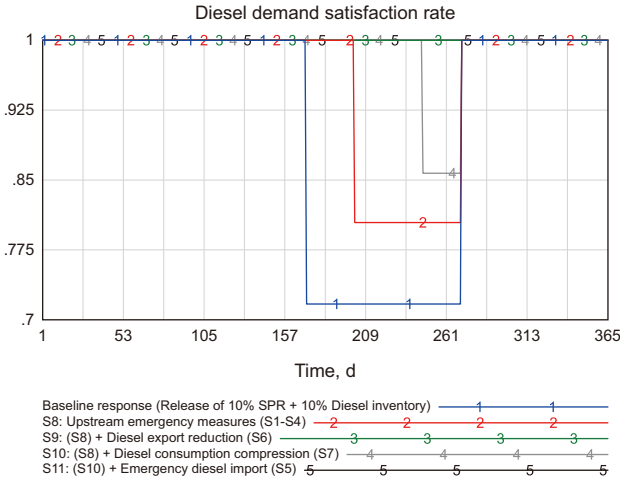


Fig. 12. Diesel DSR under combined recovery measures.

(2) Combined recovery measures

Based on the recovery performance and incremental benefit-cost results of the individual measures along the crude oil–diesel supply chain, Fig. 12 and Table 7 present the dynamic changes in the diesel DSR and the corresponding IBCRs under different combinations of recovery measures. When all upstream recovery measures are implemented on top of the baseline response, the onset of diesel shortage is postponed to day 202 in the Middle East conflict scenario, and the minimum diesel DSR rises from 0.717 to 0.804. Compared with the baseline response, this combination reduces socioeconomic losses by approximately 2.17×10^9 USD, with an IBCR of 1.90, indicating strong economic viability. However, upstream recovery measures alone are still insufficient to fully offset the diesel supply shortfall, making it necessary to further combine them with downstream measures.

When the upstream recovery measures are further combined separately with diesel export reduction and diesel consumption compression, both the onset timing and the severity of diesel shortage are substantially improved. Relative to the baseline response, these two combined strategies reduce socioeconomic losses by approximately 4.16×10^9 USD and 3.67×10^9 USD, respectively, with corresponding IBCRs of 1.02 and 1.34. These results indicate that both strategies remain economically viable. Although the cost-effectiveness of the combination involving diesel export reduction is comparatively weaker, this strategy can fully eliminate the diesel supply-demand gap caused by a 47% crude oil import disruption lasting 180 days. Since emergency diesel import exhibits weaker recovery performance than diesel consumption compression and diesel export reduction when implemented individually, an additional combination was examined by adding emergency diesel import to the upstream recovery

measures and diesel consumption compression. The results show that this combined strategy can also maintain the diesel DSR at unity throughout the simulated period of the Middle East conflict scenario. Its IBCR is 1.18, which is higher than that of the combination involving diesel export reduction. Overall, although both the combination of upstream recovery measures with diesel export reduction and the combination of upstream measures, diesel consumption compression, and emergency diesel import can fully eliminate the diesel supply-demand imbalance under the Middle East conflict scenario, the latter is more cost-effective and should therefore be prioritized in responding to prolonged crude oil import disruptions in the crude oil–diesel supply chain.

4.2.3. Crude oil–kerosene supply chain

Under the Middle East conflict scenario, the baseline response provides a certain degree of buffering capacity to the crude oil–kerosene supply chain. Through the coordinated release of 10% of the SPR and 10% of the kerosene inventory, refinery feedstock availability upstream and market supply downstream can both be supported, thereby alleviating the kerosene supply-demand gap to some extent. As a result, the onset of kerosene shortage is postponed from day 90 to day 141, at an emergency response cost of 2.52×10^8 USD. Nevertheless, this baseline response does not fully eliminate the kerosene supply-demand imbalance caused by the Middle East conflict scenario, and the remaining shortage still leads to socioeconomic losses of approximately 1.80×10^9 USD. This indicates that the baseline response mainly plays a delaying and buffering role, and that second-stage recovery measures are still required to further restore supply security in the crude oil–kerosene supply chain.

