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Impact analysis of electricity supply unreliability to interdependent economic sectors by an economic-technical approach

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ABSTRACT

This paper proposes a novel framework to quantify the economic impact of electricity supply interruptions to other economic sectors considering their interdependency and increasing penetration of wind power. It is achieved by a novel integrated model that combines economic interdependency and electricity supply reliability. Leontief Input-Output model is used to determine the dependency of other economic sectors on electricity supply and electricity reliability theory is utilised to quantify electricity supply interruptions. The two models are combined to quantify two key indexes: the inoperability of different economic sectors and their losses under electricity supply unreliability. Further, an optimal model is designed to allocate available electricity to minimise the economic losses of these sectors when electricity supply is interrupted. Two UK electricity generation scenarios are used to demonstrate the concept. It is found that economic sectors have various degrees of dependency on electricity supply and their losses also differ significantly. In addition, more wind power penetration could jeopardize electricity supply adequacy and consequences to other sectors. The findings can assist policy makers to understand the importance of electricity security to other sectors and quantify potential economic losses so that new policies and regulations can be designed to mitigate the adverse consequences, such as developing the capacity market.

1. Introduction

The modern society is growingly dependent on electricity supply, which is accomplished by the effort to decarbonise the energy sector to reduce greenhouse gas emissions [1]. Different economic sectors and infrastructure are now becoming closely linked, for example, natural gas and electricity systems are linked gas-fired generation and new power-to-gas techniques. The increasing interdependency brings many benefits but also challenges, where one consequence is that the failure impact in a system can propagate to others [2]. For example, the 2003 North America blackout was estimated to cause a total cost of about $6 billion [3]. The consequence can be further worsened when electricity supply is interrupted with increasing non-dispatchable renewable, such as wind power [4].

Thus, it is essential to understand the dependency of economic sectors on electricity supply and quantify their losses in case of electricity shortage so that mitigation solutions can be adopted. Some pioneering work has studied the interdependency between electricity and other sectors from the technical aspect [5]. Paper [6] proposes an economic feasibility analysis for a standalone house operated with a hybrid power plant consisting of gas generation, photovoltaic and wind generation. In Ref. [7], the authors propose a new concept of energy hub which consists of various resources for energy conversion and optimization. In paper [8], the authors introduce a new configuration for natural gas pressure drop stations by employing a solar thermal system. The introduced concept is assessed in terms of fuel providence and exergy destruction rate. Paper [9] introduces a new optimization model to analyse the interdependency between different energy infrastructures, such as natural gas, coal, and electricity. It is noted that the previous studies are mainly studying the physical interdependency of a limited number of energy infrastructures. Due to the lack of data, they use simplified models of some sectors and networks when examining

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the impact of failures on others. In addition, they have not quantified the economic loss of one sector due to the supply failure of other sectors/infrastructure.

The reliability of electricity systems assesses the impact of electricity supply interruptions to other sectors. Electricity system reliability mainly focuses on quantifying some key reliability indexes in predefined contingency events, such as potential load loss and occurrence probabilities of the events. It can be roughly divided into two categories: security which is to measure system's ability to withstand stability in response to disturbances, and adequacy which is to quantify the existence of sufficient supply to satisfy demand [10] [11]. In this paper, the reliability is referred to adequacy, which is also called operability in economics domain. They are assumed to be interchangeable here. In quantifying the economic loss of other sectors due to electricity shortage, electricity demand is normally classified into various categories, such as domestic, commercial, and industrial. Each type is assigned a specific Value of Lost Load (VOLL) [12] and the total economic loss is the summation of VOLL from all curtailed demand [13]. This concept has served the electricity system industry for decades, but it ignores the interdependency of other economic sectors, i.e. the propagating effect of electricity supply interruptions.

From the economic aspect, some work has investigated the impact of electricity supply interruptions on other economic sectors by using Inoperability Input-Output Model (IIM). The IIM developed from the original Input-Output (IO) model contributes to understanding infrastructure interdependency in abnormal conditions [14]. It has been applied to many areas for risk identification and mitigation, and is applicable to calculate the economic impacts of a given change to the economy. In paper [15], the authors use the IIM to measure the financial and inoperability impact of the 2003 Northeast Blackout. Paper [16] develops a static IO framework to analyse energy issues in the short run and discusses the potential barriers to its application. Papers [17,18] use the IIM to assess and manage inherent risks in different interconnected economic systems. Paper [19] studies the marginal cost of GDP due to electricity deficits but the deficit probability is predefined but not quantified. Conclusively, the disadvantage of existing work in economics is that the inoperability of electricity supply is normally prefixed i.e. hypothetically assumed or obtained from historical data. It is unable to reflect electricity system's stochastic features. On the other hand in the electricity system domain, the impact quantification of supply unreliability is fairly rudimentary, which cannot reflect the interdependency of different economic sectors. Thus, it is essential to integrate the economic and technical interdependency techniques together to quantify the potential impact of electricity interruptions on other economic sectors in a coherent way.

