Tracing Embodied Energy Use Through Global Value Chains: Channel Decomposition and Analysis of Influential Factors

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Abstract

Measurement of the energy use dispersed through international trade is crucial in the age of global value chains. This study traces international energy flows, presents the stylized facts, and analyses the major driving factors of energy flows. The findings of this study show that 20% of global energy is transmitted through global value chains and there is large energy imbalance between economies. The gravity model illustrates that energy transfers between home and host countries increase with economic size, a shared border, a same language, and a similar legal system, and decrease with geographic distance. However, distance is becoming less significant in transmitting energy due to the increasing complexity of global value chains. Global value chains have altered how the world consumes energy directly and indirectly, thus must be taken into consideration by both environmental and trade policies aiming at encouraging sustainable development, equity, and energy conservation.

Keywords: Energy Use, Global Value Chains, Multi-regional Input-Output Analysis, Gravity Model

1. Introduction

Energy, as one of the fundamental resources, is critical to support human well-being, economic growth, and sustainable development. Global energy use has been constantly increasing, from 112424 TWh (9667 million tonnes of oil equivalent, Mtoe) in 2000, to 157063 TWh (13505 Mtoe) in 2018 (Dudley, 2019[1]), by approximately 40 percent. Although the COVID-19 has lead to temporary reduction of global energy use (Le Qu´er´e et al., 2020[2], 2021[3]), the post-COVID-19 economic recovery and investments can lead to a rebounce of the worldwide energy use. To fulfill the climate targets, it highlights the importance to clearly identify the environmental responsibilities, by giving an accurate measurement of each country-sector's energy usage. However, this is not an easy task. First, there is large amount of energy trade, which accounts for 20%-32% of global energy consumption (Christopher and

Rebecca, 2020[4]), that can lead to double counting bias as some of them can be exported/imported and re-exported/imported as intermediate goods (Koopman et al., 2014[5]). Also, a considerable share of energy can be transferred across countries embodied in global trade of goods and services rather than energy itself. To formulate effective climate policies, it is essential to estimate and take into consideration the energy use redistributed across the world through global trade.

The world has witnessed the formation of a global production network, which is distributed across the world, transcending the borders of countries (Antr`as et al., 2012[6]; Antr`as and Chor, 2013[7]; Wang et al., 2017[8]). An increasing number of production activities are no longer simply to meet the local needs of each economy, but to meet the final demand of more countries through the global value chains. The energy used during production process in one country, can be driven by the consumption demand of another country through different global value chains, which can cross national borders for multiple times (Zhang et al., 2017[9]). A major part of the growth in energy consumption has been driven by developing countries, especially their production growth due to the expansion of economic scale. However, the increase in production is not only for the growing demand of developing countries, but also driven by the consumption of developed countries, who have outsourced their production to less developed regions through global trade. In the era of global value chains, researchers should go beyond the country border and trace energy use at the bilateral country-sector-value chain level.

This study aims to build an energy accounting framework under the global value chains, trace world's energy flows, and characterize its patterns. First, based on the global value chain decomposition method developed by Wang et. al. (2017[8]) and Meng et al. (2018a[10]), this study quantifies energy use of 41 countries or economies from 2000 to 2017, providing a measurement of production-based and consumption-based energy use and net energy transfer, so as to be able to better depict the energy flows between countries. Second, both production-based and consumption-based energy use has been divided according to 5 global value chain channels, including: pure domestic, returned domestic, traditional trade, simple GVCs and complex GVCs. Third, this study employs the gravity model to analyze the determinants affecting the amount of bilateral energy flows between countries through different value chains. As empirical analysis on the factors of energy flow has been thin, this deepens the understanding of bilateral energy flows embodied in trade, reveals the driving factors of energy transfer, and depicts the patterns of energy flows for different global value chains. Fourth, this study provides detailed decomposition results for 41 economies, 35 sectors, 4 types of energy, and 5 global value chain channels. It provides valuable data and information for future studies.

The results show that: (1) the energy use through world trade accounts for over 20% of world total energy use, in which energy embodied in simple GVCs and complex GVCs has increased rapidly; (2) The distribution of production-based and consumption-based energy use is considerably different. Developed economies have positive net energy transfer while developing economies' is negative; (3)The gravity model reveals that the energy flow between the home and host countries increases with larger economic scale of both countries, increases with a common border, a common language as well as a similar law system, and decreases with longer geographical distance between the countries.

