Energy Economics 50 (2015) 215–226

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Energy import resilience with input–output linear programming models

Peijun He [a], Tsan Sheng Ng [a,*], Bin Su [b]

[a] Department of Industrial and Systems Engineering, National University of Singapore, Singapore
[b] Energy Studies Institute, National University of Singapore, Singapore

A R T I C L E I N F O

Article history:
Received 16 January 2015
Received in revised form 9 May 2015
Accepted 20 May 2015
Available online 6 June 2015

JEL classification:
C44
C61
C67
Q40
Q41
Q48

Keywords:
Energy resilience
Input–output modeling
Linear programming

A B S T R A C T

In this work we develop a new approach to study the energy import resilience of an economy using linear programming and economic input–output analysis. In particular, we propose an energy import resilience index by examining the maximum level of energy import reduction that the economy can endure without sacrificing domestic demands. A mixed integer programming model is then developed to compute the resilience index efficiently. The methodology is applied to a case study using China input–output data to study the energy import resilience under different power generation portfolio assumptions. We demonstrate how our models can be used to uncover important inter-sectoral dependencies, and to guide decision-makers in improving the energy resilience in a systematic manner.

1. Introduction

The central theme of concern in this work is succinctly described by IEA's definition of national energy security (IEA, 2014), where in particular *"short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply–demand balance"*. Indeed, unanticipated disruptions in energy supplies (primary fuels, electricity, high energy-embodied goods) can lead to cascading problems in the economy due to the complex interdependency between different industry sectors. For example, the U.S. witnessed a huge decline in economic output during the 1973 oil supply crisis (Akins, 1973). In 2008, a shortage of hydroelectricity supply in Central Asia caused severe damage to the national economy, especially in agriculture sectors, which led to a major food crisis in the same year (Libert et al., 2008).

Energy import reliance is often identified as an important determinant of national energy security, as evident from the various published studies on energy security performance indicators (Geng and Ji, 2014; Kruyt et al., 2009; Le Coq and Paltseva, 2009; Löschel et al., 2010; Vivoda, 2009). It is clear that an economy highly dependent on imports for its primary energies faces greater exposure to risks of exogenous supply shocks. On the other hand, two economies with similar degree of import dependencies may have very different reactions when exposed to the same import supply shocks. This can be due simply to their inherently different inter-sectoral dependency structure. A desirable structure should allow effective mitigation of the energy import loss via redistribution of production resources to restore supply and demand balance. This is coherent with the concept of *energy resilience* as espoused in other works (Flynn, 2012; Molyneaux et al., 2012; OBrien and Hope, 2010; Thomas and Kerner, 2010). It is of interest in this work to quantify and evaluate such a concept of energy resilience using a model-based approach.

In this paper, we propose an input–output based linear programming model that focuses on the relationship between energy imports, industrial production technologies and capacities. Basically, the model can be used to simulate the impact of specified energy import losses on the sectoral production levels, and consequently, the final supply–demand balance. In reality, energy import losses may arise from various importing sectors and cannot be anticipated precisely in advance. A key technical contribution of our work is that the proposed model can be used to evaluate the worst-case impact over a family of (possibly infinite) import loss scenarios. This family of loss scenarios is defined, for instance, as the set of all loss scenarios that has the same total tonnes of coal equivalent (TCE) of energetic content. In the proposed model, the impact of an energy import loss on the economy is defined as the total final demands deficit, that is, the amount of final demands of goods that cannot be balanced by the given supply and production in

* Corresponding author. Tel.: +65 6516 2562; fax: +65 6777 1434.
E-mail addresses: Peijun_he27@nus.edu.sg (P. He), isentsa@nus.edu.sg (T.S. Ng), subin@nus.edu.sg (B. Su).

http://dx.doi.org/10.1016/j.eneco.2015.05.007
0140-9883/

the short run. This is then extended to define an *energy import resilience indicator*, which essentially evaluates the highest level of energy import loss sustainable by the economy. Such an indicator provides decision-makers with a simple way to rank the related performance of an economy.

The outline of the rest of the paper is organized as follows. The next section provides a literature review of related works in the application of input–output models for energy supply studies, and also the use of linear programming models in input–output analysis. Section 3 introduces our proposed input–output linear programming model, the uncertainty model for defining the family of energy import loss scenarios, and also our proposed energy import resilience indicator. Moreover, to evaluate the worst-case impact of the economic system from the set of import loss scenarios, we propose an equivalent formulation of the model in the format of a mixed linear integer programming model. We also extend the methodology to compute production capacity designs that achieves the maximum possible energy import resilience of a given input–output structure. In Section 4, we provide a case example based on China's input–output and power generation data to demonstrate the application of our approach. Our basic results show that energy import resilience can be significantly influenced by production capacities and technologies of non-energy producing sectors. The numerical studies also reveal that in the case of China, over-reliance on natural gas for power generation (by displacement of coal-fired generation) may compromise the energy import resilience of the economy if no changes to the existing production structure are made. Different approaches are also discussed to improve the energy resilience. Finally, Section 5 concludes this work and suggests future research directions.

