Enhancing Business Resilience under Power Shortage: Effective Allocation of Scarce Electricity Based on Power System Failure and CGE Models

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Abstract:

The study aims at presenting a methodology to capture the risk of energy shortages due to unscheduled accidents on power plants under high energy demand conditions. This type of risk becomes especially large in many of developing countries where the power demand constantly increases every year as well as disaster-prone countries where the damages to multiple power plants could occur after devastating disasters.

Basically, energy shortage risk should be captured from the viewpoints of supply capacity and demand response. From the aspect of supply side, one of the focuses in our research is to capture the vulnerability of power system and develop an appropriate functional failure model for power supply systems. On the other hand, it would be necessary to understand how the society absorbs the impacts of shortage by effectively reducing power demand. For this purpose, this study investigates the potential of CGE model as an optimal power allocation tool. Through the case study of the recent Japanese power shortages, the possibility of worse power shortage as well as the prospect to absorb the losses is calculated and compared with the achieved based on the various statistical data sets such as accidents of power plants, business power consumption, and production outputs.

1. INTRODUCTION

Power shortage is one of the common risks all over the world and frequently seen in many countries. The shortage can be induced by many incidents, such as increasing economy (e.g. Many developing nations), failure of energy market systems (e.g. California in 2001), natural disasters (e.g. The Japanese triplet disasters in 2011) and other unscheduled events. A large difference between shortages and outages lay in the degree of the adaptation capacity of households and firms. In many of the past power shortage events, large amount of power savings was achieved by the efforts of users as well as the emergency management of power supply side.

This adaptation capacity under power shortage is regarded as resilience and enhancing resilience is one of the central topics to reduce the economic impacts of the power shortage issues. The resilience could be composed not only of resilience of individual firms, such as installing backup generators, but also of total economy, such as market mechanisms. The resilience of the entire economy is sometimes cited as economic resilience, while the resilience of individual firms could be touched on as business resilience. Regarding individual business resilience, there have been many researches accumulated mainly based on business surveys. However, there are only few practical studies on the economic resilience.

As Rose and Liao (2005) point out, CGE is a promising tool to analyze the economic resilience. The model could achieve optimal allocation of scarce resources through outweighing the price of scarce resources. It is still controversial to apply the CGE to assess the disaster impacts, but it is curious to know the case of power shortage, especially the case that the affected area has relatively larger adaptation periods. For the intention of providing the applicability of CGE to the economic impact assessment of power shortage, it is necessary to verify how much the CGE model can capture the economic activities during the real events. Even it is uncovered that the CGE minimize the impacts too much through the optimal conduct of each sector, the model also could be utilized to recognize what type of apportionment of resources would be ideal for cutting the losses. In any cases, there is an advantage to test the model and discuss the results through the case study of a real event.

There is also a resilient mechanism of power supply side. The efforts of the power industries include rescheduling the maintenance period as much as possible. However, the intensive use of the generators increases the chance of unscheduled shutdowns. To appropriately grasp the impact of power shortages, it is also necessary to incorporate the risk of unscheduled shutdown of power plants.

Considering these backgrounds, this study aims to apply the CGE model to the case of the power shortage event after the 2011 Great Eastern Japan Earthquake. In specialty, the risk of unscheduled shutdown of power plants is statistically estimated based on the real data in 2011 and 2012 to derive the possibly realized worse case scenarios.

2. RESEARCH FRAMEWORK AND MODELS

2.1 Research Framework

The research framework in this study is described in Figure 1. Basically, shocks to the production capacity of the electricity sector (hypothetical capital decrease) are set as the inputs of CGE analysis. The basic scenario is the case of real power capacity losses, which is gauged from the power consumption decrease in 2011 summer in Japan. In addition, hypothetical power production capacity losses are set from the power plant failure models.

The power failure model is a survival function type of statistical model, which determine the probability on the timing of the unscheduled shutdown and is calibrated based on the real unscheduled shutdown data sets in 2011 and 2012 summers. Based on this statistical model, the probability distribution of power losses due to the unscheduled shutdown are obtained by parametric bootstrap simulations. Recovery time of each shutdown is randomly determined through resembling of actual recovery time data.