The main contributions of this study are as follows. First, despite the huge amount of debate and discussions on direct world energy imports and exports, this study focuses on the energy embodied in trade of goods and services, whose amount is already too large to be negligible. Second, to our knowledge, this is the first study to incorporate global energy use into global value chains, which reveals not only the energy use embodied in trade, but also provides information for each specific global value chain routes. Third, considering the current discussion of post-COVID19 energy use recovery and claim of carbon neutrality targets by many developed and developing countries, it is critical to have a clear picture of the world energy use embodied in trade induced by each country and characterize the pattern of energy flows. This study is conducted based on the latest data of world multi-regional input-output tables and world energy use, which reveals the latest trend of energy embodied in global value chains and has meaningful implications for post-COVID19 energy use discussions.

The rest of this paper is organized as follows. Section 2 reviews relevant literature on production-based and consumption-based principles, Input-Output Analysis, and decomposition method of global value chains. Section 3 develops the method of world energy accounting through different global value chain channels, which are: pure domestic channel, returned domestic channel, traditional trade channel, simples GVCs channel, as well as complex GVCs channel. It also outlines the data sources employed in this study. Section 4 provides the decomposition results of energy use through global value chains and discusses the main patterns of energy flows. Section 5 conducts empirical research to analyze the key factors affecting energy transfer between countries.

Section 6 provides concluding remarks and discusses the implications of this study.

2. Literature Review

The global trade pattern has witnessed significant changes, including rapid increase of intermediate goods trade and processing trade (Wang et al., 2015[11]), increase of transnational production division, and vertical specialization (Hummels, Ishii and Yi, 2001[12]). Not only goods and services are produced and consumed in a complex transnational network (Baldwin, 2013[13]), but also the environmental footprints embodied in international trade through global value chains (Wiedmann and Lenzen, 2018[14]). The geospatial separation of production and consumption (Peters, 2008[15]), the double counting of trade (Koopman, 2011[16]) and multiple times of border-crossing (Zhang et al., 2017[9]) renders the territorial-based energy use measurement biased, since it does not consider the trade of intermediate products and final products, the upstream and downstream relations between countries and industries, and the input-output relations.

One essential step toward a clearer picture of world energy use is to account for the energy uses embodied in trade or “give credit where credit is due” (Koopman, 2011[16]). Energy embodied in the goods and services consumed by domestic residents, businesses, governments are either directly from domestic markets or purchased from overseas through global trade (Davis and Caldeira, 2010[17]; Wiedmann et al., 2011[18]; Takahashi et al., 2014[19]; Feng et al., 2014[20]; Tian et al., 2014[21]; Wang et al., 2018[22]). With energy embodied in trade accounted for, it is able to measure production-based and consumption-based environmental “footprints” (Peters, 2008[23]; Atkinson et al., 2011[24]; Steininger et al., 2014[25]). In specific, the production-based energy use allocates the energy use to producers, while consumption-based energy use puts the energy use under the name of the final consumers. While the production-based energy use is often directly reported by each country as territorial use, the consumption-based energy use must be calculated through tracing the energy embodied in goods and services through international trade (Lenzen et al., 2007[26]; Peters and Hertwich, 2008a [15], Peters and Hertwich, 2008b[27]; Guan et al., 2014[28]; Jakob et al., 2014[29]; Steininger et al., 2014[25]).The Inputoutput Analysis (IOA) and the Multiregional Input-output Model (MRIO) is a common method to estimate environmental impacts of trade, such as emissions, energy use and pollutions (Leontief, 1970[30]; Wiedmann et al, 2007[31]; Wiedmann, 2009[32]; Su et al., 2010[33]; Su and Ang, 2014[34]; Liu et al., 2017[35]). The Environmentally-extended MRIO is widely adopted to calculate emissions or energy embodied in trade on international basis (Liu and Fan, 2017[35]; Meng et al., 2018[36]) or inter-regional level within nations (Guo et al., 2012[37]; Yu, 2014[38]; Pei et al., 2018[39]; Zhang et al., 2018[40]).

Recent studies on global value chains allow scholars to not only account for the production-based and consumption-based energy use, but also further decompose these energy use along global value chains. The decomposition of world trade along GVCs has provided the basic method for this issue (Koopman et al., 2011[16]; Koopman et al., 2012[41]). Previous studies have conducted decomposition on value added along the global value chains (Wang et al., 2013[42]; Koopman, Wang and Wei, 2014[5]; Wang Zhi, Wei Shangjin, Zhu kunfu, 2015[11]), which measures the amount of trade flow through each global value chain between trade partners. A growing literature aims to trace environmental footprints along global value chains (Dietzenbacher et al., 2012[43]; Su et al., 2013[44]; Liu et al., 2015[45]; Zhang et al., 2017[9]). For instance, scholars have decomposed energy, pollutions, carbon emissions as well employment embodied in global value chains (Turner et al., 2007[46]; Meng et al., 2018a[10]; Meng et al., 2018b[36]; Feenstra and Sasahara, 2018[47]; Arto et al., 2018[48]).

