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THE IMPACT OF BLACK START ON ECONOMIC RECOVERY AFTER DISASTER: A CASE STUDY OF THE POWER SYSTEM COLLAPSE IN HAINAN PROVINCE

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ABSTRACT

With the development of urbanization and industrialization, the dependence on the power system has gradually increased. It is of great significance to discuss the recovery scenario after the power system collapses. Taking the black start event of Hainan Province caused by the typhoon Damrey in 2005 as an example, this study calculates the indirect economic loss of local sectors caused by the black start using the inoperability input-output model and calculates the indirect economic loss under the scenario without the black start based on the assumptions. Through the comparison of these two scenarios, this study analyzes the impact of the black start on post-disaster economic recovery. The results show that the local power load has a rapid growth after the black start, and correspondingly, the daily indirect economic loss drops significantly. The secondary industry sectors suffer relatively larger indirect economic losses, while the primary and tertiary industry sectors are less affected. The black start scenario shows significant advantages in terms of the safety problem and economic loss.

Keywords: Hainan; black-start; Inoperability Input-Output Model; Indirect economic losses

1. INTRODUCTION

High dependence on electricity is an important feature of modern economic society [1, 2]. However, due to the complexity of the power system, aging power infrastructure, natural disasters and other factors, modern society is facing a risk of large-area black-out [3]. The power system is closely linked to the water supply, telecommunications, financial services, transportation and other systems. Large-scale power outage will cause great social and economic losses and have a serious impact on people's daily life. Therefore, a quick and reliable power system restoration plan is necessary, and the black start is one of the most important methods to restore the power system. A black start is defined as the process by which a power system suffering from a complete blackout is restarted by reconfiguring the networks and recovering its loads depending on the units with self-starting ability in the system [4].

The black start problem was put forward by American scholars in the 1980s[5], and the black start has attracted the attention of many researchers since its appearance. Dong et al.[6], Gao et al.[7] and Lin et al.[8], etc. explored the optimization of black start schemes; Liu et al.[9], Liu and Gu [10], Lin et al.[11] and Chen et al.[12] proposed several methods of evaluating the relative effectiveness of black start schemes. However, current research on the quantification of the economic effects of the black start is insufficient.

Taking the first provincial black start in Hainan province in 2005 as an example, this study quantifies the indirect economic loss caused by the power system collapse under the black start scenario and compares it with the scenario without implementing the black start. On September 26, 2005, typhoon Damrey struck Hainan and caused great power equipment damage and transmission line failures in Hainan Power Grid, which eventually led to the overall collapse of the electricity system. Hainan Power Grid successfully implemented the black start scheme [13]. This study uses the inoperability input-output model (IIM) to quantify the indirect economic loss of each sector. The IIM is based on the Leontief input-output model and describes the economic interdependencies between sectors. The IIM is widely used to analyze the loss of economic system caused by accidents [14, 15], epidemics [16], political disputes [17] or natural disasters [18]. Figure 1 shows the research framework of our study.

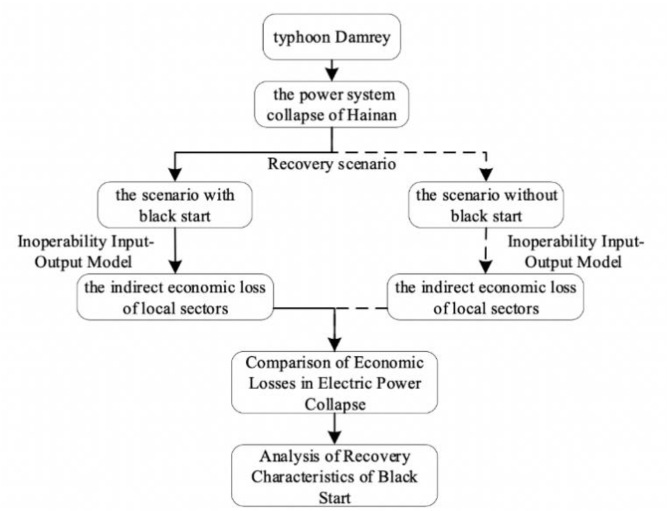

Fig. 1 The framework of this study

2. METHOD AND DATA SOURCES

2.1 The inoperability input-output model (IIM)

Direct economic loss caused by natural disasters or accidents cannot be reduced through post-disaster recovery behavior. Therefore, this study focuses on indirect economic loss, which can be reduced by positive measures.

