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Coal use embodied in globalized world economy: From source to sink through supply chain

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ABSTRACT

An empirical analysis of coal use embodied in the globalized world economy is performed in the present work via the application of a systems multi-regional input-output model for 2012. The use of primary coal is tracked from the sources of exploitation to the sinks of final use through inter-regional trade as a global supply network. Mainland China is revealed to be the largest coal user, but the per-capita coal use embodied in its household consumption is only a quarter of that in the United States, and doesn't even exceed the level in the United Kingdom, the leader in the movement away from coal. The global trade volume of coal use is in magnitude calculated up to seventy percent of the world total coal exploitation. The United States is demonstrated to be the world's leading importer of coal use, of which the imports are dominated by non-coal products as indirect coal imports. In contrast, mainland China is the leading exporter, mainly due to the massive exports of commodities 'Made in China'. Two new indicators of self-sufficiency rates are developed, in order to explore the direct and indirect external coal dependence of the region. Two-fifths of the coal finally used by the United States turns out to be exploited from foreign areas, which is different from the result that the United States has no dependence on foreign coal resources based on the conventional external dependence degree. This overview of coal use aims to provide a global insight into energy sustainability, as well as a sound scientific reference for policy making for global resources management and climate change mitigation.

1. Introduction

Coal is one of the most basic energy resources around the world. Its earliest utilization in human history can be traced back to 1500 BCE when this black resource was firstly discovered in China [1]. But it was not until the Industrial Revolution of the 18th and 19th centuries that the large-scale excavation and extensive use of coal resources were carried out worldwide. Coal served as the dominant fuel to run the new industries during that period of technological reformation. The market for coal was therefore greatly expanded, and has continued to grow ever since, with occasional temporary fluctuations [2]. Nowadays, coal still plays a vital role in the world's primary energy mix. In 2015, coal provided 29% of global primary energy needs, 41% of the world's electricity, and an essential input into 44% of the world's industry production [3,4]. Because of the low cost and wide availability, coal's role is expected to remain at the similar level over the next 20 years [4].

However, with the widespread coal use, the environmental pollution caused by coal mining and combustion has become an increasing concern [5]. Issues such as fog and haze, acid rain, and groundwater contamination have long been linked to coal. What's more, coal has a relatively high carbon content, and coal consumption is now regarded as the leading source of anthropogenic greenhouse gas emissions causing global warming threat [6]. In 2014, coal-related CO_2 emissions reached 15 Gt, nearly half of global total emissions [7]. The use of coal has therefore become the focus of both energy and environmental strategies, and has attracted an enormous amount of research attention.

Previous researches on coal have contributed significantly to facilitating people's understanding of this resource from various aspects, including its regional consumption [8,9], optimal management [10,11], market transactions [12,13], environmental disadvantages [14,15], policies and regulations [16,17], and so forth. However, those studies were confined to the direct coal use, the direct coal trade and the direct pollution induced by the direct coal use. With regard to the indirect coal use or trade, i.e., the consumption or transaction of commodities and services that require coal inputs in their production processes, few studies have ever given due consideration [18,19]. Coal as a basic natural resource provides numerous industries with energy

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Nomenclature

BCE	before common era
CO_2	carbon dioxide
IOA	input-output analysis
IEA	International Energy Agency
ASEAN	Association of Southeast Asian Nations
EU	European Union
ROW	rest of world

Formulae

z	sectoral exchanges for intermediate use
f	sectoral exchanges for final use
d	sectoral direct coal exploitation
ε	sectoral embodied coal intensity
o	sectoral total output
Z	matrix form of z
F	matrix form of f
D	matrix form of d
E	matrix form of ε
O	matrix form of o
CEF	coal embodied in regional final use
CED	coal exploited directly by region
CCD	coal consumed directly by region
CEI	coal embodied in regional imports
CEE	coal embodied in regional exports
CEB	coal embodied in regional trade balance
γ	self-sufficiency rate

and material support, and considerable amounts of indirect coal use is hidden in these industrial products and services. For example, a telephone requires electricity during its manufacturing course, while coal in some countries, like China, is the major fuel for the generation of electricity. Coal is therefore indirectly used by the telephone made in China. As a matter of fact, many high-income nations get a decline in domestic coal use and carbon emissions through importing coal-intensive goods and services from the middle- and low-income areas. With the aid of international trade, those net-importing countries successfully transfer the pressures on resources and environment to the foreign regions [20,21]. This transfer phenomenon is becoming increasingly prominent in the present globalization, and is likely to mislead the allocation of national responsibility in international cooperation for resource conversation and environmental protection. Hence, it is imperative to comprehensively explore the indirect coal use embodied in the global commodity and service flows.

