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Energy overview for globalized world economy: Source, supply chain and sink

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ABSTRACT

Energy use of the globalized world economy is comprehensively overviewed by means of a systems input-output analysis based on statistics of 2010. Emphases are put on the sources of primary energy exploitation, inter-regional trade imbalance of energy use via global supply chains, and sinks of energy use in final demand. The largest final user turns out to be the United States, compared with China as the leading energy exploiter. The global trade volume of energy use is shown in magnitude up to about 90% of the global primary energy exploited. The United States is recognized as the world's biggest energy use importer, in contrast to Russia as the biggest exporter. Approximately one third of global primary energy exploited is shown to be embodied in inter-regional net trade. Japan and Russia are respectively illustrated to be the world's leading net importer and leading net exporter of energy use. For China as the leading energy exploiter, about 30% of its exploited energy is for foreign regions' final use, and 70% for its own final use. For the European Union as the largest sink region, nearly 80% of the energy required in its final use is from foreign regions, led by Russia. As reflected in the results, the conventional perspective based only on the direct energy consumption by region inevitably leads to inter-regional "energy grabbing" and "carbon leakage", which raises a serious concern of "regional decrease at the expense of global increase". In current context of energy shortage and climate change, this global energy overview can provide essential strategic implications at the international, national and regional scales for sustainable energy policy making.

1. Introduction

The development of social economy requires massive inputs of natural resources, especially energy, which is regarded as the main driver of economic growth [1,2]. In 2014 alone, the world primary energy consumption ascended to approximately 13 billion tons oil equivalent, increasing by 22% and 54% respectively compared to that in 2004 and 1994 [3–5]. The rapidly rising demand has accelerated the exploitation of energy resources from the natural environment, and ultimately brought severe challenges of energy scarcity and climate change. According to BP, the world's proved reserves of oil, natural gas and coal at end-2014 were expected to meet 53, 54 and 110 years of global production at most, separately [3]. Energy resources conservation has therefore become an urgent concern in today's world. Meanwhile, as energy-related greenhouse gases (GHG) emissions account for over 80% of global anthropogenic emissions [6,7], energy saving is also essential for the mitigation of global warming.

In this context, extensive policies for sustainable energy use have been formulated in different countries, such as the *Thirteenth Five Year Plan* in China, the *Energy Independence and Security Act* in the United States and so forth [8–10]. However, each of the strategies was made merely for the energy consumed within its corresponding sovereign territory, and didn't account for the energy used outside the country to meet the domestic demand. In fact, the world economy has developed into an integrated network at this age of globalization dominated by international trades. All countries in the world are connected by this network and have become increasingly interdependent. It is common that a product is produced in one country using energy by either local exploitation or foreign trade and is then exported to another country for reprocessing or consumption. As a result, the actual energy requirement of a country is always overestimated or underestimated [11–13]. In order to justly identify the responsibility of countries and sectors in international cooperation for energy conservation and carbon reduction, it is imperative to perform a comprehensive review for inter-regional energy use flows and connections for the globalized village.

To reveal the systems energetics, one can resort to the well-known concept of embodied energy in systems ecology [14]. For an economic

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system, energy use can be concretely quantified by embodied energy, which is defined as the total (direct plus indirect) primary energy inputs to generate and sustain a product or service, considered as if the energy was embedded in the product or service itself [15,16]. In contrast to the direct energy accounting which merely considers the on-site immediate energy use, embodied energy analysis also incorporates historical and off-site information and facilitates the accounting for actual energy consumption from a systems perspective.

Hence, in the pursuit of effective policy to maintain energy sustainability, the embodied energy method has gained wide applications in various economic systems of different scales [17–20]. At the city scale, Li et al. [21] performed an assessment of energy embodied in Macao's external trade from 2000 to 2011, and pointed out that Macao's indirect energy consumption surpassed the direct energy consumption. This phenomenon could also be found in another embodied energy study on Beijing city [22]. Then Chen and Chen [23] carried out a further evaluation of embodied energy consumption in Beijing, and identified manufacture and services as two dominant sectors driving urban energy consumption. At the national scale, Limmeechokchai and Suksuntornsiri [24] quantified the total energy use and related GHG emissions in final consumptions within Thailand, and compiled the embodied energy intensities for 180 economic sectors in this country. Bordigoni et al. [25] examined the role and consequences of embodied energy in the European industry, and found that about one quarter of the energy embodied in the European industry output came from outside the European Union. At the global scale, Chen and Chen [5] employed a systems embodiment model to investigate the energy use of the world economy, and predicted China would take over the United States as the world's top embodied energy consumer after about one decade. Moreover, the embodied energy method has also induced attention as a valid tool to appraise the performance of production systems at the industrial scale [26–28]. Those aforementioned studies on embodied energy have contributed significantly to deepening people's understanding of direct and indirect energy use, in addition to providing precious information for energy conservation.