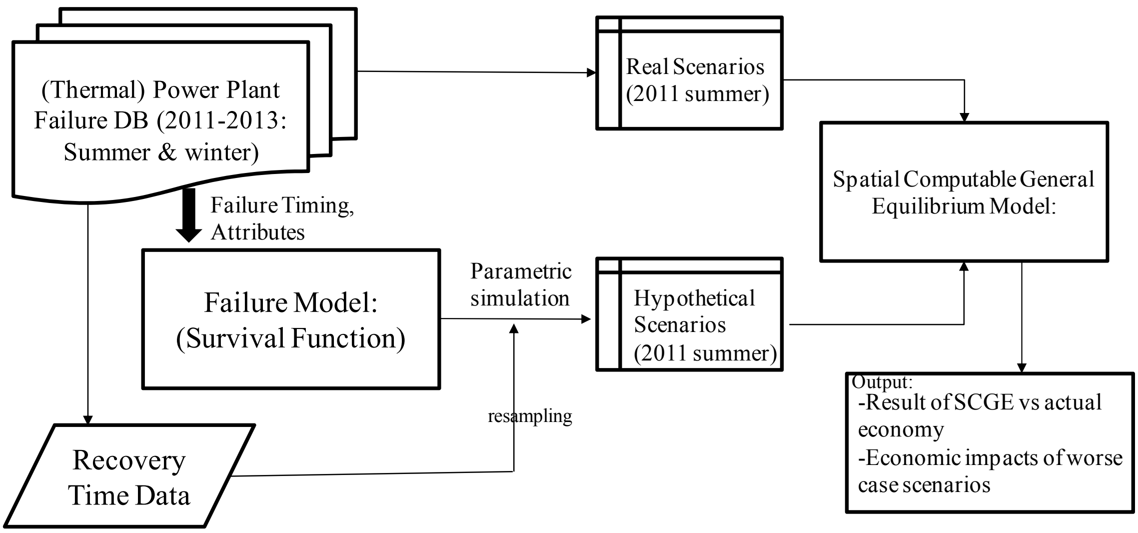

Figure 1: Analytical Flow

2.2 Failure model of Power Plants

As a failed model of power plant, several statistical models are compared. These statistical models are basically so called the family of generalized linear models, which has been applied in the area of survival analysis. The unscheduled shutdown event normally follows survival analysis. The adopted statistical distributions to be compared include log-normal, Weibull, Gaussian, logistic, and exponential. As shown in later analysis, the Weibull distribution relatively performs better for the power plant failure data sets. As an example of the statistical distributions, the cumulative density function (CDF) and the density function (DF) for the Weibull distribution are given as follows:

$$F(t) = 1 - \exp\left\{-\left(\frac{t - S(t)}{\alpha}\right)^{\sigma}\right\} \quad \text{(CDF)} \tag{1}$$

$$f(t) = \frac{t - S(t)}{\alpha}\left(\frac{t - S(t)}{\alpha}\right)^{\sigma - 1} \exp\left\{-\left(\frac{t - S(t)}{\alpha}\right)^{\sigma}\right\} \quad \text{(DF)}, \tag{2}$$

where the scale parameter α is determined by the linear combination of several potential explanatory variables $\boldsymbol{x}$ as follows.

$$\alpha = \beta_0 + \beta_{season} x_{season} + \beta_{Year} \ln(x_{year}) + \beta_{power} \ln(x_{power}) + \boldsymbol{\beta}_{\boldsymbol{fuel}} \boldsymbol{Fuel} + \beta_{accident} x_{accident} \,. \tag{3}$$

In our study, potential variables include “Season (2011 or 2012)”, “Year (age of power plant)”, Power (maximum power output of each generator unit)”, “Fuel (vector of fuel types)”, and “accident (history of previous accident, set as 1 if yes and 0 if no)”. It is ideal that other functional forms are investigated to find the better statistical model.

2.3 Outline of CGE model assessment

Figure 2 illustrates the outline of the SCGE model in this study. Japan is divided into 10 regions, which corresponds to power supply regions respectively owned by 10 major power companies. In each region, there are household and industrial sectors, and one central government is considered in Japan total. Firms produce goods using labor, capital and intermediate goods, and their products are transformed to be exported and domestic commodities. Households earn their income by providing labor and capital to firms, pay direct tax to the government, and allocate the remained income to consumption and saving. Total savings are equal to the investment demand for capital goods. Total demand is the sum of intermediate input demand, final consumption (household and government), and investment demand, and this is balanced with the total supply of goods sourced from domestic and imported commodities.

Production structure and functional types are described in Figure 3. In addition to capital and labor, energy is considered as a primary production factor. The value added, composed of “Labor” and “Capital” are combined with “Energy” by nested CES functions to be one of the inputs of Leontieff production function in the intermediate goods layer. Similarly, by using CES functions, “Energy” is composed of “Electricity” and “Non-electricity”, which is further composed of “Mining”, “Oil and coal” and “Gas”. Final products are transformed to either “Export” or “Domestic goods” by a CET function.

