Energy Policy 105 (2017) 41–52

Contents lists available at ScienceDirect

Energy Policy

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

Quantifying the supplier-portfolio diversity of embodied energy: Strategic implications for strengthening energy resilience

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ARTICLE INFO

Keywords:
Embodied energy
International trade
Resilience
Diversity
Input-output model

ABSTRACT

This paper investigates energy resilience of countries by quantifying the supplier diversification of both direct and embodied energy import. In particular, we quantify two approaches to diversify a country's supplier portfolio: by lowering the dependency on each supplier (portfolio diversification) and by having embodied energy suppliers that are different from its direct energy suppliers (portfolio differentiation). We examine possibilities for strategic utilization of embodied energy trade to compensate for low diversity of direct energy trade for three types of fossil resources: coal, oil, and gas. We find that the diversity of embodied energy import is much greater than that of direct energy import. Of the three energy resources, coal enables countries to adopt portfolio diversification and portfolio differentiation more than gas and oil. Our results suggest embodied energy can be considered as a transfer of energy resources across national borders that can directly benefit from the diversity of the world energy production by "skipping" the limited diversity of the world energy export.

Introduction

Energy security of countries is increasingly threatened by growing uncertainties and instability in energy supply chains, which include vulnerable and aging infrastructure (Farrell et al., 2004; Stern, 2004), terrorist attacks (Lilliestam, 2014; Umbach, 2010), and natural disaster (Sun et al., 2014). One common practice for improving energy security of a country has been to diversify its supplier portfolio, an approach that is similar to asset portfolio diversification (Stirling, 1994, 2010; Stringer, 2008; Vivoda, 2009, 2014; Yang et al., 2014; Yergin, 2006; Asia Pacific Energy Research Centre, 2000; Lesbirel, 2004). Broadening one's supply partners to include multiple countries and regions with varying risks could alleviate the influence of disruptive events or shocks in a particular country or region.

In today's globalized and highly connected economy, however, the diversification of direct trade partners is not sufficient for controlling major energy-related risks. A country's domestic production and consumption are based upon complex networks of production processes located both inside and outside the country. Each of these production processes has its own energy suppliers, and those energy suppliers may be different from the main direct energy suppliers of the countries that produce or consume the final products of those production processes. If segments of supply chains located in exporting countries upstream of an importing country are cut due to a sudden suspension of energy supply to the upstream country, the domestic production and consumption of the downstream country could also be impaired, even though its own direct energy imports are not affected.

Therefore, decision makers in both public and private sectors need to take into account not only the stability and reliability of direct energy import but also those of embodied energy import, that is, the sum of the energy directly imported to a country and the energy used outside of the country in the production process of the country's final products. Furthermore, we argue that, in the case of limited diversity of direct energy import, the diversification of embodied energy import could contribute to strengthening energy security. That is, if a country is heavily dependent on a single region for its direct energy supply, then the country can strategically diversify its supplier portfolio of embodied energy, and the overall supply chain will be able to compensate to some

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http://dx.doi.org/10.1016/j.enpol.2017.02.024
Received 14 June 2016; Received in revised form 4 January 2017; Accepted 14 February 2017

degree for the vulnerability of direct energy supply.

Despite the growing importance of embodied energy trade network in energy security of countries, there is no study that analyzes supplier diversification of embodied energy in a quantitative and systematic manner. This paper evaluates energy resilience of countries from the perspective of supplier diversification of both direct and embodied energy import. We examine how compositions of indirect energy suppliers can affect the resilience of the entire embodied-energy trade network. In particular, we quantify two approaches to diversify a country's supplier portfolio: by lowering the dependency on each of the suppliers (portfolio diversification) and by having embodied energy suppliers that are different from its direct energy suppliers (portfolio differentiation). We calculate the supplier-portfolio diversity for three types of fossil resources, namely, coal, oil, and gas. Then, we attempt to identify possibilities for strategic utilization of embodied energy trade to compensate for low diversity of direct energy trade for each of these resources.

Methodologically, we use a multi-regional input-output (MRIO) model to estimate the quantities and directions of embodied energy flows in the global supply chains of 134 countries/regions. We then systematically evaluate the diversity of the embodied-energy trade for coal, oil and natural gas via two steps. First, we apply the Shannon-Weaver index (SWI) to each country's supplier portfolios for each energy channel and examine the correspondence between the SWI values of direct and embodied energy import to evaluate the degree of portfolio diversification. Second, we evaluate the cosine similarity (CS) for each country's supplier portfolios of direct and embodied energy import to quantify the degree of portfolio differentiation.

The rest of the paper is structured as follows. Section 2 overviews the related literature. Section 3 gives definitions of some technical terms used in this paper, and describes the model and data. Section 4 presents the major results and analysis. Section 5 concludes and suggests future research directions.

