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Interprovincial transfer of embodied primary energy in China: A complex network approach

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HIGHLIGHTS

- A network model is constructed by integrating EEBT and network theory.
- China's multi-layer primary energy flow is tracked at the provincial level.
- Different potential drivers are identified for four types of energy flow.

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ABSTRACT

The energy supply–demand security and climate change has continued to be problematic, making it significant and necessary to investigate embodied energy flow, particularly in a large and fast-growing developing country like China. One of the effective approaches is the energy/emissions embodied in bilateral trade (EEBT) aiming to locate the destination of energy bi-directionally to evaluate how energy flow between producer and consumer sectors. However, in addition to the flow of energy and resources, the topological structure and impact of underlying components from a system science perspective are equally important for policy-making. This study therefore constructs an energy embodied in trade network (EETN) model to track multi-layer primary energy flow by integrating the EEBT approach and complex network analysis. The embodied coal, oil, natural gas, and non-fossil fuels associated with China's 30 provinces/municipalities are quantified at the provincial level. By the joint analysis of the network-oriented metrics, the EETN model elicits the possibility of understanding the heterogeneity distribution of different types of energy flow and the potential impact of province-specific policy interventions. We explain how resource endowment, economic growth, income inequality, cross-provincial industrial transfer, and infrastructures affect China's provincial energy embodiments as well as the clustering features. Other findings and policy recommendations are also presented.

1. Introduction

From 1971 to 2014, the world total primary energy supply (TPES) increased almost 2.5 times. In 2014, the TPES reached 13,700 Mtoe, releasing over 32 $GtCO_2$ [1,2]. Fossil resources accounted for almost 82% of global energy production. As stated by Hall, non-renewable fossil fuels have been inextricably linked to the economic process as well as the potential limits to growth of modern societies [3]. The security of energy supply and emission of pollutants/greenhouse gases are the main concerns relating to fossil fuel depletion, and are addressed by political initiatives and research efforts in many countries, such as India [4], China [5], and Iran [6]. In global discussions aimed at limiting carbon emissions, the national targets are tied to energy use generated within national borders. Ultimately, the key to reducing carbon intensity lies in optimizing the energy fuel mix and improving energy efficiency.

As a major contributor, China accounted for nearly 22% (3,052 Mtoe) of TPES. Under these circumstances, China has committed to reducing its carbon intensity by 60% to 65% by 2030 from the 2005 level, peaking its carbon emissions, and increasing non-fossil fuels to 20% of its energy mix. China's 13th Five-Year Plan (2016 to 2020) for energy stipulates that China will control an aggregated emission reduction, ecological environment quality, and efficiency of energy resource usage.

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Nomenclature

EEBT	energy/emissions embodied in bilateral trade
EETN	energy embodied in trade network
TPES	total primary energy supply
I-O	input-output
MRIO	multi-regional input-output
HEET	hybrid emissions embodied in trade
WIOD	world input-output database
ROW	rest-of-world
GDP	gross domestic product
LNG	liquefied natural gas
EKC	environmental Kuznets curve
MYE	middle reaches of the Yellow River
MYA	middle reaches of the Yangtze River
Mtoe	million tons of oil equivalent
$GtCO_2$	gigatonnes of carbon dioxide
TJ	terajoule
PJ	petajoule
USD	USA dollar
KW	kilowatts
kWh	kilowatt hour
NE	northeast
NC	north coast
EC	east coast
SC	south coast
NW	northwest
SW	southwest
SWD-EET	step-wise distribution of emissions embodied in trade
TIIOT	Transnational Interregional Input-Output Table
DRC	Development Research Center of the State Council of the People's Republic of China

However, China's interprovincial product trade is becoming increasingly frequent because of multiple factors, such as resource endowment, industrial structure, and level of economic development. Product trade results in the transfer of energy consumption (the so-called embodied energy). Thus, one province can reduce its local energy use by directly importing products from other provinces or by reducing the export of high-energy consuming products.

In particular, the contradiction between the energy supplier and receiver presents challenges, which leads to limited optimization configuration of clean energy across the country together with increasing risks in interprovincial channels. The effective adjustment of the relationship between local energy balance and cross-provincial supply promises to address these challenges, as well as ultimately enabling the entire decarbonization of China's interprovincial energy supply [7].