There is a basic equilibrium equation relationship in the input-output model:

$$X = AX + Y \tag{1}$$

Where *X* represents the total output column vector, *Y* represents the final demand column vector, and *A* is the direct consumption coefficient matrix which can be expressed as:

$$A = (a_{ij})_{n\times n} = \left(\frac{x_{ij}}{x_j}\right)_{n\times n} \tag{2}$$

Where a_{ij} represents the quantity of products of sector *i* needed to produce one unit output of sector *j*.

Equation (1) can be further transformed into the following form:

$$X = \left(I - A\right)^{-1} Y \tag{3}$$

where $(I-A)^{-1}$ is called the Leontief inverse matrix.

The inoperability is defined as the degree of system function failure, which can reflect the severity of the impact of extreme events on the economic system. We use *Q* to represent the inoperability:

$$Q = diag\left(\hat{x}\right)^{-1} \cdot \left(\hat{x} - \tilde{x}\right) \tag{4}$$

Where $\hat{x}$ is output under normal circumstances and $\tilde{x}$ is the output after the power system collapse.

According to equation (1) and (4), we can get the Inoperability Input-Output Model based on the decline of power supply:

$$Q = A^{*}Q + Y^{*} \tag{5}$$

$$Q = \left(I - A^{*}\right)^{-1} Y^{*} \tag{6}$$

Where Y^* represents the change in final demand, and A^* is an incidence matrix calculated by input-output data. Y^* and A^* can be calculated as follows:

$$Y^{*} = diag\left(\hat{y}\right)^{-1} \cdot \left(\hat{Y} - \tilde{Y}\right) \tag{7}$$

$$A^{*} = diag\left(\hat{x}\right)^{-1} \cdot A \cdot diag\left(\hat{x}\right) \tag{8}$$

Where $\hat{Y}$ is the final demand under normal circumatances and $\hat{Y}$ is the final demand after the power system collapse.

In 1958, Ghosh proposed a new input-output model based on the Leontief model. This new model can reflect the relationship between initial input and total output by the direct distribution coefficient, so it is also known as a supply-driven input-output model. The direct distribution coefficient matrix *H* can be expressed as follows:

$$H = (h_{ij})_{n\times n} = \left(x_{ij}/x_i\right)_{n\times n} \tag{9}$$

Then we can get the column balance as follows:

$$X = H^{T} X + V \tag{10}$$

Where *X* represents the total input vector and *V* is the column vector of the initial input (such as labor, wages, taxes, rents, etc.).

In Ghosh's input-output model, the supply-driven Inoperability Input-Output Model can be expressed as:

$$P = \left(I - H^{T*}\right)^{-1} V^{*} \tag{11}$$

Where *P* is the inoperability of the change in cost price due to the change of initial input, V^* represents the change of initial input, and H^{T*} is the incidence matrix calculated by input-output data. H^{T*} can be expressed as follows:

$$H^{T*} = diag\left(\hat{x}\right)^{-1} \cdot \left(A^{*}\right)^{T} \cdot diag\left(\hat{x}\right) \tag{12}$$

Indirect economic loss refers to the loss caused by the decline of industrial output caused by extreme events. Thus, indirect economic loss can be estimated as follows:

$$LOSS = \sum_{i} x_i p_i \tag{13}$$

Where x_i is the total output of sector *i*, p_i is the abnormal degree of sector *i*, and *LOSS* is the total loss caused by extreme events.

2.2 Data Sources

Due to the lack of an input-output table in 2005, we use the 2007 input-output table of Hainan in this study, which has the industrial situation closest to that in 2005. The input-output table of Hainan is derived from the National Bureau of Statistics [19]. Power load data of the black start scheme in Hainan are obtained from the existing literature [13, 20]. We assume that the power load of the scenario without the black start recovers linearly.

3. RESULTS AND DISCUSSION

3.1 The indirect economic loss caused by the power system collapse

Hainan's power system collapse began on September 26, 2005, and the power load of Hainan Power Grid was completely recovered by October 9, 2005, after 14 days. As shown in Figure 2, there is a total indirect economic loss of 30.2 billion yuan caused by the collapse of the Hainan power system. Due to the rich experience of black start simulation, the Hainan power grid immediately adopted the black start scheme after the power system collapsed and achieved success. According to the results, on September 26, 2005, the first day of the typhoon landing, the entire Hainan Power Grid was in a state of blackout, so the indirect economic loss on the first day was the highest, reaching 47.4% of the total loss. On the second day, the electricity load was restored to 80% of the normal load. The indirect economic losses of the first two days totaled 18.14 billion yuan, accounting for approximately 60% of the total indirect loss. On September 29, the fourth day of the typhoon landing, Hainan Power Grid recovered to 90% of the normal load, most regions in Hainan had left the blackout state, and the indirect economic loss was effectively controlled.