(1) Individual recovery measures

Fig. 13 shows the kerosene DSR under individual upstream and downstream recovery measures implemented on top of the baseline response. Under the baseline response, the minimum DSR is 0.742 and the onset of kerosene shortage is delayed to day 141. In terms of minimum DSR, the upstream individual recovery measures rank as follows: emergency crude oil import (minimum DSR = 0.780; shortage onset = day 148) > emergency crude oil production (0.768; day 147) > coal-to-liquids supply (0.754; day 143) > crude oil export reduction (0.744; day 146). Compared with the baseline response, these upstream measures can, to varying degrees, delay the onset of kerosene shortages and alleviate the kerosene supply-demand imbalance. However, given the limited scope for expanding domestic crude oil production, emergency crude oil import remains the most effective upstream option for addressing crude oil import shortages triggered by the Middle East conflict.

By contrast, the downstream individual recovery measures exhibit stronger recovery performance, ranking as follows: kerosene export reduction (minimum DSR = 1.00) > emergency kerosene import (0.862; day 177) > kerosene consumption compression (0.796; day 154). This result indicates that direct adjustment of

Table 7
Incremental costs and benefits of combined diesel recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Diesel inventory	2.26×10^9	/	4.16×10^9	/	/
S8	Upstream emergency measures (S1-S4)	3.41×10^9	1.15×10^9	1.98×10^9	2.17×10^9	1.90
S9	(S8) + Diesel export reduction (S6)	6.35×10^9	4.08×10^9	0	4.16×10^9	1.02
S10	(S8) + Diesel consumption compression (S7)	5.01×10^9	2.75×10^9	4.92×10^8	3.67×10^9	1.34
S11	(S10) + Emergency diesel import (S5)	5.78×10^9	3.51×10^9	0	4.16×10^9	1.18

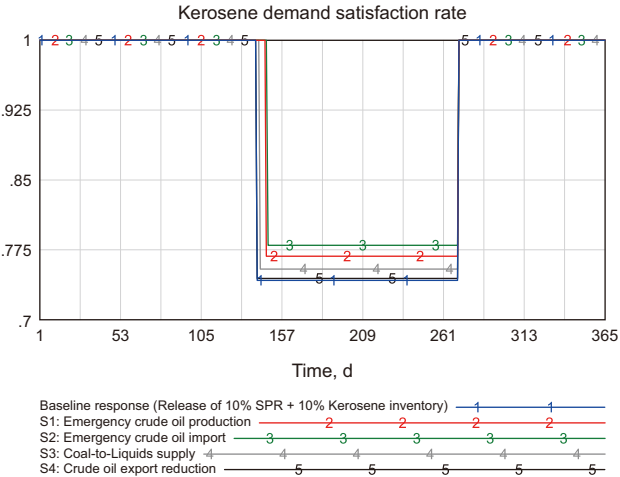


Fig. 13. Kerosene DSR under individual recovery measures.

supply and demand in the downstream kerosene market can more effectively mitigate the impact of upstream crude oil supply shortages. Notably, kerosene export reduction alone is sufficient to offset the kerosene supply shortfall caused by a 47% crude oil import disruption. This is closely related to China's kerosene market structure during the study period: kerosene consumption reached 33.521 million tonnes, while kerosene exports amounted to 12.263 million tonnes, equivalent to 36.58% of domestic consumption. Therefore, policy-based regulation of kerosene exports to prioritize domestic supply can substantially relieve kerosene supply pressure under crude oil import disruption.

The incremental costs, incremental benefits, and IBCRs of each individual recovery measure relative to the baseline response are summarized in Table 8. Specifically, among the upstream measures, emergency crude oil import has an IBCR of 2.18, which is the lowest among the upstream options but still exceeds the highest value among the downstream measures, namely the IBCR of kerosene consumption compression. This suggests that, although the upstream individual measures are less effective than the downstream measures in directly balancing kerosene supply and demand, they are generally more cost-effective. Taken together, the recovery performance and incremental benefit-cost analysis indicate that, under a scenario involving a 47% crude oil import disruption lasting 180 days, recovery strategies for the crude oil–kerosene supply chain should strike a balance between recovery effectiveness and economic performance through an appropriate combination of selected upstream and downstream recovery measures.