In line with previous studies, this study aims to quantify production-based and consumption-based energy use, decompose world's energy use according to global value chains, and research into the characteristics of energy use through different global value chains.

3. Method and Data

3.1. Method

This study analyzes transnational energy use through the Environmentally-extended Multi-regional Input-Output Model. Based on the decomposition of value added and carbon emissions along the global value chains by Koopman, Wang and Wei (2014)[5], Wang et al. (2017)[8], Meng et al. (2018a[10], 2018b[36]), it employs an Environmentally-extended Input-Output Model of m countries and n sectors to decompose energy use between countries along the global value chains. In a general input-output model, the equilibrium between product supply and demand can be expressed in the following matrix form:

$$AX + Y = X \tag{1}$$

where, A is the direct input coefficient matrix, X is the total output column vector, and Y is the final demand column vector. Put the final demand Y on the right side of the equation, equation 1 can be rewritten as follows:

$$(I - A)X = Y \tag{2}$$

Following the method in Meng et al. (2018a[10], 2018b[36]), the total output can be decomposed by global value chain routes as follows:

$$X^s = \underbrace{L^{ss}Y^{ss}}_{1.Pure\ domestic} + \underbrace{L^{ss}\sum_{r\neq s}^{G} A^{sr}\sum_{u}^{m} B^{ru}Y^{us}}_{2.Returned\ domestic}$$

$$+ \underbrace{L^{ss}\sum_{r\neq s}^{m} Y^{sr}}_{3.Traditional\ trade} + \underbrace{L^{ss}\sum_{r\neq s}^{m} A^{sr}L^{rr}Y^{rr}}_{4.Simple\ GVCs}$$

$$+ \underbrace{L^{ss}\left(\sum_{r\neq s}^{m}\sum_{t\neq s}^{m} A^{st}\sum_{u}^{m} B^{tu}Y^{ur} - \sum_{r\neq s}^{m} A^{sr}\,L^{rr}Y^{rr}\right)}_{5.Complex\ GVCs} \quad 3$$

where Y^{sr} refers to the part of final demand of country r imported from country s; $L^{ss} = (I - A^{ss})^{-1}$refers to the local Leontief inverse matrix of country s. This provides a general form of decomposition method along the value chains, which is suitable for bilateral decomposition of value added, carbon emissions, energy use and so on. The total outputs of a country can be divided into five global value chain channels according to the types of products and the number of border crossings. First, the pure domestic channel that both the production and consumption of the product happens in the same country and there is no international trade involved. Second, the returned domestic channels in which products involved in international trade return to the source country of production, thus the original production and final consumption of the products remain in the same country. Third, the traditional trade channels that the production and consumption of the products happens in two different countries, in which the products are exported to another country as final products and directly consumed by that country, with single border-crossing. Forth, the simple value chain channels that the production and consumption of the products happens in two different countries, in which the products are exported to another country as intermediate products and then processed by that country before consumption, with single border-crossing. Five, the complex value chain channels that the production and consumption of the products involved more than two countries, in which the products cross national borders for multiple times as intermediate inputs and finally consumed by another country.

Similar to the decomposition of value added and carbon emissions, pre-multiply equation 3 with the diagonal matrix of energy intensity coefficient of country country s, $\widehat{\mathrm{EI}}^{s}$, the total energy use of country s can be decomposed into its final consuming countries along the five global value chains above. Then, the production-based energy use of country s can be divided into:

$$E^s_{production} = \widehat{EI}^sX^s = \underbrace{\widehat{EI}^sL^{ss}Y^{ss}}_{1.Pure\ domestic} + \underbrace{\widehat{EI}^sL^{ss}\sum_{r\neq s}^{m} A^{sr}\sum_{u}^{m} B^{ru}Y^{us}}_{2.Returned\ domestic}$$

$$+ \underbrace{\widehat{EI}^sL^{ss}\sum_{r\neq s}^{m} Y^{sr}}_{3.Traditional\ trade} + \underbrace{\widehat{EI}^sL^{ss}\sum_{r\neq s}^{m} A^{sr}L^{rr}Y^{rr}}_{4.Simple\ GVCs}$$

$$+ \underbrace{\widehat{EI}^sL^{ss}(\sum_{r\neq s}^{m}\sum_{t\neq s}^{m} A^{st}\sum_{u}^{m} B^{tu}Y^{ur} - \sum_{r\neq s}^{m} A^{sr}\,L^{rr}Y^{rr})}_{5.Complex\ GVCs} \quad 4$$