The model is calibrated based on the social accounting matrix, which is reorganized and spatially aggregated from an interregional Input-Output table of 47 prefectures in Japan and other public statistics. Production, consumption and savings and other variables in the model are determined through the price condition at the equilibrium of the markets.

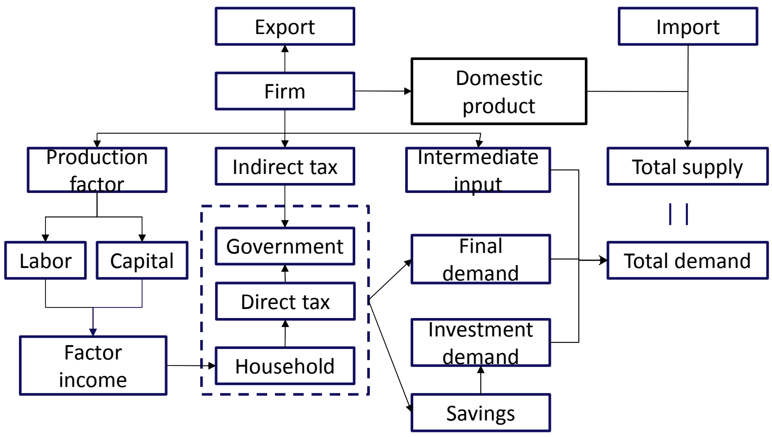

Figure 2: Outline of CGE model

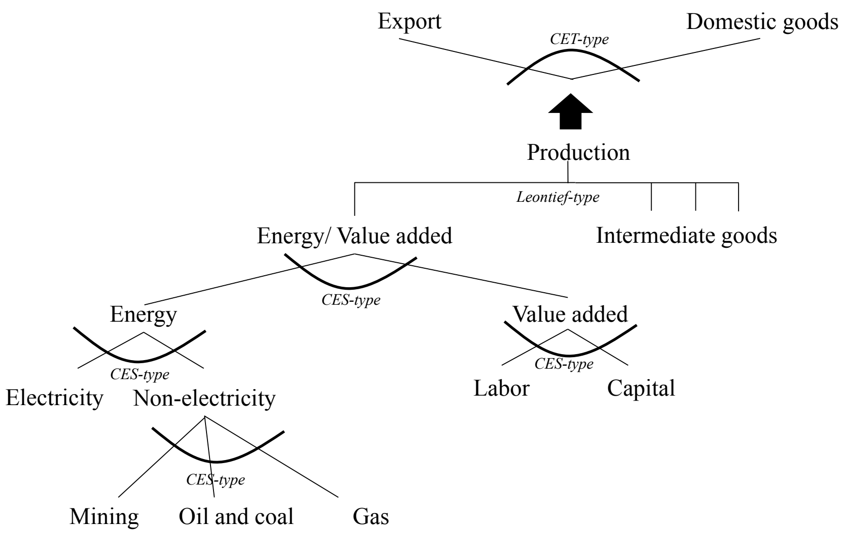

Figure 3: Production structure

3. PRELIMINARY RESULTS

3.1 Settings of Case Studies and developed database

Figure 4 illustrates the power supply and demand condition at the peak demand day in each region during the 2011 summer in Japan. During this period, Tokyo region was anticipated as the severest condition in terms of supply and demand balances. Therefore, most of the industrial sectors were requested by the central government to follow the 15% mandatory reduction of power usage compared to the peak usage of previous years. However, considerable efforts by the firms achieved the largest reduction of power consumption and the peak demand was covered by the supply with a safe margin. The demand in Tohoku exceeds the supply capacity, but the shortages were fully embraced by the imports from other areas. The severer conditions are seen in the western part of Japan, where the peak power consumptions in most of areas, excluding Chugoku region, are close or exceed supply capacity.