2. Literature review

An important application of input–output (IO) analysis is to study the impact of energy shortages on the economic system. For example, Penn and Irwin (1977) demonstrated the use of input–output models for studying energy constrained scenarios, including reduction of crude petroleum imports, shortage of refined petroleum, and restriction on natural gas imports. It was noted that the impacts of shortages were often not obvious and may present unexpected results due to the inter-sectoral dependencies. In another study, Kerschner and Hubacek (2009) applied IO analysis to investigate the impacts of oil supply shortage to the economy. The authors show that their methodology can help identify sectors most vulnerable to oil supply disruptions.

Combining linear programming (LP) (Dantzig, 1949) with IO modeling is a popular approach to study various energy–economy–environment problems in the research literature. Chenery and Clark (1960) proposed an LP model to optimize the use of primary resources such as labor, capital and land by maximizing the total value of total output. Just (1974) presented a methodology to quantify the impact of technological change on the economy. In particular, the authors studied how the adoption of High-BTU or Low-BTU coal gasification and combined gas and steam cycle generation impacts the output of several sectors and change energy consumption, using 1985 projections of U.S. data. Schluter and Dyer (1976) in a later work extended the study by introducing additional constraints on the total output level and maximizing the gross domestic production.

James et al. (1986) proposed an integration of the input–output model with a dynamic energy technology optimization model to project the change in total energy demand and technological mix. The authors then identified some economic implications of technological change and inter-fuel substitution using the model. Leung and Hsu (1984) proposed the use of an LP model to study the economic impacts of energy supply reductions on the Hawaiian economy. The authors used the LP model to compute shadow prices for different levels of gasoline availability, and they demonstrated that the LP solution can be used as an efficient allocation of energy resources to various industry sectors during energy shortages. Other works proposing IO–LP models include Wang and Miller (1995), who analyzed the economic impact of a transportation and energy supply bottleneck on the economy of Taiwan. Rose et al. (1997) used IO–LP to study the regional economic impact of an earthquake and they found that a disruption in electricity was caused but reallocation of the scarce electricity across sectors could reduce the impacts substantially. Wilting et al. (2008) propose a dynamic IO–LP model used to perform scenario analysis with various levels of production and carbon emissions based on different assumptions of future (2030) technological change. Vogstad (2009) provided a more recent review of the modeling capability of LP in IO analysis. Tunkay and Bilge (2012) performed a case study using data from Turkey to develop a IO–LP model for optimizing the distribution of economic resources on sectoral basis to maximize national income.

Most reviewed works on IO–LP in the above focused on using the proposed LP model to optimize some socio-economic objective function (e.g. GDP), assuming that energy availability will remain the same as the data. They have not considered the issues of energy shortages and energy resilience under uncertainty. In our opinion, the latter problems are of greater interest from an energy security point of view, and warrant a deeper study. Hence, in this work, we propose the advancement and enhancement of the IO–LP modeling approach for the analysis of energy resilience. In particular, our focus in this work is to use the IO–LP model as a means to develop an energy resilience indicator of the economy in the event of uncertain energy import shortages.

3. Methodology

In this section, our major goal is to develop a quantitative indicator for evaluating the energy import resilience of a given economy. More specifically, the energy import resilience indicator measures the highest level of energy import losses that can be absorbed by the economy, while maintaining production supply and demand balance in the short run. To achieve a rigorous and meaningful definition of the energy import resilience indicator, however, we first need to develop various related components based on the traditional economic IO model. The relevant notations in this paper are stated as follows. Other notation will be defined as when appropriate and necessary.

s_j	Demand deficit in commodity j
d_j	Domestic demand of commodity j (the domestic exports are included in the domestic demand)
$y_{j,t}$	Output of commodity j using technology t.
u_j	Import of commodity j in physical unit (tonnes of coal equivalent, TCE) for energy sectors, while in monetary unit (in monetary value) for non-energy sectors
a_{ji}^t	Amount of good j consumed for each \$1 production of good i using technology t
r_j	Price for energy import j (in monetary value), while it equals one for non-energy imports
ε_j	Import loss of energy sector j, it equals to zero for non-energy sectors
ε	Vector of import loss
P	Total output
J	Set of economic sectors in the input–output model
J_E	Set of energy goods sectors of interest
T_j	Set of technologies of sector j
$\bar{U}$	Import limit for energy sectors
u_{j_max}	Import limit for non-energy sectors
ω_j	Import limit of commodity, $\omega_j = u_{j\_max}$, $for j \notin J_E$; $\omega = \bar{U}, for j \in J_E$
$x_{j,t}$	Production capacity of commodity j using technology t
$\boldsymbol{x}$	Vector of production capacity
$\boldsymbol{\lambda}, \boldsymbol{\pi}, \boldsymbol{\delta}, \boldsymbol{\mu}$	Dual variables

The economic IO model is developed by Wassily Leontief in the 1930s to study the interdependencies between different sectors using a system of linear equations. It is well-known that the IO model can be