The Resilience of Embodied Energy Networks: A Critical Dimension for Sustainable Development Goals (SDGs)

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Abstract

Access, renewables and efficiency have been identified as targets in the field of energy under the Sustainable Development Goals (SDGs). Resilience is also a critical dimension that needs to be considered in moving towards sustainable energy. Diversification of direct energy suppliers has been the conventional recourse for achieving energy security. In consideration of the increasingly globalized nature of trade, energy and supply chain networks, however, this approach would be insufficient for addressing the resilience of energy supplies to potential environmental, economic and social shocks and disruptions. In this paper, we investigate countries' energy resilience by quantifying diversity in suppliers of both direct and embodied energy and examine how selections of indirect energy supplies can affect the resilience of the entire embodied-energy trade network. We find that the geographical diversity of embodied energy imports is much greater than that of direct energy imports, and there are considerable variations across countries in the diversification of embodied energy imports. This suggests a possible strategy for countries that depend heavily on a few neighbors for their direct energy imports to diversify their supply chains globally in order to benefit from larger diversity of embodied energy supplies, thereby strengthening the energy resilience of their economies.

Key words: embodied energy, energy resilience, multi-regional input-output model

1. Introduction

Sustainability involves coming to terms with long-term constraints on various types of resources, especially energy, as one of the most critical issues at the global level. The fundamental link between sustainable development and sustainable energy has been recognized internationally since the UN General Assembly's declaration of 2012 as the International Year of Sustainable Energy for All and also of 2014–2024 as the UN Decade for Sustainable Energy for All. The UN Secretary General's Sustainable Energy for All (SE4ALL) initiative set three specific goals for the year 2030, namely, ensuring universal access to modern energy services, doubling the global rate of improvement in energy efficiency, and doubling the share of renewable energy in the global energy mix (Secretary-General's High-Level Group on Sustainable Energy for All, 2012). The importance of promoting access, renewables and efficiency for energy has been formally adopted for Goal 7, "Ensure access to affordable, reliable, sustainable and modern energy for all," in the Sustainable Development Goals (SDGs) at the United Nations General Assembly in September 2015 (United Nations, 2015).

In addition to these three aspects, resilience is also a critical dimension that needs to be considered in moving towards sustainability (Kharrazi *et al.*, 2014; Kharrazi *et al.*, 2015; Kharrazi *et al.*, 2013). As we live in a complex, interconnected natural-social system, it is crucial for us to maintain capacities for coping with various types of shocks, disruptions and extreme events, which often happen unexpectedly (Yarime & Kharrazi, 2015). A small-scale, unexpected disturbance to the delivery of energy could lead to major socio-economic and environmental consequences. The idea of resilience hence is explicitly emphasized in some of the goals and targets identified in the SDGs (United Nations, 2015). In Goal 1 for ending poverty in all its forms everywhere, for example, Target 1.5 is specifically aimed at building the resilience of the poor and those in vulnerable situations and reducing their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters by 2030. Goal 11 calls for making cities and human settlements inclusive, safe, resilient and sustainable, and a target is set by 2020 to substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, as well as resilience to disasters, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030. Goal 13 also targets strengthening of resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. Goal 14 is set to sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts by strengthening their resilience by 2020.

The energy resilience of a country is, in general, influenced by a combination of its internal and external conditions. In addition to the physical energy endowment, internal conditions are characterized by the country's economic structure related to energy, such as the energy intensity of production systems and the degree of concentration on specific energy carriers. Governments and companies can have direct and indirect influences on those conditions through domestic energy policies and technological improvements. External conditions are mainly characterized by the country's overall dependence on foreign energy resources and the way it ensures a secure access to them. One of the most important components of strategies to improve external conditions is the choice of countries/regions to supply the country's primary energy. Governments and companies determine their suppliers by considering not only the price, quality and transport costs of energy, but also various economic, social and environmental factors such as diplomatic relations, security of transportation corridors, e.g., sea lanes and pipelines, the possibility of production adjustments resulting from international energy cartels, e.g., the Organization of the Petroleum Exporting Countries (OPEC) and the Gas Exporting Countries Forum (GECF), and risks of regional conflicts and wars.

In an increasingly globalized economy, however, the selection of direct trade partners is not sufficient for controlling major energy-related risks. A country's domestic production and consumption are built upon complex networks of production processes located both inside and outside the country. Each step in the production processes has its own energy suppliers, which may differ from those of the country of final destination in the entire supply chain. If segments of upstream production of an exporting country stagnate due to a sudden suspension of energy supply from a particular region, the domestic production and consumption of the final destination country could also be impaired, even though its own direct energy imports are not affected. Thus, governments and companies need to consider not only the conditions of the suppliers directly exporting energy to them, but also those supplying energy to other manufacturers throughout the whole supply chain. In other words, secure and sustainable energy in the global economy requires us to consider suppliers by evaluating embodied energy imports, which are generally defined as the sum of direct energy imports and indirect energy use in the production process outside the final destination country.

A common practice for improving the energy security of a country has traditionally been to diversify its supply portfolio (Sovacool & Brown, 2010). Heavy dependence on a single supplying country or geographical area would make energy supplies vulnerable to risks of particular regions. Broadening one's supply partners to include multiple regions with varying geopolitical risks could alleviate the influence of undesirable events or shocks in a particular country or region.

In the context of the accelerating globalization of trade, however, the practice of direct supply diversification would not be sufficient to cope with various types of disruptions and disturbances that could happen throughout the supply chain of embodied energy. If the energy supplies of a country's trade partners are heavily dependent on a high-risk region, the entire supply chains of the final destination country, even if it sufficiently diversified its direct energy suppliers, would become vulnerable to energy-related shocks specific to the region. On the other hand, if a country is heavily dependent on a single region for its direct energy supply, but it strategically differentiates its supplier portfolio of indirect energy from that of direct energy, the indirect energy supply network could compensate for the vulnerability of its direct energy supply and strengthen the resilience of the entire supply chain of embodied energy.

While the above concepts are critical to energy policy and strategy, the selection of embodied energy suppliers and their diversity has rarely been investigated in the literature. In this paper, we evaluate countries' energy resilience from the perspective of diversity in suppliers both of direct and embodied energy and examine how selections of indirect energy supplies can weaken or strengthen the resilience of the entire embodied-energy trade network. Specifically, we use a multi-regional input output (MRIO) model to estimate the quantities and directions of energy flows in the global supply-chains of 134 countries proceeding via three different energy channels: a) direct energy imports, b) embodied energy imports for production, and c) embodied energy imports for consumption. We then systematically evaluate the diversity of suppliers for each of these three channels by applying the Shannon-Weaver index (SWI) and cosine similarities (CS) to the supplier portfolio of each channel used to import energy by each of the 134 countries.

Direct energy imports to a country are the importation of energy resources such as coal, oil and gas transported directly from energy-producing countries to that country. The imported energy may be used in domestic electricity or heat generation, transportation systems or domestic industrial processes as material inputs. We define embodied energy imports for production as the sum of the direct energy imports that are consumed in the domestic production process of all final goods, including ones that are exported, and the energy that is consumed in other countries for producing those final goods, that is, the amount of energy consumed in the supply chains leading to the final goods but located in other countries. We define embodied energy imports for consumption as the sum of the direct energy imports that are consumed in the country for producing final goods that are consumed domestically and the energy consumed in other countries to produce final goods imported for consumption in the country.