(2) Combined recovery measures

Although kerosene export reduction alone can eliminate the kerosene supply-demand imbalance under the Middle East conflict scenario, its cost-effectiveness is weaker than that of most

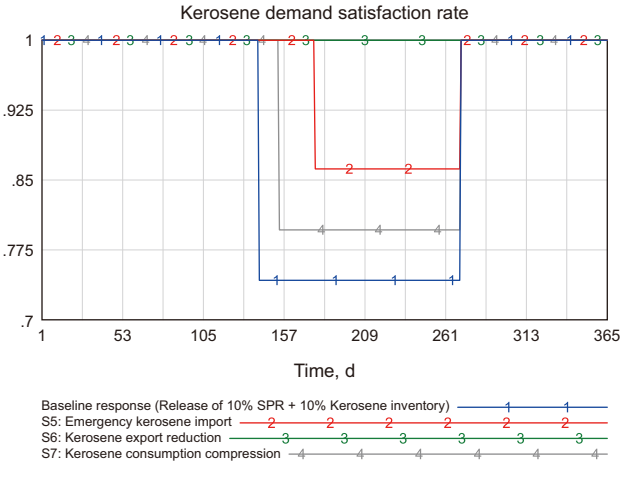


Fig. 14. Kerosene DSR under combined recovery measures.

other individual recovery measures. Therefore, Fig. 14 and Table 9 present the changes in kerosene DSR, incremental costs, and incremental benefits under different combinations of upstream and downstream recovery measures in the crude oil–kerosene supply chain.

Compared with the baseline response, the implementation of all upstream recovery measures postpones the onset of kerosene supply shortage from day 141 to day 158 and increases the minimum kerosene DSR from 0.742 to 0.819. In addition, this combination reduces socioeconomic losses by approximately 7.09×10^8 USD, with an IBCR of 2.51, indicating strong economic viability. To further offset the kerosene supply-demand imbalance caused by a

Table 8
Incremental costs and benefits of individual kerosene recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Kerosene inventory	2.52×10^8	/	1.80×10^9	/	/
S1	Emergency crude oil production	3.46×10^8	9.45×10^7	1.55×10^9	2.56×10^8	2.71
S2	Emergency crude oil import	4.10×10^8	1.58×10^8	1.46×10^9	3.46×10^8	2.18
S3	Coal-to-liquids supply	2.84×10^8	3.20×10^7	1.69×10^9	1.12×10^8	3.48
S4	Crude oil export reduction	2.57×10^8	5.11×10^6	1.79×10^9	1.50×10^7	2.93
S5	Emergency kerosene import	1.37×10^9	1.12×10^9	6.99×10^8	1.11×10^9	0.99
S6	Kerosene export reduction	1.98×10^9	1.73×10^9	0	1.80×10^9	1.05
S7	Kerosene consumption compression	7.87×10^8	5.35×10^8	1.19×10^9	6.10×10^8	1.14

Table 9
Incremental costs and benefits of combined kerosene recovery measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Kerosene inventory	2.52×10^8	/	1.80×10^9	/	/
S8	Upstream emergency measures (S1–S4)	5.35×10^8	2.83×10^8	1.10×10^9	7.09×10^8	2.51
S9	(S8) + Kerosene consumption compression (S7)	1.09×10^9	8.34×10^8	4.82×10^8	1.32×10^9	1.59
S10	(S8) + Emergency kerosene import (S5)	1.67×10^9	1.42×10^9	0	1.80×10^9	1.27

47% crude oil import disruption lasting 180 days, all upstream recovery measures are then separately combined with kerosene consumption compression and emergency kerosene import. The results show that both combinations can further improve the kerosene DSR. Their total emergency response costs are approximately 1.09×10^9 USD and 1.67×10^9 USD, respectively, while their corresponding incremental costs relative to the baseline response are 8.34×10^8 USD and 1.42×10^9 USD. The corresponding IBCRs are 1.59 and 1.27, indicating that both combinations remain economically viable. Notably, all upstream recovery measures combined with emergency kerosene import can maintain the kerosene DSR at 1 throughout the simulated period under the Middle East conflict scenario. Its IBCR is also higher than that of kerosene export reduction alone. This suggests that the coordinated combination provides a slightly more favorable balance between complete recovery and cost-effectiveness for the crude oil–kerosene supply chain under a prolonged crude oil import disruption.