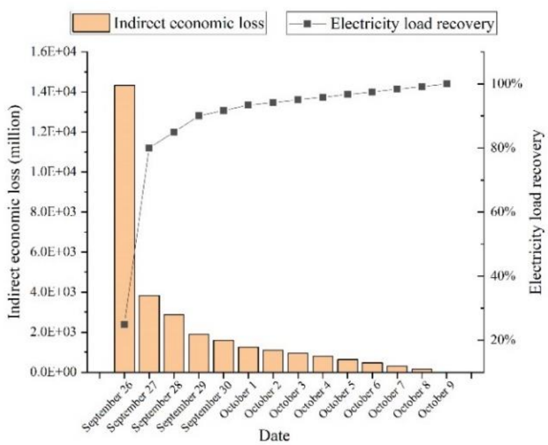

Fig. 2 The electrical load recovery and the indirect economic loss in Hainan

3.2 The impact of power collapse on the sectors under the black start

Different sectors have different degrees of dependence on electricity, so the indirect economic losses of different sectors caused by the power collapse are also different. Figure 3 shows the ten sectors with the largest indirect economic losses caused by the collapse of the power system in Hainan with the implementation of the black start.

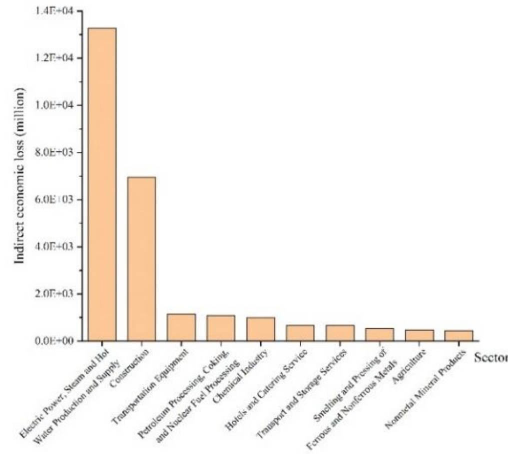

Fig. 3 The 10 sectors with the largest indirect economic loss caused by the power system collapse in Hainan

In general, the secondary industry is the most affected, with indirect economic loss of up to 26.1 billion yuan, explaining 87% of the total indirect economic loss. The indirect economic loss of the tertiary industry accounts for 12%, and the primary industry is the least affected, with an indirect loss of approximately 400 million yuan, accounting for only approximately 1%.

3.3 The comparison of economic losses under the scenarios with and without the black start

According to the prediction of the Hainan power grid, the recovery would take 25 days if the black start scheme were not implemented. Therefore, we assume that the recovery of the power load increases linearly; that is, 4% of the electrical load per day is restored. Using the inoperability input-output model, we can calculate the indirect economic losses of all sectors in Hainan without the implementation of the black start scheme. There will be an indirect economic loss of 229.1 billion yuan, approximately 7.6 times the indirect economic loss under the black start scheme. Through the comparison of the two scenarios in Figure 4, it is found that the black start scheme has a significant acceleration effect on economic recovery.

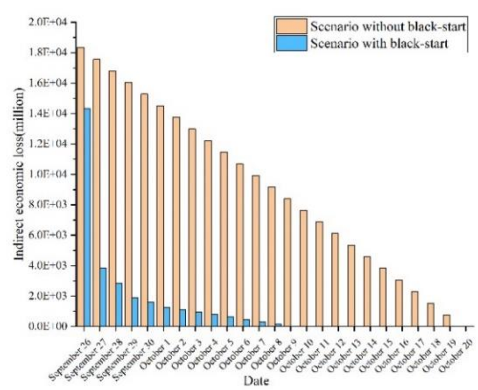

Fig. 4 Comparison of indirect economic loss under the scenarios with and without black start

4. CONCLUSION

This study uses the inoperability input-output model to analyze the impact of the 2005 black start scheme on economic recovery. The main conclusions are as follows:

(1) The black start scheme can quickly recover the power system after power system collapse.

(2) After the implementation of the black start, the indirect economic loss of the sectors decreased rapidly, effectively controlling the indirect economic loss caused by the collapse of the power system.

(3) Industries with close links to the power sector suffer from more indirect economic losses.

This study shows the importance of implementing the black start scheme. However, our study only considers the indirect economic loss caused by the reduction of the power supply, ignoring the impact of power facility damage. In addition, the assumption of linear recovery speed in the scenario without the black start needs to be further improved.

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