The rest of the paper is structured as follows. Section 2 gives an overview of related literature that focuses on the differences between direct energy and embodied energy trade from the perspective of energy resilience. Section 3 describes the model and data used in this paper. Section 4 presents the major results and an analysis. The conclusion follows in Section 5.

2. Related Literature

A large body of literature has proposed methodologies of quantifying energy resilience of countries, which include indicators such as the ratio of energy consumption to gross domestic product (GDP), the ratio of imported primal energy to total energy consumption, and the consumption share of particular energy carriers. Although some of these studies consider the choice of supplier countries and their geographical diversity (Gupta, 2008; Cohen *et al*., 2011; Bhattacharyya, 2009; Frondel & Schmidt, 2014; Le Coq & Paltseva, 2009; Löschel *et al*., 2010), their analyses have been restricted to the diversification of direct energy imports.

As for embodied energy, Bortolamedi (2015) quantifies the direct and indirect energy use of 25 European countries by a MRIO model by extending three widely used indicators of energy dependency to embodied energy: (i) primary energy intensity (EI), which reflects the degree to which economic activities depend on primary energy as an input, (ii) net import dependency (NID), which reflects the domestic economy's exposure to price and quantity risks in global primary energy markets, and (iii) primary energy carrier dependency (PECD), which reflects the reliance of economic activities on specific energy carriers. Bordigoni *et al.* (2012) also quantified the embodied energy flows of 28 European countries through an MRIO model. They broke down the origin of embodied energy consumption in each country and in each sector into national, European Union (EU) (except national), and non-EU categories. However, neither Bortolamedi (2015) nor Bordigoni *et al.* (2012) consider geographical diversity of supplier countries.

Kharrazi *et al.* (2015) examined the world's embodied electricity trade from a perspective of the diversity of energy carriers, such as coal, oil, gas, nuclear, hydro, solar and wind, using an MRIO model and the SWI. This paper applies their methodologies to geographical diversity of supplier countries.

Tang *et al.* (2013) calculated the fossil energy embodied in the UK's imports and exports through a single-region input-output (SRIO) model. They quantify the national distribution of the UK's embodied energy exports, imports and net imports. China, accounting for 43% of the UK's total net embodied energy imports, has become the UK's biggest net importer since 2008. Our paper extends this perspective to a worldwide comparison that explicitly quantifies the diversity of embodied energy networks.

3. Model and Data

We estimate embodied energy flows between countries using an MRIO model. The theoretical framework of MRIO models is as follows. Suppose there are M countries with N sectors. In equilibrium, the $N \times 1$ output vector $\mathbf{x}^r \equiv \{x_i^r\}_{i=1,\dots N}$ of country r can be expressed as

$$\mathbf{x}^r = \mathbf{Z}^{rr}\,\mathbf{1} + \mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{d}^{rs}, \tag{1}$$

where $\mathbf{Z}^{rr} \equiv \{Z_{ij}^{rr}\}_{i,j=1,\dots N}$ is the $N \times N$ transaction matrix between domestic sectors obtained from domestic input-output tables, $\mathbf{1}$ is a column vector of 1s ($N \times 1$), $\mathbf{y}^{rr}$ is the vector of final demand for domestic goods ($N \times 1$), and $\mathbf{d}^{rs}$ is the vector of exports of domestic goods to country s ($N \times 1$). $\mathbf{d}^{rs}$ can be divided into intermediate inputs and final demand as $\mathbf{d}^{rs} = \mathbf{Z}^{rs}\,\mathbf{1} + \mathbf{y}^{rs}$, where $\mathbf{Z}^{rs}$ is a transaction matrix from r's sectors to s's sectors, and $\mathbf{y}^{rs}$ is s's final demand for r's goods. Equation (1) can thus be transformed into $\mathbf{x}^r = \mathbf{Z}^{rr}\,\mathbf{1} + \mathbf{y}^{rr} + \sum_{s \neq r}(\mathbf{Z}^{rs}\,\mathbf{1} + \mathbf{y}^{rs})$. Let $\mathbf{A}^{rr} \equiv \{a_{ij}^{rr}\}_{i,j=1,\dots N}$ denote the coefficient matrix of domestic transactions with each technical coefficient of $a_{ij}^{rr} \equiv Z_{ij}^{rr}/x_j^r$, and $\mathbf{A}^{rs} \equiv \{a_{ij}^{rs}\}_{i,j=1,\dots N}$ be the coefficient matrix of transactions from r's sectors to s's sectors with $a_{ij}^{rs} \equiv Z_{ij}^{rs}/x_j^s$. Then we get $\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \sum_{s \neq r}\mathbf{A}^{rs}\mathbf{x}^s + \mathbf{y}^{rr} + \sum_{s \neq r}\mathbf{y}^{rs}$. By defining

$$\mathbf{X} \equiv \begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^M \end{bmatrix}, \quad \mathbf{A} \equiv \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \cdots & \mathbf{A}^{1M} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \cdots & \mathbf{A}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{M1} & \mathbf{A}^{M2} & \cdots & \mathbf{A}^{MM} \end{bmatrix}, \quad \mathbf{Y} \equiv \sum_s \begin{bmatrix} \mathbf{y}^{1s} \\ \mathbf{y}^{2s} \\ \vdots \\ \mathbf{y}^{Ms} \end{bmatrix}$$

we have $\mathbf{X} = \mathbf{AX} + \mathbf{Y}$. By transforming this, we obtain the equilibrium equation of the MRIO model as

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{Y}. \tag{2}$$

The data for $\mathbf{Z}^{rs}$, which are necessary for calculating the off-diagonal elements of $\mathbf{A}$, are estimated from the bilateral trade-flow data and domestic input-output tables of the Global Trade Analysis Project (GTAP). In particular, we estimated the amount of intermediate good trade, Z_{ij}^{rs}, by using the same methodology as Peters *et al.* (2011); i.e., assigning the total amount of transactions of good *i* from country *r* to country *s*, which is the sum of imports for both intermediate and final demand, to *s*'s individual sector in proportion to the share of that sector in *s*'s total imports of that good from the world, which can be calculated from GTAP's bilateral trade-flow data.

Let $\mathbf{c}^r \equiv \{c_i^r\}_{i=1,\ldots N}$ be the column vector $(N \times 1)$ with the amount of energy (million tons oil equivalent, MTOE) per dollar of production in the three energy sectors, coal, gas and oil, in country *r* and zero in the other entries. We call this unit "amount energy intensity." Let $\mathbf{C} \equiv [\mathbf{c}^{1\prime}\ \mathbf{c}^{2\prime} \cdots\ \mathbf{c}^{M\prime}]'$ be a vector of world energy intensities, where the primes indicate transposes of the vectors.

