Energy Policy 86 (2015) 651–663

Contents lists available at ScienceDirect

Energy Policy

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

Multi-regional input–output model and ecological network analysis for regional embodied energy accounting in China

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HIGHLIGHTS

- We integrated multi-regional input–output analysis with ecological network analysis.
- We accounted for both direct and indirect energy consumption.
- The centers of gravity for embodied energy flows moved southeast from 2002 to 2007.
- The results support planning of energy consumption and energy flows among regions.

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form
8 August 2015
Accepted 11 August 2015

Keywords:
Urban ecology
Embodied energy
Ecological network analysis
Multi-regional input–output
China

ABSTRACT

Chinese regions frequently exchange materials, but regional differences in economic development create unbalanced flows of these resources. In this study, we examined energy by assessing embodied energy consumption to describe the energy-flow structure in China's seven regions. Based on multi-regional monetary input–output tables and energy statistical yearbooks for Chinese provinces in 2002 and 2007, we accounted for both direct and indirect energy consumption, respectively, and the integral input and output of the provinces. Most integral inputs of energy flowed from north to south or from east to west, whereas integral output flows were mainly from northeast to southwest. This differed from the direct flows, which were predominantly from north to south and west to east. This demonstrates the importance of calculating both direct and indirect energy flows. Analysis of the distance and direction traveled by the energy consumption centers of gravity showed that the centers for embodied energy consumption and inputs moved southeast because of the movements of the centers of the Eastern region. However, the center for outputs moved northeast because the movement of the Central region. These analyses provide a basis for identifying how regional economic development policies influence the embodied energy consumption and its flows among regions.

1. Introduction

Since 2012, China's energy consumption has ranked first in the world (BP Global, 2012). China's goal of regionally integrated development has tightened the economic relationships among regions. However, the resulting exchanges of products create large flows of energy within and between regions. Chinese regions exchange large quantities of materials, energy, products, services, and information, but an uneven distribution of these flows results from obvious differences in regional resource endowments, industrial structures, and degrees of economic development (Zhang et al., 2012c). Energy is a crucial, but limited, resource and its consumption has large environmental consequences. Therefore, it is increasingly important to find ways to conserve energy by better understanding its consumption by China's regions.

The production of goods or services in a system requires both direct energy consumption, with the energy coming from the external environment (in the form of various forms of fuel), and indirect energy consumption that arises during the utilization or exchange of intermediate products (i.e., energy contained in non-energy products and materials). In 1974, the International Federation of Institutes for Advanced Studies defined embodied energy as the total energy (both direct and indirect) consumed during a production process (IFIAS, 1974). The concepts of ecological footprints (Rees, 1992), virtual water (Allan, 1997), and

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http://dx.doi.org/10.1016/j.enpol.2015.08.014
0301-4215/

embodied energy (Odum, 1998) have been used to evaluate the direct and indirect consumption of resources, including energy, during the production of products and delivery of services.

During the 1970s, the input–output method, which tracks the flows of materials among the components of a system, became widely used to account for the flows of embodied resources (Costanza, 1980), including water (Hite and Laurent, 1971), energy (Wright, 1974), and natural resources (Wright, 1975). The high cost of energy promoted the use of this approach in studies of embodied energy in the United States (Cleveland et al., 1984), the European Union (Odum, 1998), and China (Chen et al., 2010; Li et al., 2007). However, most of these studies focused on the energy embodied in domestic final consumption (Reinders et al., 2003) or international trade (Li et al., 2007). To quantify the embodied energy of the socioeconomic sectors within a region, researchers have combined concepts from systems ecology with economic input–output models to develop equilibrium equations that account for this consumption from a macro-scale perspective (Chen and Chen, 2013; Chen et al., 2010; Xu, 2010). This approach supports research on the sectoral energy distribution and lets researchers consider other factors, such as the impacts of this consumption for climate change (Proops et al., 1993; Wier et al., 2001).

To support analyses of the economic exchanges among cities or regions, researchers have compiled multi-regional input–output tables based on input–output analysis. These tables reveal differing production practices for the same sector in different regions and can capture trade relationships between sectors in different regions (Wiedmann, 2009). As a result, the tables were first used to analyze regional economies, and were subsequently expanded to support analyses of the energy consumption (Chen, 2011; Liang et al., 2007), material footprints (Wiedmann et al., 2012), carbon emissions (Guo et al., 2012), and water footprints (Zhang and Anadon, 2014) that resulted from the flows among regions.