4.3. Geopolitical disruption: the Strait of Malacca blockade

4.3.1. Crude oil–gasoline supply chain

Compared with the Middle East conflict scenario, the Strait of Malacca blockade scenario causes a much more severe disruption to China's COSC, corresponding to a 73.5% crude oil import shortfall lasting 180 days. Meanwhile, external price shocks further increase the costs of emergency measures to varying degrees. Fig. 15 and Table 10 present the gasoline DSR, incremental costs, and incremental benefits associated with the three-stage emergency strategy for the crude oil–gasoline supply chain under the Strait of Malacca blockade scenario.

Under the baseline response, which consists of releasing 10% SPR and 10% gasoline inventory, the emergency response cost is approximately 1.32×10^9 USD, while the resulting socioeconomic loss reaches approximately 7.60×10^9 USD. When the

combined recovery measures previously identified in the Middle East conflict scenario—namely, upstream recovery measures, gasoline export reduction, and gasoline consumption compression—are applied, the second-stage strategy delays the onset of the gasoline shortage from day 130 under the baseline response to day 155 and raises the minimum gasoline DSR from 0.490 to 0.665. Nevertheless, the two-stage emergency strategy remains insufficient to fully eliminate the downstream gasoline supply-demand gap caused by the Malacca blockade, leaving a residual socioeconomic loss of 3.40×10^9 USD. Since China's gasoline imports in 2020 were only 0.48 million tonnes, and the Strait of Malacca blockade would substantially intensify international gasoline price shocks, adding emergency gasoline import to the above combination yields only a limited improvement in gasoline DSR. At the same time, the IBCR of the combined strategy decreases from 0.90 to 0.86. Therefore, a third-stage enhanced response is required.

Building upon the two-stage strategy, the upper limit of gasoline inventory release is further increased to 39%. Under this enhanced response, the gasoline DSR can be maintained at unity throughout the disruption period in the Malacca blockade scenario, and the socioeconomic loss is fully eliminated. Compared with the baseline response, this enhanced strategy yields an IBCR of 0.99, which is higher than the 0.86 obtained under the second-stage strategy. This improvement can be mainly attributed to the relatively weak pass-through of external price shocks to inventory release measures.

4.3.2. Crude oil–diesel supply chain

To evaluate the effectiveness of emergency responses to the diesel supply-demand imbalance caused by the Strait of Malacca blockade, Fig. 16 presents the diesel DSR under the three-stage emergency strategy, while Table 11 reports the corresponding costs, incremental costs, socioeconomic losses, incremental benefits, and IBCRs for the crude oil–diesel supply chain. Drawing on the recovery-measure combinations identified under the Middle East conflict scenario, the combination of all upstream recovery measures, diesel consumption compression, and emergency diesel import substantially improves diesel supply security relative to the baseline response. Specifically, the onset of diesel supply-demand imbalance is delayed from day 138 to day 153, and the minimum diesel DSR increases from 0.506 to 0.631. In addition, this combined strategy reduces socioeconomic losses by approximately 3.66×10^9 USD relative to the baseline response, with an IBCR of 1.18, indicating favorable cost-effectiveness. To further strengthen the emergency response, two alternative combinations were examined. The first combines all upstream recovery measures with diesel export reduction and emergency diesel import, while the second combines all upstream recovery measures with diesel export reduction and diesel consumption compression. The results show that both strategies further mitigate the diesel supply-demand imbalance caused by the Malacca blockade, but still leave residual socioeconomic losses of approximately 4.26×10^9 USD and 3.28×10^9 USD, respectively. To further alleviate the adverse effect of crude oil import shortages on diesel supply, all second-stage recovery measures in the crude oil–diesel supply