The vector of embodied energy for production in country *r*, $\mathbf{E}_{\mathrm{P}}^r$, is obtained by using equation (2) as

$$\mathbf{E}_{\mathrm{P}}^r = \dot{\mathbf{C}}(\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{Y}^r,$$

where $\dot{\mathbf{C}}$ is a diagonal matrix that has each element of $\mathbf{C}$ on the diagonal. $\mathbf{E}_{\mathrm{P}}^r$ and $\mathbf{Y}^r$ are defined respectively as $\mathbf{E}_{\mathrm{P}}^r \equiv [\mathbf{e}_{\mathrm{P},1}^{r\prime}\, \mathbf{e}_{\mathrm{P},2}^{r\prime} \cdots \mathbf{e}_{\mathrm{P},M}^{r\prime}]'$ and $\mathbf{Y}^r \equiv [\mathbf{0}' \cdots (\sum_s \boldsymbol{y}^{rs})'\, \mathbf{0}' \cdots]'$, where $\mathbf{e}_{\mathrm{P},q}^r \equiv \{e_{\mathrm{P},q,i}^r\}_{i=1,\ldots N}$ is the column vector $(N \times 1)$ of the energy production in country *q* embodied in the final production in country *r*, and $\mathbf{0}$ is a column vector of 0s $(N \times 1)$. The vector of embodied energy imports for production $\mathbf{E}_{\mathrm{MP}}^r$ is obtained by replacing $\mathbf{e}_{\mathrm{P},r}^r$ with $\mathbf{0}$.

The vector of embodied energy for consumption in country *r*, $\mathbf{E}_{\mathrm{C}}^r$, is obtained as

$$\mathbf{E}_{\mathrm{C}}^r = \dot{\mathbf{C}}(\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{Y}^{wr},$$

where $\mathbf{E}_{\mathrm{C}}^r$ is defined as $[\mathbf{e}_{\mathrm{C},1}^{r\prime}\ \mathbf{e}_{\mathrm{C},2}^{r\prime} \cdots \mathbf{e}_{\mathrm{C},M}^{r\prime}]'$ and $\mathbf{e}_{\mathrm{C},q}^r \equiv \{e_{\mathrm{C},q,i}^r\}_{i=1,\ldots N}$ is the column vector $(N \times 1)$ of the energy production in country *q* embodied in the final consumption in country *r*. $\mathbf{Y}^{wr}$ is the part of final production that is exported to country *r*; and $\mathbf{Y}^{wr} \equiv [\mathbf{y}^{1r\prime}\ \mathbf{y}^{2r\prime} \cdots \mathbf{y}^{Mr\prime}]'$. The vector of embodied energy imports for consumption $\mathbf{E}_{\mathrm{MC}}^r$ is obtained by replacing $\mathbf{e}_{\mathrm{C},r}^r$ with $\mathbf{0}$.

Note that, as described in the introduction, the vector of embodied energy imports for production and consumption contains part of the direct energy imports of that country. Therefore, embodied energy imports here are not the same as "virtual" energy imports, which do not include any energy that is physically transported to that country.

We used the bilateral trade-flow and domestic input-output data of GTAP version 8.1 with 134 countries/regions and 57 sectors (Narayanan *et al.*, 2012) to construct our MRIO model. The energy intensities were calculated for each energy sector (coal, gas and oil) of each country by dividing the amount of energy production in the sector, obtained from the IEA Energy Atlas country database (IEA, 2015), by its output in dollars calculated from the GTAP database. We used the averages of energy productions in 2002–2012, which covered the five years before and after the reference year 2007 of GTAP version 8.1. The international transportation pool in GTAP was incorporated into $\mathbf{A}$ by following the steps of Peters *et al.* (2011).

We evaluated the geographic diversity of energy imports in two steps. First, as a basic measure of geographic diversity within each energy channel, we used the Shannon-Weaver index (SWI) (Shannon, 1948; Simpson, 1949). The SWI of direct energy imports of energy type *k* to country *r* is defined as

$$H_{\mathrm{D},k}^r = -\sum_q p_{\mathrm{D},q,k}^r \ln p_{\mathrm{D},q,k}^r$$

$p_{\mathrm{D},q,k}^r \equiv e_{\mathrm{D},q,k}^r / \sum_{u \neq r} e_{\mathrm{D},u,k}^r$ represents the share of energy produced in country *q* in the total amount of direct energy imports of type *k* to country r, where $e_{\mathrm{D},u,k}^r$ is the amount of energy directly imported from country *u* to country *r*. If the distribution is completely even, it takes the maximum value, which is $H_{\mathrm{D},max,k}^r \equiv -\sum_q \overline{p_{\mathrm{D},k}^r} \ln \overline{p_{\mathrm{D},k}^r} = -\ln(1/m)$, where $\overline{p_{\mathrm{D},k}^r} \equiv [(1/m)\sum_{u \neq r} e_{\mathrm{D},u,k}^r]/\sum_{u \neq r} e_{\mathrm{D},u,k}^r$. Thus, the SWI can be normalized to a value between 0 and 1 if divided by this maximum, i.e. $E_{\mathrm{D},k}^r = H_{\mathrm{D},k}^r / H_{\mathrm{D},max,k}^r$. This is called Shannon's Equitability (SE), which is typically used as an index of evenness.

Similarly, the SWI of embodied energy imports (for production or consumption) of energy type *k* to country *r* is defined as

$$H_{\mathrm{E},k}^r = -\sum_q p_{\mathrm{E},q,k}^r \ln p_{\mathrm{E},q,k}^r$$

$p_{\mathrm{E},q,k}^r \equiv e_{\mathrm{E},q,k}^r / \sum_{u \neq r} e_{\mathrm{E},u,k}^r$ represents the share of energy produced in country *q* in the total amount of embodied energy imports (for production or consumption) to country *r*, where $e_{\mathrm{E},u,k}^r$ is the amount of energy production in country *u* of type *k* that is embodied in the final goods that are produced or consumed in country *r*. SE in this case is given as $E_{\mathrm{E},k}^r = H_{\mathrm{E},k}^r / H_{\mathrm{E},max,k}^r$. The higher the value of $H_{\mathrm{D},k}^r$, $H_{\mathrm{P},k}^r$ and $H_{\mathrm{C},k}^r$, or, equivalently, the closer the value of $E_{\mathrm{D},k}^r$, $E_{\mathrm{P},k}^r$ and $E_{\mathrm{C},k}^r$ to one, the more diverse a system is evaluated to be. Case 1 in Fig. 1 illustrates this evaluation step as a comparison between (a) and (b). Comparisons can be made between different energy channels of a particular country (i.e., $H_{\mathrm{D},k}^r$, $H_{\mathrm{P},k}^r$, $H_{\mathrm{C},k}^r$), and between a particular energy channel of different countries (i.e., $H_{\mathrm{P},k}^r$ $H_{\mathrm{P},k}^s$,).

The SWI, however, is insufficient for comparing the resilience of a combination of direct energy imports and embodied energy imports. Consider one country having a direct energy import portfolio like (c) and an embodied energy import portfolio like (d). Another country having a direct energy import portfolio like (d) and an embodied energy import profile like (e) will have exactly the same SWI. Obviously, though, the latter country is more resilient to shocks in country A, since its embodied energy does not depend on country A as much as the former.