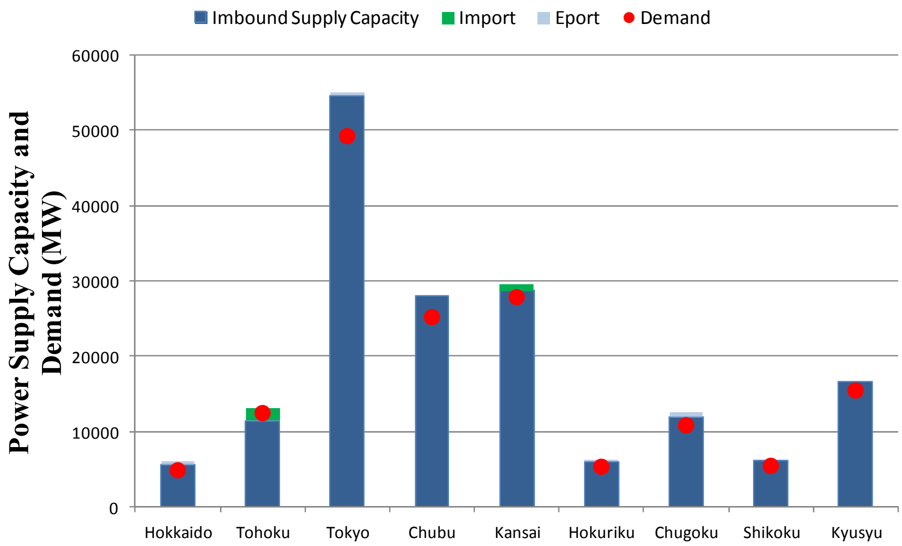

Figure 4: Power supply and demand conditions after the 2011 earthquake and tsunami

Most of the supply capacity in each region was covered by thermal power plants in 2011 as in Figure 5. They were intensively used especially during the peak seasons (summer and winter), and unscheduled disruption of these power plants was the risk to enlarge the economic impacts of power shortages. In order to analyze the accident trends and develop a failure model of thermal power plants based on the actual performance, we have created a failure database of power generation unit operated in Japan. This database contains 327 (number of turbines is 371[1]) units in 147 thermal power plants owned by 10 electric power companies including steam turbine plants, gas turbine plants, combined cycle plants and internal-combustion engines.

The operational status of each unit during summer (July - September) and winter (December - February) season in the past 3 years (2011 - 2013) are investigated. The accident information in this period has been collected from the report of the Electric Power Safety

[1] Combined cycle includes several turbines for one generator unit.

Subcommittee (Ministry of Economy, Trade and Industry), Electricity Supply-Demand Verification Committee (Cabinet Secretariat) and companies' websites. The failure events extracted from these data sources are totally 319 cases (failure of turbines) through 6 seasons: 92 cases in 2011 summer, 19 cases in 2011 winter, 126 cases in 2012 summer, 30 cases in 2012 winter, 30 cases in 2013 summer, 22 cases in 2013 winter. They basically track all major accidents that power companies have obliged to inform the authorities of, though some minor incidents that companies do not have reporting responsibility are also included. In addition to the basic information about the accident (e.g. The date of occurrence and recovery, failure mode, power loss), several attributes associated with the accident history (e.g. Recovery duration of the previous accident, cumulative frequency of accidents) is also specified to assess their influence on failure occurrence pattern. As an example, the failure timing of power plants (excluding combined cycles) is drawn in Figure 6.

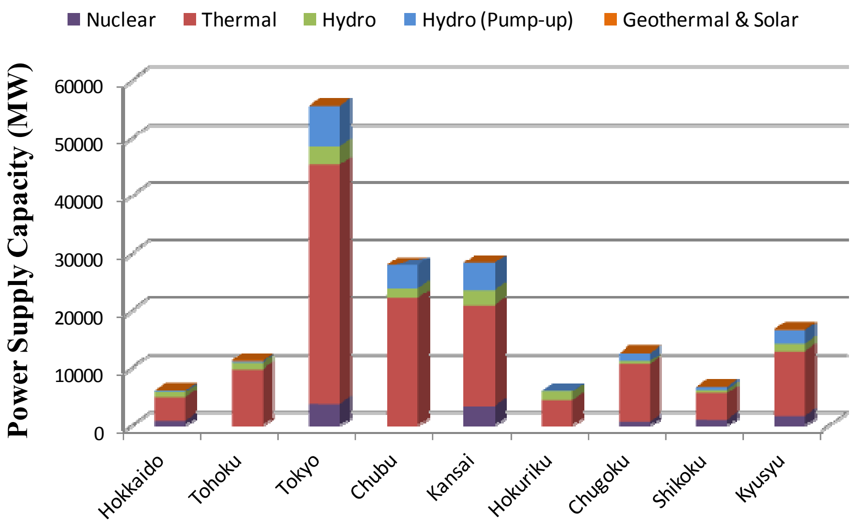

Figure 5 : Power capacity of each generation source (at the demand peak day in 2011 summer)