The indirect effects have been emphasized previously regarding energy use [22,23], greenhouse gas emissions [24–26], freshwater consumption [27–29], land occupancy [30,31], mercury pollution [32], etc. Typically, Lenzen et al. [33] provided an energy evaluation for the city of Sydney, and showed that the indirect energy consumption in Sydney was 2.3 times of the direct energy consumption. A similar ratio can also be found in another report on the energy use of Macao, China [34]. For the European Union overall, Steen-Olsen et al. [35] pointed out that 43% of its total carbon emissions, 47% of total land use and 52% of total water consumption occurred indirectly because of the internal and external trade. According to Wiedmann et al. [36] on raw material consumption of the whole world, the indirect trade volume of materials and products is presented in magnitude twice larger than that of the direct physical trade. It can be seen that the indirect effects are now playing an even more important role than the direct ones. Given the unique status of coal in both energy and environmental fields, this work aims to present a systematic overview for both the direct and indirect coal use in the world economy by means of the embodiment analysis for the first time.

The embodiment analysis has its origin in the theory of systems ecology [37,38], and has been extensively applied to reveal the systems energetics. A well-known concept is the embodied energy, which is defined as the total (direct plus indirect) primary energy inputs to generate and sustain a product or service [39]. Here, this concept is specialized for primary coal as total coal embedded in the product or service, which can be termed as embodied coal, parallel to the terms of embodied oil [40], embodied solar energy [41] and embodied nuclear energy [42] in previous studies. For the economy, coal is essentially an exogenous primary resource from the environment [43]. To obtain the utility of coal to maintain the economic system, human beings exploit coal resource from the environment. From the perspective of systems ecology, this resource is used once it is exploited because the resource leaves the environmental system at the point. Then in the economic system, the utility of coal is embodied in various goods and services and consumed by the final use activities. In this regard, the present research of embodied coal is conducted based on coal exploitation from the environment for the economy in terms of coal's economic use, which is different from the previous embodiment analyses focusing on coal's technological consumption, i.e., the combustion of coal [44,45]. Here coal use embodied in the world economy is overviewed and the coal use flows embodied in the inter-regional trade are tracked from the source of exploitation to the sink of final use, to make an inclusive world coal budget.

2. Methodology and data

2.1. Multi-regional input-output model

The input-output analysis (IOA) is acknowledged to be a useful top-down technique to underpin the embodiment accounting. The input-output tables document the interactions between industries within an economic system, and thus enable us to trace both the direct and indirect effects through the complex trade exchanges [46,47]. Since the original introduction of IOA to economic simulation in 1936 [48], it has induced vast attention in the academic field and many related models like single-regional IOA [49,50], multi-regional IOA [51–53] and inter-regional IOA [54–56] have been proposed. As an improvement of single-regional IOA by distinguishing between domestic and foreign production technologies, and a simplification of inter-regional IOA dealing with data limitations, multi-regional IOA shows a significant advantage to describe the world economy, and finds broad application to embodiment studies [57].

In recent years, a systems multi-regional IOA model is developed based on the embodiment concept in the systems ecology, in terms of the biophysical balance that total resources use induced by total outputs equals exogenous resources inputs plus resources embodied in intermediate inputs [58]. This model pays equal attention to the intermediate use and the final use as two basic components of the total output. The ecological endowments flows associated with both the two components can therefore be depicted to help perceive the complete picture of how resources or emissions flow within the system. So far, this model has been applied to numerous systems, including industrial production systems [59–61] and economic systems at regional [62,63], national [64,65] and global [66–68] scales. In the present paper, the systems multi-regional IOA is adopted for a systematic analysis of coal use by the globalized economy.

2.2. Algorithm

The world economy is considered as a m-region, n-sector coupled network. For each sector in each region as an individual entry, the

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