In order to distinguish such cases, we introduced the

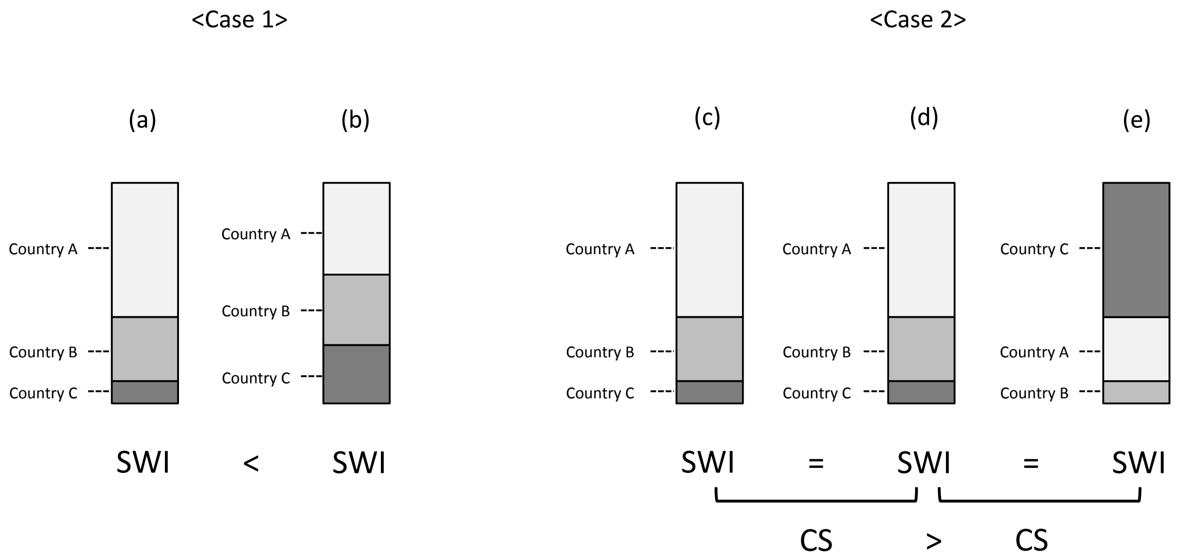

Fig. 1 Illustrative examples comparing SWI and in CS.

concept of cosine similarity (CS) as a complementary index to the SWI. Cosine similarity is an indicator of similarity between two vectors of an inner product space that measures the cosine of the angle between them. It is defined as

$$C_k^r = \frac{\mathbf{E}_{\mathrm{D},k}^r \cdot \mathbf{E}_{\mathrm{E},k}^r}{|\mathbf{E}_{\mathrm{D},k}^r||\mathbf{E}_{\mathrm{E},k}^r|} = \frac{\sum_{q \neq r} e_{\mathrm{D},q,k}^r \cdot e_{\mathrm{E},q,k}^r}{\sum_{q \neq r}\sqrt{(e_{\mathrm{D},q,k}^r)^2} \cdot \sum_{q \neq r}\sqrt{(e_{\mathrm{E},q,k}^r)^2}},$$

where $\mathbf{E}_{\mathrm{D},k}^r$ and $\mathbf{E}_{\mathrm{E},k}^r$ denote the vector of direct energy imports and that of embodied energy imports (for production or consumption) of energy type *k*, respectively. $e_{\mathrm{D},q,k}^r$ is the amount of energy directly imported from country *q* to country *r*, and $e_{\mathrm{E},q,k}^r$ is the amount of energy production in country *q* embodied in the production or consumption of final goods in country *r* (Tan *et al.*, 2005). The value of C_k^r ranges from 0, indicating the orthogonality, to 1, meaning the exact similarity of the two vectors. In the above case, the CS between (c) and (d) is 1, which is larger than the CS between (d) and (e).

4. Results

4.1 Overview

(a) Geographical diversity of global energy endowment, production and exports

Before analyzing direct and embodied energy trade, we considered the underlying geographical diversity of the world energy endowment, production and exportation on a country basis and a regional basis. Table 1 illustrates the SWI values of production and exportation of coal, oil and gas on a country-by-country basis and a regional basis. For production, oil is the most diversified, followed by gas and then coal. This reflects the situation shown in Fig. 2, where East Asia produces 43.4 percent of the world's coal, almost all of which is from China. Looking at exports, oil is still the most diversified on a country-by-country basis, but the positions of coal and gas become reversed. One of the reasons is that China, the world largest coal-producing country, consumes most of the coal it produces domestically and exports only a small fraction of its production. In fact, the total exports from China amount to only 9.8 MTOE, nearly 60 percent of which goes to South Korea, while Australia, the largest coal-exporting country, exports 115.4 MTOE of coal. This significantly increases the diversity of coal exporting regions. In addition, most of the large gas-producing regions, including North America, Europe and Russia and other former Soviet Union countries, do not export gas to countries outside the region. This increases the share of the Middle East from 12.6 percent for production to 48.4 percent for export, resulting in a decrease in the SWI of gas from 3.05 to 1.97.

Table 1 SWIs of world energy production and exports*.

	Country basis		**Regional basis**	
	Production	Exports	Production	Exports
Coal	2.12 [0.43]	2.40 [0.49]	1.78 [0.36]	1.94 [0.40]
Oil	3.23 [0.66]	2.94 [0.60]	2.01 [0.41]	1.75 [0.36]
Gas	3.05 [0.62]	1.97 [0.40]	1.99 [0.41]	1.35 [0.28]

* Figures in square brackets are SEs, which take values between 0 and 1.

Table 2 Mean and variance of countries' SWIs through the three energy channels (country basis)*.

		Direct energy imports	**Embodied energy imports for production**	**Embodied energy imports for consumption**
Mean	Coal	1.14 [0.23]	2.01 [0.41]	2.02 [0.41]
	Oil	1.41 [0.29]	2.43 [0.50]	2.56 [0.52]
	Gas	0.89 [0.18]	2.41 [0.49]	2.52 [0.51]
Standard deviation	Coal	0.72 [0.15]	0.37 [0.08]	0.35 [0.07]
	Oil	0.81 [0.16]	0.47 [0.10]	0.41 [0.08]
	Gas	0.61 [0.13]	0.73 [0.15]	0.68 [0.14]

* Figures in square brackets are SEs, which take values between 0 and 1.

(b) Geographical diversity of direct and embodied energy imports

In general, the geographical diversity of energy imports is more important for a country that depends on imported energy for most of its domestic energy use. We therefore focus our analysis, unless specified otherwise, on countries with an energy self-sufficiency rate of less than 10 percent.

Table 2 illustrates some basic statistics of the SWI values of the three import channels. The mean SWI values of embodied energy imports are much higher than those of direct energy imports. This is because the former reflect the compositions of energy imports of each of the countries located in the global supply-chains, while the latter reflect only those of a single country. This tendency is reflected in the overall distributions of countries in Fig. 3, in which almost all countries are located above the 45-degree line. In addition, embodied energy imports for consumption are slightly more diversified than those for production (except coal). This is in part because most countries consume a broader range of final goods than they produce due to international production specializations.