Therefore, more reasonable energy saving and trade adjustment measures between provinces will benefit the realization of national targets. The first task is to fully grasp the characteristics and potential drivers of interprovincial energy transfer from a systems view. The contributions of this paper include (a) combine the global input-output tables and China's interregional input-output tables to investigate the embodied energy flows at the regional level by different energy types; (b) combine the embodied energy flows analysis with the complex network approach to identify the structure of the regional embodied energy flow network; (c) use the community concept to reveal the driving forces involved in the interwoven embodied energy flows.

The remainder of this paper is organized as follows: in Section 2, a detailed literature review is provided. Section 3 of the paper explains the estimation of energy embodied in trade using a multi-regional input-output framework and constructs the energy embodied in trade network using complex network theory. The empirical results of the constructed network are presented in Section 4. The final section summarizes the paper's main findings and future prospects.

2. Literature review

With the magnitude of potential energy consumption, research into embodied energy has been a lively topic. Abundant examples can be found in recent literature that has been applied to different subjects. For example, Liu et al. explored energy use from all industrial sectors in China and found that total indirect energy consumption accounted for 80.6% of total embodied energy consumption [8]. Yang and Chen evaluated the embodied energy of a wind power generation system. The results showed that wind power is more competitive in terms of energy savings compared with other power generation systems [9]. Miró et al. accounted for embodied energy in terms of the total energy inputs of thermal energy storage complementing solar plants [10]. Wu et al. established a complete inventory of energy inputs in a typical coal-power plant and considered the energy embodied in materials, equipment, and services [11]. Most of these studies have focused on the energy directly and indirectly used for the production and delivery of goods or services along their whole life cycle. To reduce the energy consumption of China's building sector, Zhang and Wang used the hybrid input-output approach to analyze supply-chain energy by dividing the life cycle into construction, operation, and disposal stages, finding that energy in the disposal stage contributes significantly to the impact of the overall life cycle [12].

In addition, embodied energy transfer is also a part of the normal pattern of economic phenomena occurring through international trade. Some scholars have studied the energy embodied in trade for a certain country or the main economies in the world. Machado et al., for example, evaluated the total impact of international trade on Brazil's energy use and suggested that the extra influence of international trade policy to be of concern [13]. Cortés-Borda et al. quantified the amount of solar energy embodied in trade between 10 economies [14]. In the existing literature, input-output (I-O) analysis is widely recognized as the appropriate methodological tool to perform energy embodiment analysis. Wiedmann et al. demonstrated that there is no "best" model, but only a "best" model for a specific purpose. I-O analysis is very detailed in its description of commodities produced in economies and can provide detailed static ex-post accounting tools for monetary and non-monetary (physical) quantities [15]. Rocco and Colombo evaluated the energy embodied in national products through I-O analysis and suggested that the use of appropriate international trade treatment methods is needed [16]. Since the I-O tables capture the exact quantitative economic relationships between industrial sectors, scholars have carried out large numbers of I-O analyses regarding the energy embodied in trade. See, for example, the review of methods in Sato [17] and the survey of the empirical literature studying embodiments in China's foreign trade in Zhang et al. [18].

The above studies provide two main environmentally extended I-O models to study the energy embodied in multi-national trade: the multi-regional input-output approach (MRIO) and energy/emissions embodied in bilateral trade approach (EEBT) [19]. MRIO considers trade to final consumption and endogenously determined trade to intermediate consumption. For example, Wiedmann compared energy footprints embodied in trade in the UK in 2002, and concluded that MRIO models will be particularly suitable to estimate the ecological footprints of national trade and to track their origin via inter-industry linkages, international supply chains, and multi-national trade flows [20]. Sato et al. used an MRIO model to estimate the quantities and directions of embodied energy flows in the global supply chains of 134 countries, and evaluated the diversity of the embodied-energy trade [21]. The new approach of the MRIO model to alleviate energy embodied in the commodity trading process leads to more people being concerned with this issue. EEBT focuses more on the domestic supply chain and