In the present study, energy use flows within the 2010 world economy are depicted by means of the embodied energy method. Different from most existing researches based on the environmentally extended input-output analysis associated with technical consumption of primary or secondary energies within technical apparatus belonging to various production sectors [29,30], this work presents an embodied energy study in terms of systems input-output analysis based on primary energy exploitation from the environment for the economy. Associated with technical processes, primary energy resources like crude oil and coal are burned to provide heat, wind kinetic energy and hydro-potential are converted to provide power, and secondary energy resources like petroleum is burned to propel an engine and electricity is utilized in different ways. There are so many different ways of technical consumption of energy resources. But from the perspective of system ecology, primary energy resources are natural resources that originally belong to the environmental system outside the economic system [14,31,32]. Once being exploited, energy resources are removed from the environmental system and enter the economic system. From the economic point of view, the genuine primary energy resources are used at the point of energy exploitation, and all the non-primary energy resources, no matter conventionally referred to as primary or secondary energies, are only energy products, out of the economic use of primary energy and other primary natural resources such as water. In this regard, primary energy is used in the interaction boundary between the environment and the economy through the exploitation by quarrying, mining and recipient processes, then the energy use is embodied in the product flows within the economy to the final demand by the society. In short, primary energy is an environmental input for the economy, and there are only embodied energy flows in the socio-economy. Costanza [33] evaluated both the technical consumption and the economic use of energy resources in the United States economy in 1963, 1967 and 1972. Wiedmann et al. [34] presented a time series analysis of various natural resources flows from the point of resources exploitation in the global economy. Grounded in the existing studies, this work takes the exploitation process as the source of energy use flows to explore an all-inclusive world energy budget. Energy flows embodied in inter-regional trades are tracked from the source of energy exploitation to the sink of final use connected by the global energy supply chains.

The remainder of this paper is structured as follows. In Section 2 the methodology is described, with emphases on detailed illustrations of models and algorithm. Section 3 demonstrates the main results for embodied energy flows in regional consumption and inter-regional trades, and major findings are discussed. Finally, concluding remarks are made in Section 4.

2. Methodology and data sources

2.1. The input-output analysis (IOA)

The input-output analysis (IOA) was originally proposed in the 1930s as a technique to describe interactions between industries within an economic system [35,36]. Then to explore the relationship between the environment and the economy, numerous efforts were made to apply the method of IOA to environmental researches [37–39]. Leontief [40] firstly extended the IOA to measure the carbon monoxide released by economic activities, which has been widely used for environmental studies and referred to as environmentally extended IOA [41–45]. Then based on the conservation law, Bullard and Herendeen [46] proposed a modified IOA scheme to study the flows of energy embodied in goods flows, as generalized by Chen and his collaborators for embodiment analysis for various ecological elements as natural resources and environmental resources, in terms of the systems IOA model [47–49].

In the two IOA models, the economic input-output table is extended to include two types of energy data, one for internal, technical energy consumption and another for external, environmental energy supply. In the environmentally extended IOA, for each economic sector the direct technical consumption of energy (the internal technical consumption of secondary energy as product of primary energy as environmental supply) is assigned to be the virtual energy consumption of the final demand satisfied by the sector. In this way, one tries to promptly predict the energy requirement when there is a change in the final demand for a certain commodity [20,50]. As intermediate products are considered as internal feedback within the economy for finally providing the society with the final use, energy use flows caused by intermediate production are not depicted. That is, the concept of virtual energy is only applied to the final demand, explicitly exclusive to the intermediate product. In contrast, by the systems IOA model as a conservational scheme, for each sector the embodied energy, defined as the total primary energy use induced by the total output, is equal to the exogenous primary energy input by the sector plus embodied energy of intermediate input from the economy into the sector [33,46,51]. Not only energy utilization for final demand but also energy communication among intermediate production activities are delineated.

Let's consider the energy use flows associated with a typical sector. Illustrated in Fig. 1 are the physical input-output flows of the sector. From an economic perspective, this sector receives intermediate inputs from other sectors or itself (Z_{in}) to produce total outputs (X), which is composed by the outputs for sectors' intermediate production (Z_{out}) in the economic system, and the outputs for final use (F) in the social system. With regard to energy resources, $E_{exploitation}$ records the sector's exploitation of primary energy resources from the environmental system as the exogenous, external supply for the economic system, and is denoted by a blue line. Given the fact that all primary energy resources exploited by a sector is usually not technically