To support such analyses, it is important to develop a model of the system, and this is often done using a network model, since networks allow researcher to examine both the components of a system and the flows among them. For example, at a national level, Liang et al. (2007) used this approach to divide China into eight regions based on Chinese administrative divisions. At a finer resolution, Chen (2011) analyzed energy consumption in 2002 for China's 30 provinces. Similarly, Zhang et al. (2012a) studied the energy consumption in 30 Chinese provinces with 30 socioeconomic sectors in 2007. To examine worldwide energy consumption, Chen and Chen (2013) established a network model of the global economy in 2007. They estimated the interregional energy flows for ten major economies.

These studies showed that multi-regional input–output analysis can effectively describe the energy distribution in international trade and the domestic flows between pairs of sectors through a single path (i.e., direct connections between any two sectors), but neglected the important energy consumption that results from flows between any pair of sectors that pass through one or more intermediate sectors. To fully understand a system, researchers can understand both the direct and indirect consumption, and how these energy change over time.

The tools provided by ecological network analysis can comprehensively assess the embodied energy consumption of regions and provinces. This method evolved from input–output analysis, and was introduced by Hannon (1973) to simulate the relationships among an ecological system's components. Subsequently, Patten (1991) built on this approach by proposing a method to systematically simulate the flows and the resulting functional relationships among a system's components, which he named “network environ analysis”. This approach has been applied to analyses of both natural ecosystems and socioeconomic systems (Borrett et al., 2007), including studies of energy (Zhang et al., 2011), urban systems (Li et al., 2012), virtual water (Yang et al., 2012), and carbon (Chen and Chen, 2012). This method can also identify the indirect qualitative relationships among the members in a network and the “benefits” each member receives from belonging to the system (Fath and Patten, 1998). By analogy with natural ecosystems, these relationships among members in a socioeconomic system can be described as competition, mutualism, or exploitation. The “benefits” in this model are related to the concept of “synergism” in ecology, in which the relationships among two or more species produce a greater effect than the sum of their individual effects (Gugumus, 2002; Guo et al., 2009). For natural or socioeconomic systems, synergism reflects the utilities created by the relationships among the system's members. These benefits can be used for analyses at scales ranging from small (e.g., the relationships between genes or species; Dubois (1986)) to very large (e.g., the relationships between climate change and ecology; Schneider and Root (2004)). Many researchers have studied urban socioeconomic systems using these tools. For example, Li et al. (2012) calculated the benefits of Beijing's metabolic system from 1998 to 2007, Chen and Chen (2012) used a synergism index to evaluate the carbon metabolic system of Vienna, and Zhang et al. (2014a) analyzed the benefits obtained by seven socioeconomic sectors in Beijing. Lu et al. (2012) have used these tools to study industrial systems.

Researchers have studied how to use the combination of input–output analysis and ecological network analysis to study the consumption of embodied resources, ecological elements, and energy in urban systems. For example, Zhang et al. (2014b) combined the two methods to convert monetary input–output tables for Beijing from 1997 to 2007 into tables of the flows of materials among the city's socioeconomic sectors. Zhang et al. (2014c) studied Beijing from 2000 to 2010 to analyze the energy consumption of 28 socioeconomic sectors, and characterized Beijing's energy utilization status. These analyses illustrated how the combination of these two methods can trace energy consumption both backwards and forwards through a system to account for the total (embodied) energy consumption involved in producing both intermediate products and final goods, and to reveal the relationships among sectors.

In addition to knowing the quantities of the consumption, it is helpful to know where they are concentrated and how that location is changing over time. The “center of gravity” model offers an effective way to understand the location of this concentration, and the directions and distance it is moving over time (Klein, 2009; Peng and Lin, 2010). Hilgard (1872) first used this method for socioeconomic systems to study population problems in the American west and sunbelt. Since then, this approach has been widely used to analyze the center of gravity for a range of subjects: populations (Aboufadel and Austin, 2006), environmental pollution (Wang et al., 2009), economic parameters (Grether and Mathys, 2010), consumption goods (Fu et al., 2011), ecosystem services (He et al., 2011), and food provision (Wang et al., 2012). However, few researchers have studied the center of gravity for energy consumption (Fesharaki, 1996; Peng and Lin, 2010).

This approach can scale from cities to regions and can track changes over time. For example, Fesharaki (1996) analyzed the energy consumption center of gravity in Asia, and Wang et al. (2006) described the distribution of coal in China. Peng and Lin (2010) traced the changes in the centers of gravity of sulfur dioxide and industrial dust produced by energy consumption in China from 1990 to 2007, and Zhang et al. (2012c) analyzed how the centers of gravity of multiple energy sources changed from 1997 to 2009, and found different movements for the production and consumption centers of gravity. These differences provided guidance on how to optimizeregional energy consumption.

In addition to understanding the magnitude of the flows of