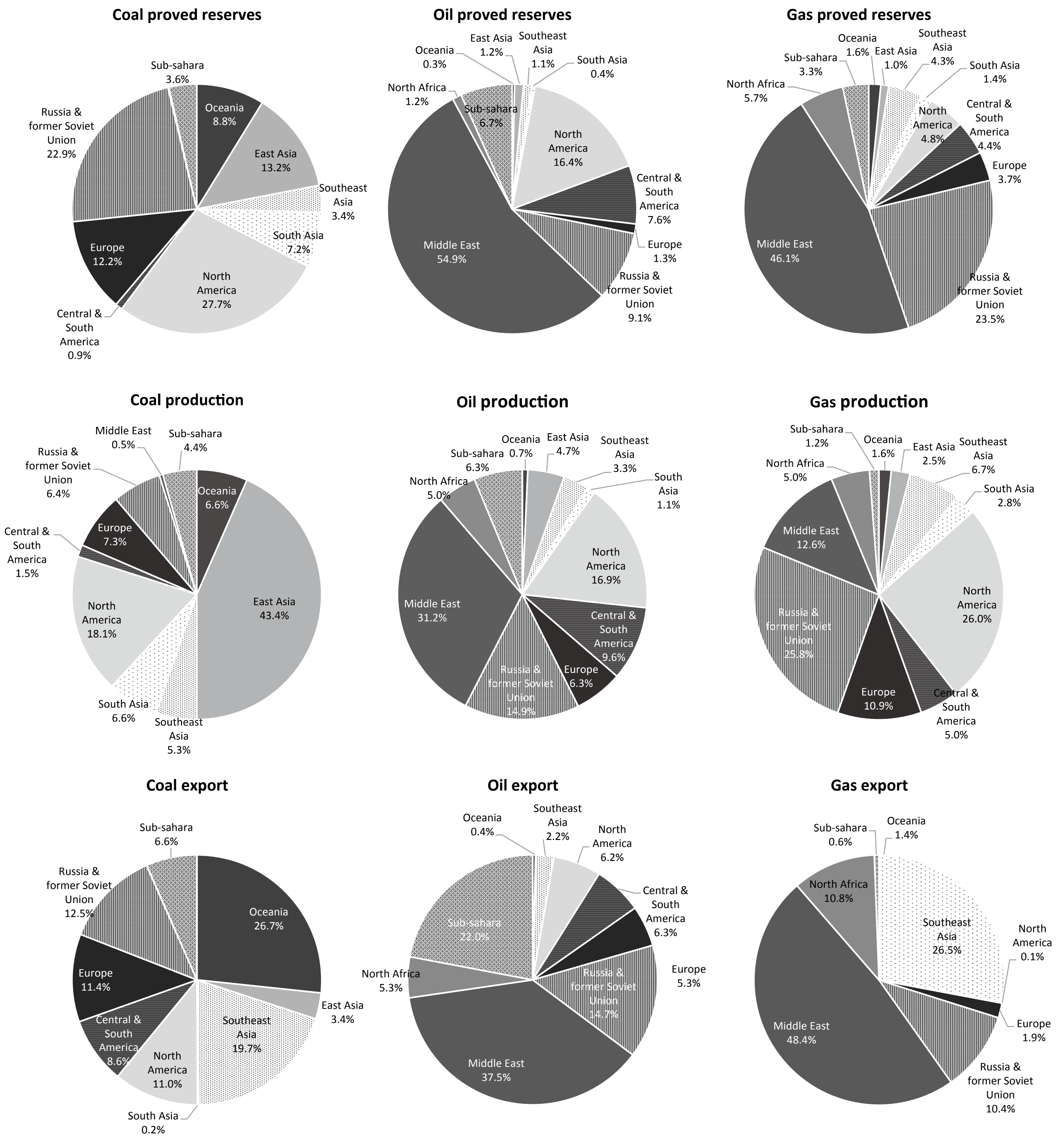

Fig. 2 Shares of regional energy endowment, production and export.
Sources: proven reserves: BP (2015); production and exports: IEA (2015) and Narayanan *et al.* (2012).

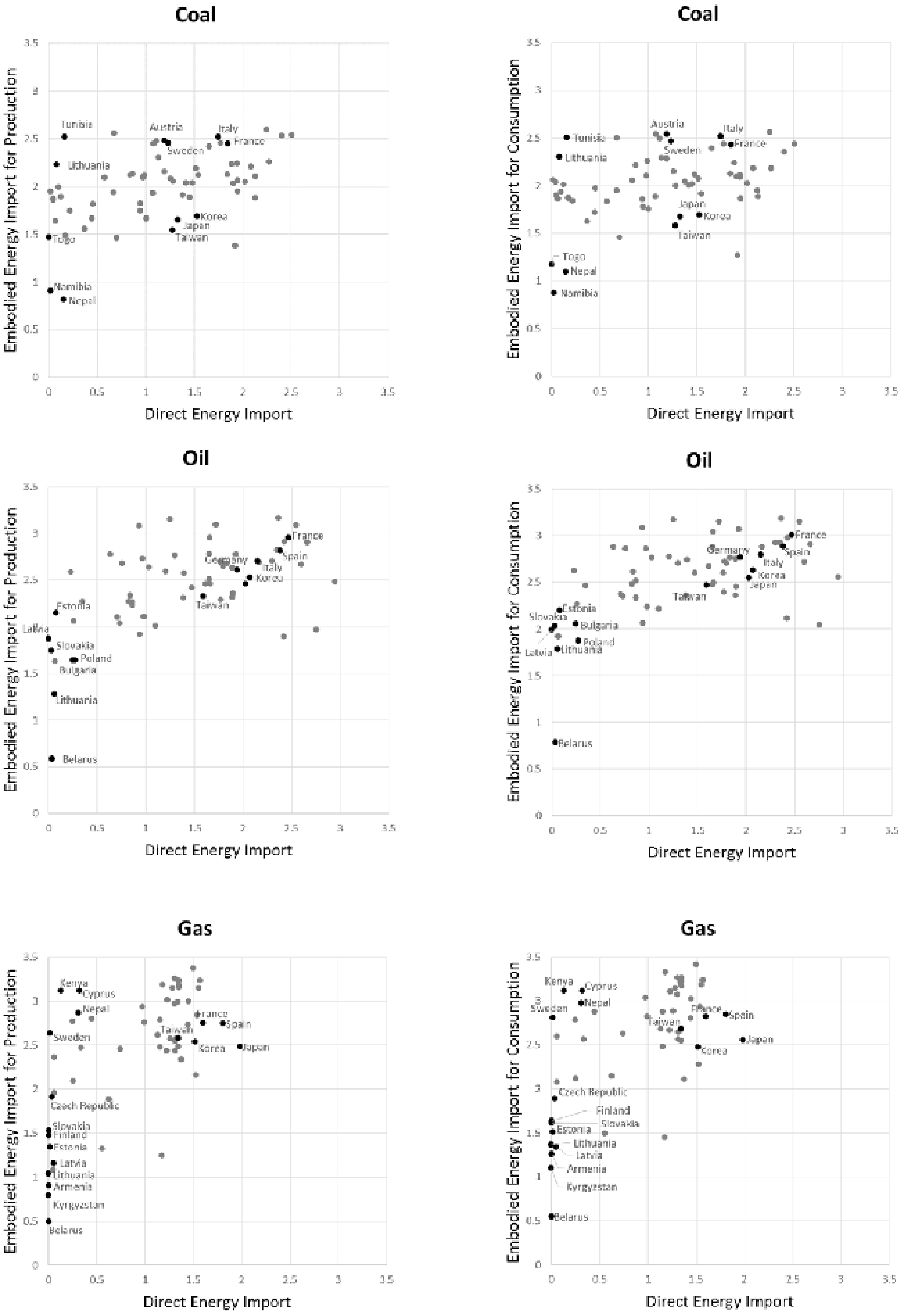

Fig. 3 Distribution of countries' SWIs through the three channels (country basis).