Related literature

Diversification of energy supply has long been argued in the energy literature as an essential strategy for ensuring energy security (Helm, 2002; Stirling, 1994, 2010; Stringer, 2008; Vivoda, 2009, 2014; Yang et al., 2014; Yergin, 2006) and sometimes treated even as a proxy for energy security (Ranjan and Hughes, 2014). It reduces the risks of supply disruption that may arise from excessive dependence on a single source (Asia Pacific Energy Research Centre, 2000; Lesbirel, 2004; Vivoda, 2009). Some studies provide a theoretical background for the function of diversification. For example, Stringer (2008) conceptualizes diversification of energy supply using modern portfolio theory: the idea is to create a portfolio that includes multiple investments in order to reduce risk. Helm (2002) also argues that the function of diversity is best seen as a portfolio effect: in the same way that risks are spread in financial markets by diversification, diversifying fuel sources can reduce risk. Stirling (2010) defines energy diversification as a pursuit of an evenly balanced reliance on a variety of mutually disparate options, and argues that diversity remains effective (at least in part) even if the sources or modalities of the prospective disruptions are effectively unknown. These risk-reducing functions of diversification are also applicable to embodied energy, and thus, as we will see bellow, we attempt to extend the theoretical frameworks of previous studies on diversification of direct energy supply to that of embodied energy supply.

Diversification of energy supply can be viewed from several different dimensions. Two major dimensions commonly discussed in the energy literature are source diversification and supplier diversification.[1] Source diversification refers to the diversification of fuel-types, such as oil, gas, coal, nuclear, hydroelectric, wind, solar and biofuels. Several studies argue the importance of source diversification for ensuring energy security of a country (Bhattacharyya, 2009; Helm, 2002; Salameh, 2003; Stringer, 2008). Concerning embodied energy, Kharrazi et al. (2015) examines the source diversification of the world's embodied electricity trade. Supplier diversification refers to the diversification of the countries or regions that supply energy commodities to the target country. Several researchers have analyzed the role of supplier diversification qualitatively or quantitatively (Cohen et al., 2011; Ge and Fan, 2013; Gupta, 2008; Le Coq and Paltseva, 2009; Löschel et al., 2010; van Moerkerk and Crijns-Graus, 2016; Wu et al., 2009; Yang et al., 2014). However, these studies only consider the diversification of direct energy import. Our paper seeks to extend these works by broadening the analyses of supplier diversification to incorporate embodied energy.

Only a few studies have examined energy security from a perspective of embodied energy. Based on a breakdown of the origins of the embodied energy flows of 28 European countries into national, EU, and non-EU categories, Bordigoni et al. (2012) argues that taking into account only national energy prices is insufficient since domestic industries also depend on energy price variations of foreign countries through imported intermediate products. Similarly, from the fossil energy embodied in UK's imports and exports, Tang et al. (2013) concludes that, in addition to direct energy imports, indirect energy imports are also points of vulnerability that should be considered in energy security. Bortolamedi (2015) provides a more comprehensive framework, which quantifies the direct and indirect energy use of 25 European countries by extending three widely-used indicators of energy dependency to embodied energy: primary energy intensity (EI), net import dependency (NID), and primary energy carrier dependency (PECD).

While these studies partially extend the concept of a country's energy dependency to embodied energy, they do not consider supplier diversification of embodied energy.[2] For example, the difference in energy security between two countries cannot be evaluated by energy dependency alone in the case where, although both of the countries have exactly the same dependency rate, the embodied energy import of one country depends entirely on a single country whereas the other country diversifies its supplier portfolio. In this paper, we address this issue by quantifying the diversity of a country's embodied energy portfolio and examining the relationship between direct energy import and embodied energy import in improving energy resilience of a country.

We acknowledge that diversification alone is insufficient to ensure energy security of a country. As has been pointed out in several papers, diversification is only one of numerous measures that can enhance energy security of a country (Bahgat, 2006; Ranjan and Hughes, 2014; Stirling, 2010; Yergin, 2005; Vivoda, 2009). Other important dimensions of supply security include energy conservation, energy efficiency, technological innovation, strategic stockpile, reliance on indigenous resources, improving energy infrastructure, efficient functioning of energy markets, increasing international cooperation among the importers, and improving political relations with the exporters (Stirling, 2010; Vivoda, 2009, 2014). In addition, Lesbirel (2004) and Månsson et al. (2014) point out that diversification can only address specific risks where events that affect supply are uniquely related to an individual supplier. It cannot reduce systematic risks that affect all agents on the market (Lesbirel, 2004; Månsson et al., 2014) or systemic risks, such as the risk of market collapse, which originate from interdependencies enabling events to cascade within systems that are

[1] Other dimensions include diversification of transportation routes, infrastructure, (*footnote continued*) energy-related industries, energy-related R&D spending, and ownership of energy companies (Månsson et al., 2014; Sovacool, 2011; Vivoda, 2010, 2014).

[2] Tang et al. (2013) show supplier distribution of UK's embodied energy trade, but they do not quantify the degree of diversity.