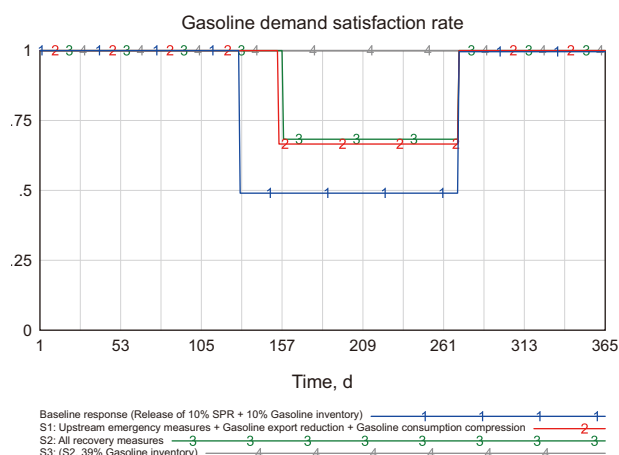
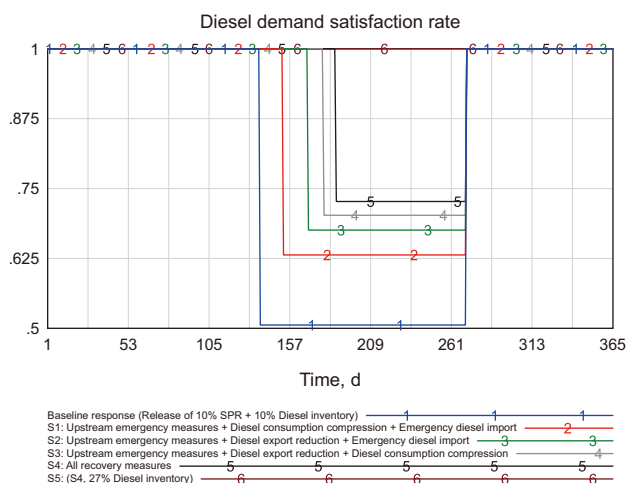
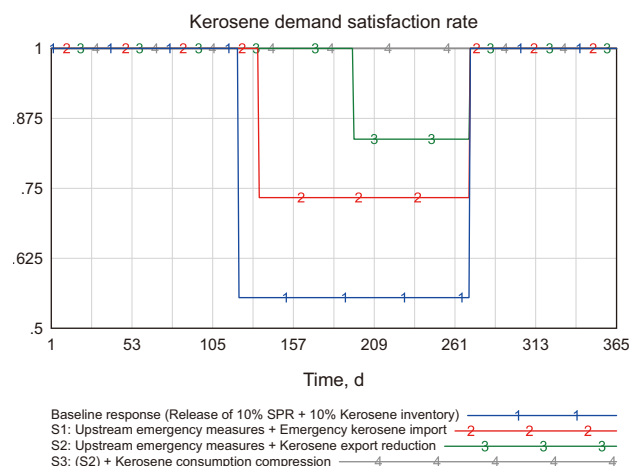


Fig. 15. Gasoline DSR under combined emergency measures.

Table 10
Incremental costs and benefits of combined gasoline emergency measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% gasoline inventory	1.32×10^9	/	7.60×10^9	/	/
S1	Upstream emergency measures + Gasoline export reduction + Gasoline consumption compression	5.97×10^9	4.66×10^9	3.40×10^9	4.20×10^9	0.90
S2	All recovery measures	6.52×10^9	5.21×10^9	3.14×10^9	4.46×10^9	0.86
S3	(S2, 39% Gasoline inventory)	9.00×10^9	7.69×10^9	0	7.60×10^9	0.99

**Fig. 16.** Diesel DSR under combined emergency measures.**Fig. 17.** Kerosene DSR under combined emergency measures.

chain were then implemented simultaneously. Under this strategy, the diesel DSR remains at 0.727 from day 187 to day 270, and the IBCR is 1.01. The limited improvement in economic performance is mainly attributable to the constrained emergency diesel import capacity and the substantial increase in import costs under external price shocks.

Since the first two stages of emergency response remain insufficient to fully offset the impact of a 73.5% crude oil import disruption lasting 180 days, a third-stage enhanced response is required. Under this response, the upper limit of diesel inventory release is further increased to 27%, the impact of the Malacca blockade on the crude oil–diesel supply chain is fully eliminated, and the diesel DSR remains at unity throughout the disruption period. Moreover, this enhanced measure in the third stage is less sensitive to external price shocks, and its IBCR value is 1.04, indicating favorable cost-effectiveness.