For visibility, country names are omitted (gray dots), except for the countries mentioned in the text (black dots).

One striking fact compared to the diversity of world energy production in Table 1 is that the direct importation of gas is the least diversified with a mean SWI value of 0.89. In fact, the percentage of countries that directly import more than 90 percent of each energy type from a single country is 35 percent for gas but only 23 percent and 17 percent for coal and oil, respectively. This is mainly due to the low diversity of world gas exports themselves, as shown in Table 1. In contrast to the low diversity of direct gas imports, embodied gas imports maintain higher diversity. The mean SWI value of embodied gas is 2.41 for production and 2.52 for consumption, almost the same as those for embodied oil.

Of the three energy types, embodied coal imports are the least diversified, while direct coal imports are at an intermediate position between oil and gas. There are two factors behind that. First, as we will explain in the following sections, for coal there is only a limited extent of correlation between direct and embodied energy imports, mainly due to its relative position in the supply chain. Second, the weak correlation makes the situation of embodied coal imports reflect that of world coal production, whereas direct coal imports reflect world coal exports. Although China's large share of world coal production makes its SWI the lowest of the three energy types, the world's coal exports are well diversified, especially on a regional basis (Table 1), since China exports only a small fraction of the coal it produces. China does export coal in the form of embodied energy, however, reflecting its position as the "world's factory," which in turn decreases the diversity of embodied coal imports.

(c) Correlation between direct energy imports and embodied energy imports

Table 3 compares the correlation coefficients of the SWI values of the two types of embodied energy imports with those of direct energy imports, which are calculated both for all countries and for only those whose SWI of direct energy imports is less than the median.

Of the three energy types, coal has generally the weakest correlation between direct energy imports and embodied energy imports. For countries with lower diversity in direct energy imports, however, the correlation of gas is the weakest. In contrast, oil has high correlation between direct energy imports and embodied energy imports.

Table 4 illustrates the average CS between the vector of direct energy imports and that of embodied energy imports. If we focus on the countries with lower diversity in direct energy imports, the CS values of oil and gas are much higher than that of coal. In fact, as we will see in the following section, for most countries the primary suppliers of embodied coal imports do not coincide with those of direct coal imports, in sharp contrast to the cases of oil and gas.

4.2 Analysis of Selected Countries

(a) Coal

Because for coal there is only limited correspondence between direct and embodied energy imports, countries with similar SWI values of direct coal imports often have variation in the SWI values of embodied coal imports. For instance, Lithuania and Tunisia, whose SWI values of direct imports are 0.08 and 0.16 respectively, have SWI values of embodied coal imports that are as high as some European countries with much more diverse suppliers of direct imports, such as France, Italy, Austria and Sweden (Fig. 3 and Table 5 (a)). On the other hand, Togo, Namibia and Nepal, whose SWI values of direct imports are 0.00, 0.02 and 0.15, respectively, also have the lowest SWI values for embodied coal imports, obtaining 65–83 percent of their embodied coal imports from a single country.

Another important feature of coal is that the large variation across countries is not limited to those with low diversity in direct imports. Specifically, the coal-importing countries in Europe, including France, Italy, Austria and Sweden, are much more diversified in their embodied coal imports than East Asian countries like Japan, Korea and Taiwan, even though their SWI values of their direct coal imports differ little from those of their European counterparts (Fig. 3). The low diversity in the embodied coal imports of East Asian countries is due to the heavier dependency on coal production in nearby resource-rich countries in the Asia-Pacific region, notably China, Australia and Indonesia (Table 6). The higher dependency leads to higher efficiencies of their global supply-chains with respect to energy delivery in the region. On the other hand, that would also indicate a weaker degree of energy resilience for these countries, because some shocks related to coal production in the region, for example, strengthened emission regulations for coal-fired power plants in China, may affect these countries through direct and embodied energy import channels simultaneously.

(b) Oil

A striking feature of oil is the high dependency of some Eastern European countries on a single country both for direct and embodied oil. For instance, Latvia,

Table 3 Correlation coefficients between the SWIs of direct energy imports and embodied energy imports.

	Embodied energy imports for production		**Embodied energy imports for consumption**	
SWI of real energy imports	All	Not above median	All	Not above median
Coal	0.47	0.54	0.37	0.37
Oil	0.60	0.63	0.55	0.61
Gas	0.63	0.43	0.62	0.43

Table 4 Mean of the CSs between direct energy import vector and embodied energy import vector.

	Embodied energy imports for production		**Embodied energy imports for consumption**	
SWI of real energy imports	All	Not more than the median	All	Not more than the median
Coal	0.65	0.57	0.59	0.49
Oil	0.61	0.80	0.59	0.78
Gas	0.66	0.81	0.66	0.80

Table 5 Primary suppliers of the countries with smallest SWIs in direct energy imports (bottom 20)*.

(a) Coal

Importing country	Direct energy imports			Embodied energy imports for production				Embodied energy imports for consumption			
	SWI	Primary supplier	Share	SWI	CS	Primary supplier	Share	SWI	CS	Primary supplier	Share
Togo	0.00	South Africa	100.0%	1.06	0.05	China	65.1%	1.21	0.03	China	75.6%
Mauritius	0.02	South Africa	99.8%	1.98	0.59	China	31.5%	2.04	0.54	China	32.6%
Namibia	0.02	South Africa	99.7%	0.92	1.00	South Africa	82.8%	0.82	1.00	South Africa	82.9%
Senegal	0.04	South Africa	99.5%	2.38	0.91	South Africa	48.6%	2.00	0.72	South Africa	33.6%
Laos	0.04	Viet Nam	99.5%	1.87	0.24	China	42.7%	1.89	0.19	China	35.9%
Cambodia	0.07	Indonesia	99.1%	1.80	0.25	China	50.6%	1.68	0.34	China	40.6%
Lithuania	0.08	Russia	98.9%	2.26	0.83	Russia	35.6%	2.27	0.72	Russia	29.0%
UAE	0.10	South Africa	98.5%	1.98	0.15	China	39.0%	1.93	0.12	China	41.8%
Honduras	0.12	Colombia	98.4%	1.95	0.69	Colombia	32.4%	1.94	0.55	China	27.8%
Nepal	0.15	India	97.9%	0.96	0.99	India	82.4%	1.02	0.97	India	71.1%
Tunisia	0.16	South Africa	97.7%	2.55	0.27	China	28.4%	2.52	0.25	China	30.9%
Peru	0.17	Colombia	97.1%	1.52	0.92	Colombia	56.4%	1.84	0.63	China	36.7%
Sri Lanka	0.22	Indonesia	96.5%	1.82	0.26	China	38.8%	1.78	0.24	China	35.1%
Malawi	0.37	Mozambique	91.4%	1.44	0.67	South Africa	42.8%	1.58	0.53	South Africa	47.2%
Madagascar	0.44	South Africa	88.2%	1.73	0.49	China	50.8%	1.66	0.49	China	49.8%
Guatemala	0.45	Colombia	87.8%	1.80	0.83	Colombia	42.0%	1.93	0.63	China	31.7%
Guinea	0.57	Australia	90.0%	2.12	0.55	China	36.9%	1.91	0.22	China	53.9%
Kenya	0.67	South Africa	71.7%	1.94	0.58	China	34.4%	1.94	0.52	China	36.4%
Switzerland	0.67	Indonesia	81.8%	2.53	0.18	China	21.2%	2.53	0.17	China	28.2%
Hong Kong	0.70	Indonesia	79.8%	1.44	0.73	China	43.9%	1.47	0.52	China	55.2%

