Analysis of Vulnerability and Recoverability of the Energy System in China Based On Inoperability Input-Output Model and a Dynamic Extension

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Abstract. In this paper, the Inoperability Input-Output Model (IIM) is used to simulate the degree of functional decline of the energy sectors under the perturbation of demand and supply. The Dynamic Inoperability Input-Output Model (DIIM) is used to simulate the time-varying operation state of the energy sectors. The paper then performs some case study that utilizes accounts from 2012 Input-Output Tables of China. The vulnerability and recoverability of energy system are analyzed by using relevant indicators in order to manage and develop the energy system.

1. Introduction
When a sector of the energy system is disturbed or unexpectedly damaged, it cannot operate well and its inability to quickly resume operation following a disruptive event can result in further inoperability in many other sectors. This is not conducive to the sustainable development of energy and even threatens the country's energy security. Therefore, in order to manage and develop the energy system, it’s useful to study the vulnerability and recoverability of the energy system and focus on the most impacted sectors and discuss the corresponding strategies and measures.

IIM has been proved to be applicable in practice and there is some extension to the IIM. Barker K and Santos J R pay attention to the key sectors that have small energy consumption but have great impact on economic development based on the inventory dynamic inoperability input-output model [1]. KDS Yu, et al develop an optimization model which includes a vulnerability measure to study electricity shortage in the Philippine and it is approved by GDP in Philippine [2]. Ali Niknejad and Dobrila Petrovic develop a novel Fuzzy Dynamic Inoperability Input-Output Model (Fuzzy DIIM) for risk evaluation of Global Production Networks [3]. Kuznetsova E, et al use IIM to study Eco-Industrial Park and the results provide guidance for establishing measures of resilience to disruptive events [4]. He P, et al develop a new linear programming to guide decision-makers to improve the energy resilience [5]. Santos and Haimes offer a framework for describing how terrorism-induced perturbations can propagate due to interconnectedness [6].

Vulnerability is the manifestation of the inherent states of the system (e.g., physical, technical, organizational) that can be exploited to adversely affect (cause harm or damage to) that system [7]. This paper uses the term inoperability and economic loss to measure the vulnerability of the energy system. The term inoperability connotes the level of a system’s dysfunction expressed as a percentage of its “as-
planned” production capacity [8]. The recoverability is measured by the degree and time back to the normal operation.

This paper is organized as follow: (1) introduction of the Inoperability Input-Output Model (IIM) to lay the foundation for the Dynamic Inoperability Input-Output Model (DIIM); (2) case study that utilizes accounts from 2012 Input-Output Tables of China with the IIM and DIIM; (3) summary and conclusions of this paper.

2. IIM and DIIM

2.1. IIM

IIM is a useful tool that emphasizes the interdependence of system sectors and has been developed for vulnerability analysis. The IIM is presented in Eq. (1) for \( n \) sectors.

\[
q = A'q + c' \Rightarrow q = [I - A']^{-1}c'
\]  

(1)

The \( q \) represents the inoperability, which measures the proportion of unrealized production per as-planned production and the normalized interdependency matrix \( A' \) describes the interdependence between sectors [9].

If demand is reduced, the \( c' \) represents Demand perturbation and quantifies reduced final demand as a proportion of total as-planned output. Similarly, if supply is reduced, the \( c' \) represents Supply perturbation.

2.2. DIIM

DIIM establishes a dynamic model considering time factors and is provided in discrete-time form in Eq. (3).

\[
q(t + 1) = q(t) + K[A'q(t) + c'(t) - q(t)]
\]  

(2)

The \( A' \) is same as that in the IIM, \( q(t) \) and \( c'(t) \) represent those values at time \( t \). \( K \) is a diagonal matrix with resilience coefficients \( k_1, \ldots, k_n \) on the diagonals, the resilience coefficients \( k_i \) represents the ability of Sector \( i \) to recover following a disruptive event, where the greater \( k_i \) values correspond to a faster response by the sector[9]. The \( k_i \) can be assessed as Eq. (4) [10].

\[
k_i = \frac{\ln[q_i(0)/q_i(T_i)]}{T_i} \left( \frac{1}{1-a'_{ii}} \right)
\]  

(3)

\( T_i \) describes the recovery time for Sector \( i \) from its initial inoperability \( q_i(0) > 0 \) (e.g., 100%) to a \( q_i(T_i) \) (e.g., 1%) inoperability, \( a'_{ii} \) represents the diagonal element in matrix \( A' \).

3. Case Study of Energy System in China

3.1. Vulnerability Analysis with the IIM

Assuming that the energy system suffers the disruptive events, inoperability of each sector is calculated with the IIM and the sectors can be seen intuitively, which are more vulnerable.

Based on the status of energy system in China, two real situations are assumed to analyze vulnerability of the energy system as follows:

(1) coal is the main body of energy consumption structure in China, which brings more environmental pollution. Moreover, for a long period of time in the future, the status of coal as the main energy will not change. In recent years, China has focused on energy conservation, emission reduction and sustainable development, using more clean energy (e.g., natural gas). Assuming that China
implements emission reduction strategy, the demand for coal would reduce, that is, it’s assumed that the initial value of demand perturbation of sector 2 (Mining and Washing of Coal) is 20%.