Table 11
Incremental costs and benefits of combined diesel emergency measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Diesel inventory	2.27×10^9	/	9.66×10^9	/	/
S1	Upstream emergency measures + Diesel consumption compression + Emergency diesel import	5.37×10^9	3.10×10^9	6.00×10^9	3.66×10^9	1.18
S2	Upstream emergency measures + Diesel export reduction + Emergency diesel import	7.65×10^9	5.38×10^9	4.26×10^9	5.40×10^9	1.00
S3	Upstream emergency measures + Diesel export reduction + Diesel consumption compression	8.32×10^9	6.05×10^9	3.28×10^9	6.37×10^9	1.05
S4	All recovery measures	9.13×10^9	6.86×10^9	2.75×10^9	6.91×10^9	1.01
S5	(S4, 27% Diesel inventory)	1.15×10^{10}	9.25×10^9	0	9.66×10^9	1.04

4.3.3. Crude oil–kerosene supply chain

Fig. 17 and Table 12 present the kerosene DSR and the corresponding economic evaluation results for different combinations of recovery measures in the crude oil–kerosene supply chain under the Strait of Malacca blockade scenario. Under the baseline response, which consists of releasing 10% SPR and 10% kerosene inventory, the emergency response cost is 2.66×10^8 USD, while the downstream kerosene supply–demand imbalance results in a socioeconomic loss of approximately 3.57×10^9 USD. Based on the second-stage recovery measure combinations identified under the Middle East conflict scenario, the combination of all upstream emergency measures with downstream emergency kerosene import increases the minimum kerosene DSR from 0.554 to 0.733 relative to the baseline response, while delaying the onset of kerosene supply shortage from day 122 to day 135. By comparison, the combination of all upstream emergency measures with

Table 12
Incremental costs and benefits of combined kerosene emergency measures.

Response	Emergency measure	Cost	Incremental costs	Socioeconomic loss	Incremental benefits	IBCR
Baseline	Release of 10% SPR + 10% Kerosene inventory	2.66×10^8	/	3.57×10^9	/	/
S1	Upstream emergency measures + Emergency kerosene import	1.62×10^9	1.36×10^9	1.95×10^9	1.62×10^9	1.19
S2	Upstream emergency measures + Kerosene export reduction	2.46×10^9	2.20×10^9	4.79×10^8	3.09×10^9	1.41
S3	(S2) + Kerosene consumption compression	2.92×10^9	2.65×10^9	0	3.57×10^9	1.35

downstream kerosene export reduction performs better, maintaining the kerosene DSR at 0.838 from day 196 to day 270. Relative to the baseline response, this strategy reduces socioeconomic loss by approximately 3.09×10^9 USD, with an IBCR of 1.41, indicating favorable cost-effectiveness.

However, neither of the above recovery-measure combinations is sufficient to fully offset the kerosene supply-demand imbalance caused by a 73.5% crude oil import shortfall lasting 180 days. Among the downstream individual recovery measures, kerosene consumption compression exhibits weaker recovery performance than kerosene export reduction and emergency kerosene import, but it delivers the best incremental cost-effectiveness. Therefore, a further combination is examined by adding kerosene consumption compression to the strategy combining all upstream emergency measures with kerosene export reduction. The results show that this combined strategy can fully restore the kerosene supply-demand balance under the Malacca blockade scenario. Specifically, it reduces the socioeconomic loss to zero and yields an IBCR of 1.35, demonstrating economic feasibility.

5. Discussion

5.1. Comparison with other literature

In studies of energy system resilience, recovery strategies for external shocks are typically designed from both supply-side and the demand-side perspectives. Unlike previous studies focusing on a single energy carrier, such as natural gas (Ding et al., 2022), this study investigates the resilience of China's COSC by designing distinct sets of emergency measures for the upstream crude oil supply subsystem and the downstream refined oil consumption subsystem. Scenario simulations and recovery capacity assessments demonstrate that, when confronted with crude oil import disruptions, gasoline, kerosene, and diesel each require different combinations of emergency measures to restore supply-demand balance. This finding extends and refines the perspective advanced by Chen et al. (2020) on the resilience of China's oil import system under external shocks, and reveals heterogeneity across fuel types in both emergency response and supply flexibility during import interruptions. Furthermore, energy system resilience is often achieved through multiple feasible recovery pathways, yet the prioritization among these alternatives has received limited attention. To address this gap, we introduce a coupled SD and I-O model and use the IBCR to quantify the relative economic performance of different recovery measure combinations. This provides a quantitative basis for decision-makers to identify relatively cost-effective recovery strategies under resource constraints.