This paper proposes a novel integrated technical-economic framework to assess and manage the unreliability of electricity supply to other economic sectors. The IIM technique is adopted to analyse the economic dependency and energy system reliability is used to capture the technical dependency of other economic sectors on electricity supply considering the penetration of wind power. The IIM is built by using national economic statistic data and the reliability of wind power is analytically modelled by a Markov Model. Three key inoperability indexes are designed to measure the dependency degree of different economic sectors on electricity supply. An optimal model is also introduced to manage available electricity to minimise the economic losses of other sectors when electricity supply is partially interrupted. The UK electricity supply scenarios with various wind penetration levels are utilized to illustrate the concept. Results reveal that the proposed framework can effectively measure and manage the impact of electricity supply inoperability on other sectors.

The key innovations of this paper are that: i) it integrates economic IIM and technical reliability approaches to quantify the impact of electricity supply interruptions; ii) it designs new indexes to measure the inoperability of electricity systems on other economic sectors, and iii) it studies the impact of increasing wind power on the operability and economic losses of other sectors; iv) it introduces an optimal management strategy to minimise the economic losses of sectors with electricity supply interrupted. The study can benefit electricity system operators and policymakers to understand the importance of electricity supply security and take remedy actions to ensure supply reliability to other economic sectors.

The rest of this paper is organized as: Section 2 introduces the IO and IIM models. In section 3, electricity supply reliability with wind power is presented and Section 4 defines some interdependency indexes. Section 5 proposes an approach to quantify the impact of inoperable electricity supply and in Section 6, an optimal management model is proposed. Section 7 employs the UK case to demonstrate the proposed method. Section 8 concludes this paper.

2. Interdependency and the input-output model

This section briefly introduces the Leontief IO model and IIM for interdependency analysis, and the application to electricity supply.

2.1. Leontief input-output model for interdependency analysis

Fig. 1 illustrates the interdependency of three sectors and their external demand. By taking the electricity supply as an example, one part of its output is consumed by itself, one part is exported to Sectors A and B for their production, and the remaining part is to meet external demand. In turn, electricity generation also needs the output from Sectors A and B to produce electricity. Thus, any deficits of electricity to either Sector A or B will adversely affect electricity production. This indicates the importance of considering the natural linkage/interdependency between different sectors in quantifying electricity supply security.

The Leontief IO model designed by Noble Laureate Leontief is an effective tool for examining the interactions and interdependency of different economic sectors. It provides a framework to analyse the economic impact for an equilibrium economic system with a set of interdependent subsystems or sectors. The IO model employs matrices to display the supply and demand between different sectors, called transactions table. An illustrative example is given in Table 1 with two sectors and one external demand column, where a row in the table displays the distribution of a producer's output and a column is the composition of inputs required by a sector in order to produce its output [20]. The total output of one section is the sum of the output to all sectors including itself and external demand.

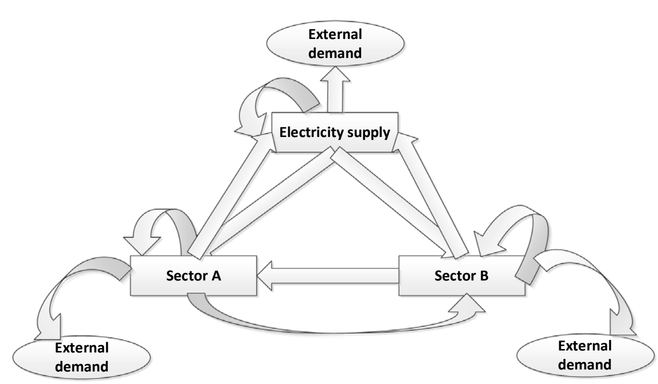

Fig. 1. Input-output of a three-sector system.