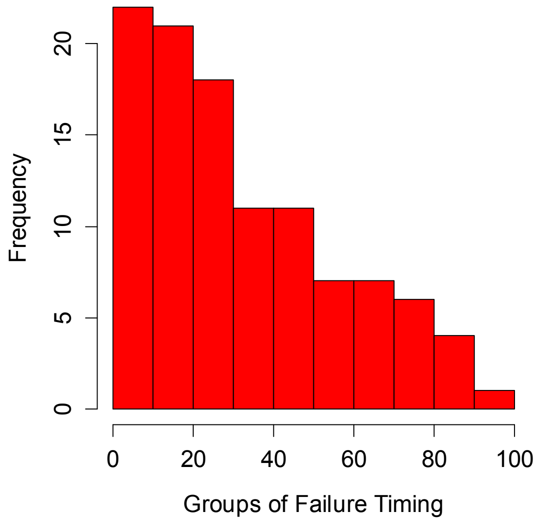

Figure 6: Distribution of failure timing (starting time is set at July 1st, 2011)

3.2 Identification of TPP Failure Model and Parametric Bootstrap Simulation

Considering the cases of failures in 2013 are by far smaller than other years[2] and generally demand is larger during the summer, the statistical model is estimated from the accident data during summers in 2011 and 2012. Moreover, the data are divided into combined cycle thermal power plants (CC) and other thermal power plants (NCC) considering their structures are different (the accident to one turbine induce a total unit failure or not). Through the comparison of various statistical distributions shown in **2.**, In the case of NCC, Weibull distribution performed best and the significantly contributing variables are fuel types, accident history and seasons (2012 is worse than 2012).

Figure 7 illustrates the cumulative density of failures and empirical (observed) cumulative density classified by accident histories. The model indicates that the power plant which experienced an accident tend to have higher risk to get next accidents. The fitted value of second or more accidents is slightly lower than observed values. In a current status of the model, the values of parameters and variables except accident history are shared by two cases, but the result indicates that the parameters of these two cases can be different.

[2] More detailed investigations are required to know the reasons, but the plausible reasons could be the improved efforts to power plant management and the larger margin of power supply compared to demand.

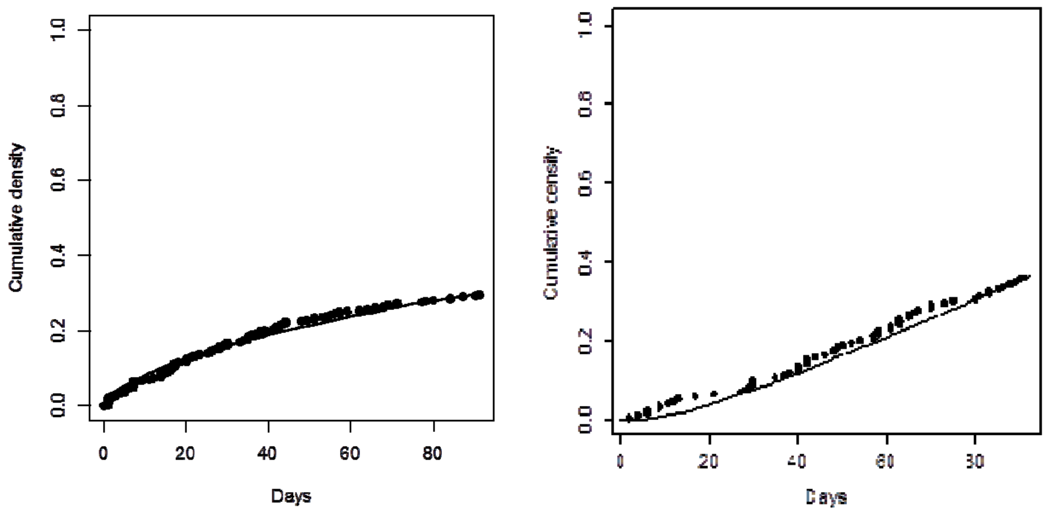

Figure 7: comparison of estimated cumulative probability density of failure (solid line) and empirical cumulative density (dotted line) for the First accident (left) and second or more accidents (right) during the summer in 2011 and 2012.

3.3 Results of Power Allocations and Economic Impacts

The result will be reported in a conference after the confirmation of data and calculation processes.

4. FUTURE WORKS

This study investigated an appropriate methodology with which to estimate the impact of power shortage and consider an optimal power allocation to reduce the economic impacts. This methodology consists of power plant failure and CGE models, and is applied to the case of the power shortage case after the Great Eastern Japan Earthquake of March 11, 2011. There still exists a large part of work to fill in, but the basic database construction works, frameworks of the analysis and preliminary result of the power failure model are described in this paper.

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