Methodologically, existing studies (Qian et al., 2023; Wu et al., 2018) have applied a supply-driven I-O model to estimate the economic impacts of power or gas shortages. These studies commonly adopt a 'value-added invariant ($\Delta V = 0$)' assumption, treating sectoral factor incomes (e.g., wages, profits, net

production taxes) as exogenous and unchanged during short-term shocks. This assumption simplifies the computation of intermediate output losses by decoupling intermediate inputs from value-added components. However, from an economic mechanism perspective, output reductions are typically accompanied by declines in value added. Hence, the $\Delta V = 0$ assumption can underestimate the true socioeconomic costs of supply shortages. To address this shortcoming, we incorporate value-added losses into the accounting framework by treating them as fiscal subsidies. Our approach retains the conventional measurement of intermediate-sector losses caused by refined oil shortages while making explicit the fiscal cost required to sustain constant value added as a policy intervention. Therefore, this extension provides a more comprehensive and accurate estimate of the socioeconomic losses triggered by downstream refined oil supply disruptions.

5.2. Limitations and future research

This study dynamically simulates the recovery performance and cost-effectiveness of emergency responses in the COSC, thereby enriching the literature on energy system resilience. However, several limitations should be acknowledged. First, data availability constrained our analysis. Many model inputs were inferred from annual and monthly statistics to generate daily time series, which may not fully capture high-frequency dynamics and short-term volatility in energy systems. Future work should prioritize obtaining higher-frequency operational data through partnerships with industry and regulators to improve model calibration and enhance the robustness of the results. Second, this study focuses on China's COSC and does not include broad cross-country comparative analysis. This scope limitation may restrict the external validity and policy applicability of the findings. Future research could extend the proposed framework to other countries or regions to examine its applicability under different institutional, market, and energy supply conditions. Third, the supply-driven I-O model adopted in this study is inherently static and assumes fixed input-output coefficients during disruption and recovery processes. As a result, it does not explicitly capture longer-term structural adjustments such as input substitution, adaptive sectoral responses, and price feedbacks, which may introduce bias into the estimation of economic losses and the cost-benefit evaluation of recovery measures, especially under prolonged disruptions. Future research could address this limitation by incorporating dynamic input-output relationships, sectoral adaptation mechanisms, and price transmission effects into the analytical framework.

6. Conclusions and policy implications

As a major crude oil consumer that is highly dependent on external markets, the resilience of China's COSC is crucial to national energy security. This study develops a resilience assessment framework based on DSR and IBCR, and constructs

an SD model coupled with an I-O model to characterize the dynamic processes of disruption transmission and resilience response in the COSC under geopolitical shocks. Based on a three-stage emergency recovery framework, this study identifies and prioritizes response strategies for gasoline, diesel, and kerosene under two representative disruption scenarios, namely the Middle East conflict and the Strait of Malacca blockade, with the aim of supporting more effective emergency decision-making by improving supply-demand balance and recovery efficiency in the COSC. The key findings are summarized as follows.