(b) Oil

Importing country	Direct energy imports			Embodied energy imports for production				Embodied energy imports for consumption			
	SWI	Primary supplier	Share	SWI	CS	Primary supplier	Share	SWI	CS	Primary supplier	Share
Latvia	0.00	Russia	100.0%	1.77	0.99	Russia	63.3%	1.94	0.99	China	36.4%
Slovakia	0.03	Russia	99.7%	1.53	0.99	Russia	66.6%	2.26	0.99	South Africa	27.5%
Belarus	0.04	Russia	99.6%	0.50	1.00	Russia	91.2%	2.12	1.00	Ukraine	33.4%
Lithuania	0.06	Russia	99.3%	1.22	1.00	Russia	77.6%	1.69	0.99	China	42.2%
Uruguay	0.07	Venezuela	99.2%	1.55	0.97	Venezuela	62.3%	1.93	0.95	China	41.8%
Estonia	0.08	Belarus	98.9%	2.12	0.02	Russia	56.3%	2.12	0.02	China	44.7%
Tanzania	0.23	Qatar	95.6%	2.44	0.05	Saudi Arabia	34.5%	2.53	0.06	China	28.2%
Bulgaria	0.25	Russia	94.0%	1.60	1.00	Russia	68.0%	2.41	0.99	China	31.9%
Kenya	0.26	UAE	94.1%	1.88	0.92	UAE	46.5%	1.85	0.86	South Africa	44.1%
Poland	0.28	Russia	94.5%	1.48	1.00	Russia	68.2%	2.09	0.99	China	43.8%
Costa Rica	0.35	Venezuela	90.5%	1.86	0.95	Venezuela	46.4%	1.68	0.92	China	40.6%
Zambia	0.63	UAE	77.0%	2.61	0.87	UAE	29.8%	2.17	0.81	China	30.4%
Nicaragua	0.71	Mexico	78.3%	2.02	0.92	Mexico	40.9%	2.03	0.87	South Africa	28.2%
Morocco	0.73	Saudi Arabia	51.5%	1.80	0.98	Saudi Arabia	34.7%	1.58	0.96	South Africa	47.2%
Senegal	0.75	Nigeria	65.3%	2.62	0.91	Nigeria	28.9%	1.84	0.87	China	50.0%
Sri Lanka	0.82	Saudi Arabia	54.1%	2.06	0.94	Saudi Arabia	36.0%	2.00	0.90	South Africa	33.6%
El Salvador	0.84	Ecuador	66.4%	2.19	0.94	Ecuador	35.0%	2.04	0.88	China	40.9%
Israel	0.86	Kazakhstan	74.8%	2.11	0.97	Kazakhstan	45.1%	1.91	0.95	China	53.9%
Czech Republic	0.87	Russia	64.4%	1.99	0.97	Russia	47.9%	2.06	0.97	China	35.1%
Ethiopia	0.93	Iran	61.7%	3.07	0.50	Saudi Arabia	13.4%	2.53	0.49	China	20.2%

(c) Gas

Importing country	Direct energy import			Embodied energy import for production				Embodied energy import for consumption			
	SWI	Primary supplier	Share	SWI	CS	Primary supplier	Share	SWI	CS	Primary supplier	Share
Kyrgyzstan	0.00	Uzbekistan**	100.0%	0.78	0.97	Uzbekistan**	77.2%	1.04	0.91	Uzbekistan**	63.5%
Lithuania	0.00	Russia	100.0%	0.93	1.00	Russia	81.4%	1.16	1.00	Russia	74.3%
Finland	0.00	Russia	100.0%	1.36	1.00	Russia	72.7%	1.52	0.99	Russia	69.0%
Slovakia	0.00	Russia	100.0%	1.22	0.99	Russia	71.1%	1.59	0.99	Russia	69.2%
Belarus	0.00	Russia	100.0%	0.37	1.00	Russia	91.3%	0.49	1.00	Russia	90.3%
Armenia	0.00	Kazakhstan	100.0%	0.76	0.99	Kazakhstan	79.6%	1.11	0.97	Kazakhstan	68.2%
Sweden	0.02	Denmark	99.8%	2.50	0.66	Denmark	24.5%	2.70	0.55	Russia	23.1%
Estonia	0.02	Russia	99.8%	1.25	1.00	Russia	75.3%	1.42	1.00	Russia	71.7%
Czech Republic	0.04	Russia	99.4%	1.65	0.99	Russia	61.5%	1.96	0.99	Russia	62.7%
Ireland	0.05	United Kingdom	99.3%	0.83	1.00	United Kingdom	80.2%	1.37	1.00	United Kingdom	74.4%
Greece	0.06	Russia	99.1%	2.30	0.97	Russia	47.9%	2.50	0.94	Russia	40.9%
Latvia	0.06	Russia	99.0%	1.03	1.00	Russia	79.3%	1.26	1.00	Russia	75.4%
Uruguay	0.06	Argentina	99.1%	1.93	0.95	Argentina	52.8%	2.06	0.95	Argentina	50.6%
Kenya	0.13	Tanzania	98.0%	3.15	0.04	Saudi Arabia	22.2%	3.06	0.03	Saudi Arabia	21.9%
Botswana	0.25	South Africa	95.3%	2.74	0.46	Mozambique	28.4%	2.64	0.46	Mozambique	28.7%
Laos	0.25	Thailand	95.2%	2.06	0.91	Thailand	46.9%	2.04	0.91	Thailand	46.4%
Nepal	0.31	India	93.8%	2.69	0.79	India	25.6%	2.90	0.77	India	23.2%
Cyprus	0.32	Russia	93.7%	3.10	0.78	Russia	21.3%	3.08	0.86	Russia	25.0%
Slovenia	0.34	Russia	92.2%	2.46	0.96	Russia	45.4%	2.41	0.96	Russia	42.8%
Namibia	0.45	South Africa	90.2%	2.78	0.42	Mozambique	22.3%	2.82	0.44	Mozambique	23.3%

* The table shows only countries with a self-sufficiency rate for gas of less than 10%.

** Since the primary trade partner of Kyrgyzstan in the GTAP database is only referred to as "Rest of former Soviet Union," we specify the country from UN Comtrade database.

Table 6 Suppliers of embodied coal to the countries of East Asia and Europe.