(2) Due to relatively insufficient high-quality energy resources and limited supply capacity in China, in order to maintain energy supply and expansion, some energy needs to be imported, such as natural gas, which is more dependent on foreign countries. In case of destructive events, such as the current Sino-US trade war, it’s assumed that natural gas imports will be interrupted and supply will be reduced. That is, the initial value of supply perturbation of sector 26 (Production and Distribution of Gas) is assumed to be 20%.

In case (1), the initial value of demand perturbation of Mining and Washing of Coal is 20%. According to the inoperability, the top 5 sectors are shown in Figure 1.

![Figure 1. Top 5 sectors according to the inoperability](image1)

According to the inoperability, the ranking is as follows: sector 2 (Mining and Washing of Coal), sector 3 (Extraction of Crude Petroleum and Natural Gas), sector 4 (Mining of Metal Ores), sector 25 (Production and Supply of Electricity and Steam), sector 23 (Scrap and Waste).

Figure 1 shows that the demand perturbation of sector 2 has a greater impact on sector 3, 4, 25, 23. These sectors are more vulnerable and have a higher degree of decline in their functions. They should be protected and their resistance to perturbation should be hardened. sector 2, 3, 4 represent the exploitation of energy, sector 25 represents the utilization of energy, and sector 23 represents the waste and reuse of energy. This shows that the exploitation, utilization and waste of resources are closely related. Therefore, we should manage energy reasonably, exploit them appropriately, use them effectively and reduce waste.

In case (2), the initial value of supply perturbation of Production and Distribution of Gas is 20%. According to the inoperability, the top 5 sectors are shown in Figure 2.

![Figure 2. Top 5 sectors according to the inoperability](image2)

Sector 30 (Transportation, Storage and Post) is most vulnerable. It shows that sector 30 has the highest degree of functional decline and are most seriously affected by sector 26. Transportation, storage and postal services have a wide range of radiation and strong driving effect, which is of great significance to the development of society. However, they are severely constrained by Production and Distribution of Gas. If the gas supply is short or interrupted, the transportation system will have no
power, cannot operate normally or even be paralyzed. Therefore, it is necessary to protect it from short gas supply.

3.2. Recoverability Analysis with the DIIM
With the DIIM, this paper chooses all 42 sectors in input-output table in China to do the recoverability analysis. Due to extensive calculation, the calculation process is omitted in this paper. Then the n sectors’ dynamic recovery trajectory curves are obtained.

It is assumed that sector 26 (Production and Distribution of Gas) suffers a sudden supply shortage due to a destructive event, which makes the sector’s inoperability equal to 0.1, and the other sectors are not directly affected when t = 0, their inoperability value is 0.

Use MATLAB software to calculate parameters in DIIM and the n sectors’ dynamic recovery trajectory curves are shown in Figure 3 and Figure 4.

![Figure 3. Dynamic recovery trajectory curve of sector 26](image)

![Figure 4. Dynamic recovery trajectory curves of the other sectors](image)

The X axis represents the number of days, and the Y axis represents the inoperability. The inoperability of sector 26 decreases with time and tends to 0 and the rate of reduction is decreasing. The inoperability increases to the peak and then decreases to zero with time, and both the increase rate and
the decrease rate become smaller and smaller. It’s known that the best time to take measures to reduce the loss.

According to Figure 4, we can see that the top 5 sectors are: sector 30 (Transportation, storage and Post), sector 38 (Services to Households, Repair and Other services), sector 37 (Management of Water conservancy, Environmental and Public facilities), sector 31 (Accommodations Food and Beverage Services), sector 22 (Other Manufacture). Sector 30 has highest inoperability extremes and takes longest time back to the normal operation. Both vulnerability and recoverability of sector 30 are worst. Moreover, dynamic recovery trajectory curves are helpful to know the best time and deadline to take measures to reduce the loss.

4. Summary and Conclusion
With the IIM and DIIM, this paper chooses all 42 sectors in input-output table in china and obtains inoperability and dynamic recovery trajectory curve of each sector. The results provide guidance for improving the energy system in China, by analyzing their vulnerability and recoverability.

The demand perturbation of Mining and Washing of Coal has a greater impact on Extraction of Crude Petroleum and Natural Gas, Mining of Metal Ores, Production and Supply of Electricity and Steam, Scrap and Waste. These sectors are vulnerable and have a higher degree of decline in their functions. If the initial value of supply perturbation of the gas production and supply sector is 20%, sector 30 (Transportation, Storage and Post) is most vulnerable. They should be protected and their resistance to perturbation should be hardened.

If sector 26 (Production and Distribution of Gas) suffers a sudden supply shortage due to a destructive event, sector 30 (Transportation, Storage and Post) has highest inoperability extremes and takes longest time return to the normal operation. Both vulnerability and recoverability of sector 30 are worst. Moreover, dynamic recovery trajectory curves are helpful to know the best time and deadline to take measures to reduce the loss.

Acknowledgments
We acknowledge the financial support from the National Natural Science Foundation of China (grant nos. 51475179 and 51679099), and the Fundamental Research Funds for the Central Universities HUST. 2016JCTD207.

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