- (1) The coordinated release of 10% SPR and 10% refined oil inventories constitutes a practical first-stage response, but its recovery capacity is limited under severe crude oil import disruptions. Under the Middle East conflict scenario, involving a 47% crude oil import shortfall lasting 180 days, this baseline response can delay shortage onset and partially mitigate supply-demand imbalances across the gasoline, diesel, and kerosene supply chains. However, the second-stage individual recovery measures exhibit substantial heterogeneity across products. Overall, upstream measures are generally more cost-effective and should be prioritized in responding to crude oil import disruptions. For gasoline and diesel, export reduction delivers the strongest downstream recovery effect, whereas consumption compression performs better in terms of cost-effectiveness. In contrast, the crude oil–kerosene supply chain is more responsive to downstream intervention, and kerosene export reduction alone is sufficient to eliminate the kerosene supply-demand imbalance under the Middle East conflict scenario.
- (2) When individual recovery measures are insufficient under the Middle East conflict scenario, coordinated upstream-downstream combinations become necessary. For the crude oil–gasoline supply chain, full recovery can be achieved either through upstream recovery measures combined with gasoline export reduction and gasoline consumption compression or through upstream recovery measures combined with gasoline export reduction and emergency gasoline import. Among these, the former should be prioritized because of its superior cost-effectiveness. For the crude oil–diesel supply chain, both the combination of upstream recovery measures with diesel export reduction and the combination of upstream recovery measures with diesel consumption compression and emergency diesel import can achieve full recovery, while the latter offers better economic performance and should therefore be preferred. For the crude oil–kerosene supply chain, the combination of all upstream recovery measures with emergency kerosene import can maintain the kerosene DSR at unity throughout the Middle East conflict scenario, and its IBCR is higher than that of kerosene export reduction alone.
- (3) Under the Strait of Malacca blockade scenario, involving a 73.5% crude oil import shortfall lasting 180 days, the COSC is exposed to a much more severe shock. For the crude oil–gasoline and crude oil–diesel supply chains, second-stage responses remain insufficient, and third-stage enhanced responses are required to achieve full recovery. Specifically, full restoration is achieved only when the upper limit of gasoline inventory release is increased to 39% and that of diesel inventory release is raised to 27%.

Because inventory release measures are less sensitive to external price shocks, these third-stage responses still exhibit relatively favorable cost-effectiveness. By contrast, the crude oil–kerosene supply chain can restore supply-demand balance through a more targeted second-stage combination, and the combination of upstream emergency measures, kerosene export reduction, and kerosene consumption compression shows favorable economic feasibility.

Considering these conclusions, the following policy recommendations are proposed.

- (1) Upstream supply-enhancing measures should be prioritized in the early stages of emergency response, and reserve governance should be strengthened to enable flexible escalation. China should improve its emergency crude oil import capacity, domestic emergency production capability, coal-to-liquids supply capacity, and the coordination mechanism for crude oil export reduction. In addition, beyond the SPR, commercial and enterprise inventories should be incorporated into an integrated reserve system with clearly defined trigger conditions, release priorities, and adjustable release caps, so that inventory release can be rapidly scaled up from routine levels to higher emergency levels when severe disruptions occur.
- (2) Emergency planning should differentiate among gasoline, diesel, and kerosene with respect to response priorities, sequencing, and resource allocation. For both gasoline and diesel, responses to prolonged geopolitical disruptions should center on measures that secure upstream crude oil supply for refining, while prioritizing downstream export reduction and consumption compression. When even the full set of recovery measures is insufficient to sustain normal supply chain functioning, expanded inventory release should be adopted as a strengthened response. Although gasoline and diesel share broadly similar response pathways, the cost-effectiveness of their respective emergency measure combinations differs and should therefore be assessed on a case-by-case basis. For kerosene, downstream measures should be prioritized. Export reduction may serve as the first-line response under crude oil import disruptions, whereas emergency import, particularly when coordinated with upstream measures, should be considered when higher recovery effectiveness and economic performance are required.
- (3) China should strengthen import-source diversification and maritime transport resilience, while also developing a real-time risk early-warning and emergency decision-support platform. Given the substantially stronger shock posed by a blockade of the Strait of Malacca, China should reduce excessive dependence on specific maritime routes and import regions by diversifying crude oil import sources, deepening cooperation with politically stable suppliers, and improving alternative shipping arrangements. At the same time, a real-time platform integrating trade, shipping, refining, inventory, and consumption data into the SD and I-O analytical framework should be established to support dynamic disruption assessment, comparison of the cost-effectiveness of alternative response options, and rapid selection of prioritized emergency strategies.

CRediT authorship contribution statement

Jing-Ye Liu: Writing – original draft, Data curation. **Shuang-Shuang Long:** Visualization, Software. **Feng-Qi Guo:** Writing – review & editing, Software, Methodology. **Huan-Huan He:** Supervision, Formal analysis, Conceptualization. **Ri-Jia Ding:** Resources, Project administration, Investigation.

Declaration of competing interests

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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Supplementary data

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