(a) Embodied coal imports for production

Japan		**Korea**		**Taiwan**		**Austria**		**France**		**Italy**		**Sweden**	
SWI	1.60	SWI	1.67	SWI	1.47	SWI	2,39	SWI	2.44	SWI	2.50	SWI	2.42
CS	0.95	CS	0.95	CS	0.97	CS	0.79	CS	0.72	CS	0.76	CS	0.65
Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share
Australia	42.5%	China	40.0%	Indonesia	37.2%	Czech R.	21.7%	China	24.5%	China	20.7%	China	25.0%
China	24.4%	Indonesia	23.3%	China	28.1%	Poland	14.0%	S. Africa	17.2%	S. Africa	18.1%	Australia	17.7%
Indonesia	16.5%	Australia	18.9%	Australia	24.1%	China	13.7%	Australia	11.8%	Indonesia	12.9%	USA	11.7%
Russia	6.0%	Russia	6.6%	Russia	2.7%	Germany	12.6%	USA	10.7%	USA	10.0%	Russia	11.3%
Canada	3.3%	Canada	3.8%	S. Africa	2.3%	Russia	7.6%	Russia	8.1%	Australia	7.3%	Poland	5.9%

(b) Embodied coal imports for consumption

Japan		**Korea**		**Taiwan**		**Austria**		**France**		**Italy**		**Sweden**	
SWI	1.69	SWI	1.69	SWI	1.59	SWI	2.53	SWI	2.44	SWI	2.53	SWI	2.47
CS	0.88	CS	0.93	CS	0.96	CS	0.66	CS	0.60	CS	0.65	CS	0.50
Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share	Supplier	Share
Australia	37.2%	China	42.2%	Indonesia	34.9%	China	17.9%	China	29.5%	China	25.4%	China	29.7%
China	31.4%	Indonesia	21.9%	China	30.8%	Czech R.	16.9%	S. Africa	14.7%	S. Africa	15.4%	Australia	13.5%
Indonesia	14.9%	Australia	17.8%	Australia	22.8%	Germany	13.8%	Australia	10.3%	Indonesia	11.0%	Russia	10.2%
Russia	5.4%	Russia	6.3%	Russia	2.7%	Poland	11.6%	USA	9.7%	USA	9.3%	USA	9.9%
Canada	2.9%	Canada	3.5%	S. Africa	2.2%	Russia	7.7%	Russia	8.0%	Australia	6.9%	S. Africa	6.4%

Slovakia, Belarus, Lithuania, Bulgaria and Poland obtain more than 94% of direct oil imports and 63 – 91% of embodied oil imports for production from Russia (See Table 5 (b)), with their CS values being almost one. Although this probably reflects the economic integrity of this area that is mediated by the cheap oil supply from Russia, it also indicates that these countries may be vulnerable to shocks in Russia's oil production via both direct and embodied import channels.

(c) Gas

The high dependency of Eastern European countries on a single supplier is also distinctive for gas. In fact, Kyrgyzstan, Lithuania, Finland, Slovakia, Belarus, Armenia, Estonia and Latvia have both their direct and embodied gas imports significantly concentrated either on Russia, Uzbekistan or Kazakhstan (See Table 5 (c)).

On the other hand, in contrast to oil, some other countries with small diversity in their direct imports, have high diversity in their embodied gas supplies. For instance, Kenya, Cyprus, Nepal and Sweden have diversified their suppliers of embodied gas as much as, or even more than, countries in Europe and East Asia, such as Spain, France, Japan, Korea and Taiwan. This suggests a possibility for countries that depend heavily on a few neighbors for their direct energy imports to take a strategy of diversifying their supply-chains globally in order to benefit from larger diversity for their supply of embodied gas, thereby strengthening the energy resilience of their economies.

5. Conclusions

Resilience is a crucial component to consider for sustainable energy. This paper evaluates the energy resilience of countries from the perspective of diversity in suppliers both of direct and embodied energy and examines how selections of indirect energy supplies can affect the resilience of the entire embodied-energy trade network. First, we find that the geographical diversity of embodied energy imports is much greater than that of direct energy imports. Second, while the supply diversification level of direct gas imports is low mainly due to the low diversity of world gas exports themselves, embodied gas imports maintain as high a diversity as embodied oil imports. Third, embodied coal imports are the least diversified, while direct coal imports are at an intermediate position between oil and gas. The situation of embodied coal imports reflects the small diversity of world coal production, while that of direct coal imports reflects the large diversity of world coal exports. The reason behind that is the fact that China, the world largest coal-producing country, exports only a small fraction of the coal it produces, but it does export coal in the form of embodied energy, reflecting its position as the "world's factory." Fourth, for coal (and gas in the countries having lower direct energy diversities) there is lower correlation between direct energy imports and embodied energy imports than for oil. Fifth, the diversification of embodied energy imports of coal (and gas) varies considerably across countries. This suggests that countries heavily dependent on a few neighbors for their direct energy imports might diversify their supply chains globally in order to benefit from larger diversity in their supply of embodied energy, thereby strengthening the energy resilience of their economy.

As noted in the previous sections, geographical diversity of supplying countries is just one component of energy resilience. For a comprehensive evaluation of energy resilience, it would be essential to combine the diversification indicators presented in this paper with other measurement methodologies that have mostly been practiced in a context of direct energy trade. One possibility would be to incorporate geopolitical risk measures into the diversification indicators. For instance, Gupta (2008) quantifies the degree of supply concentration through a modified Herfindahl-Hirschman index with the market shares adjusted for political risk in the oil-exporting countries using the International Country Risk Guide (ICRG) ratings.

Finally, we observe that the correlations between the SWI values of embodied energy imports and those of direct imports are larger for oil (and to a lesser extent gas) than for coal and that the CS values of coal are much lower than those of oil and gas. It is difficult to find a single systematic reason for this. One possible factor, however, is the difference in the relative position in a supply chain at which each energy type tends to be used most intensively. As mentioned before, embodied energy imports contain a part of the direct energy imports, but how much of the direct energy is included in embodied energy depends on the stage of the supply chain at which the direct imports occur. In general, the closer the stage is to the domestic final production or final consumption, the more likely it is that the direct energy imports are included in the embodied energy of that country. If energy is used in more upstream stages, on the other hand, it is more likely that the intermediate goods that are produced are exported and used for final production in other countries.

It is possible that the differences in the correlations can be explained in part by a tendency for oil and gas to be used more intensely in the downstream stages of production than coal. In many countries, a significant amount of oil is used for road transportation, which is needed for transporting construction materials such as cement and for distribution of various wholesale products. Similarly, a certain amount of gas is transformed into town gas for domestic and industrial use, especially in developed countries. In both cases the energy is used at stages relatively close to domestic final production or consumption. In contrast, coal is mainly used for power generation and steel-making. Electricity generally is used in a broad range of industries from upstream to downstream, and the steel industry is one of the most upstream stages of production. To verify that, it would be necessary to track the locations of consumption of direct energy imports in each country. It is expected that this issue will be addressed in future research.

Acknowledgements

The authors are grateful to the Ministry of the Environment, Japan, for supporting this research through the Environment Research and Technology Development Fund, S-11 Project.

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(Received 8 September 2015, Accepted 30 November 2015)