According to equation 4, the total production-based energy use of country s induced by country s is $\widehat{EI}^s L^{ss} Y^{ss} + \widehat{EI}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{u}^{m} B^{ru} Y^{us}$, in which $\widehat{EI}^s L^{ss} Y^{ss}$ is the energy use directly induced by the final demand of country s itself, and $\widehat{EI}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{u}^{m} B^{ru} Y^{us}$ is the energy use induced by the final demand of country s through products returned domestic. The total production-based energy use of country s induced by other countries is $\widehat{EI}^s L^{ss} \sum_{r \neq s}^{m} Y^{sr} + \widehat{EI}^s L^{ss} \sum_{r \neq s}^{m} A^{sr} L^{rr} Y^{rr} + \widehat{EI}^s L^{ss} (\sum_{r \neq s}^{m} \sum_{t \neq s}^{m} A^{st} \sum_{u}^{m} B^{tu} Y^{ur} - \sum_{r \neq s}^{m} A^{sr} L^{rr} Y^{rr})$. In specific, without loss of generality, the production-based energy use of country s induced by country r can be expressed as $\widehat{EI}^s L^{ss} Y^{sr} + \widehat{EI}^s L^{ss} A^{sr} L^{rr} Y^{rr} + \widehat{EI}^s L^{ss} (\sum_{t \neq s}^{m} A^{st} \sum_{u}^{m} B^{tu} Y^{ur} - A^{sr} L^{rr} Y^{rr})$. Further, the production-based energy use of country s induced by country r through traditional trade, simple GVCs and Complex GVCs are respectively $\widehat{EI}^s L^{ss} Y^{sr}$, $\widehat{EI}^s L^{ss} A^{sr} L^{rr} Y^{rr}$ and $\widehat{EI}^s L^{ss} (\sum_{t \neq s}^{m} A^{st} \sum_{u}^{m} B^{tu} Y^{ur} - A^{sr} L^{rr} Y^{rr})$.

Then, the consumption-based energy use of country s, which is either produced by itself or by other countries through global value chains, can be expressed as follows:

$$E^s_{consumption} = \underbrace{\widehat{EI}^s L^{ss} Y^{ss}}_{1.Pure\ domestic} + \underbrace{\widehat{EI}^s L^{ss} \sum_{r \neq s}^{m} A^{sr} \sum_{u}^{m} B^{ru} Y^{us}}_{2.Returned\ domestic} + \underbrace{\sum_{r \neq s}^{m} \widehat{EI}^r L^{rr} Y^{rs}}_{3.Traditional\ trade} + \underbrace{\sum_{r \neq s}^{m} \widehat{EI}^r L^{rr} A^{rs} L^{ss} Y^{ss}}_{4.Simple\ GVCs} + \underbrace{\sum_{r \neq s}^{m} \widehat{EI}^r L^{rr} (\sum_{t \neq r}^{m} A^{rt} \sum_{u}^{m} B^{tu} Y^{us} - A^{rs} L^{ss} Y^{ss})}_{5.Complex\ GVCs} \quad 5$$

Further, the net energy use transfer of country s, namely the net energy use it "outsourced" to other countries, which is the difference between its production-based energy use and consumption-based energy use, can be expressed as follows:

$$E_n^s = E_c^s - E_p^s \quad 6$$

By replacing the energy intensity matrix in above decomposition with that of coal, oil, gas and other energy types, we can further decompose the energy use of coal, oil, gas and other energies along the GVCs.

3.2. Data

The data used in this study mainly includes input-output data and energy use data. The multi-country input-output table comes from WIOD13 database for 1995-2010 (Timmer et al., 2016[49]), and ADB Multi-Regional Input-Output Database for 2011-2017. To cover a longer time span, this study integrates WIOD13 and ADB-MRIO, in which WIOD13 covers the input-output data of 41 countries or regions and 35 industries in 1995-2009 and ADB-MRIO covers the input-output data of 62 countries or regions and 35 industries in 2010-2021. This study first harmonized the countries/regions according to the concordance table provided as Table A3 in Appendix A.

The second data source is the energy accounts, which reflect the amount of energy inputs of each country-sector during production process. The original data is drawn from World Energy Balances from International Energy Agency (IEA). The World Energy Balances provides the energy balance for 150 countries and 35 regional aggregates. The energy balances as in the IEA can be seen as a matrix, where the columns represent the different energy product categories and rows represent all the different "flows", with detailed information on energy production and imports/exports, energy transformation and final energy consumption. Following the method developed to obtain the energy accounts in WIOD (Corsatea et al., 2016), we compile the energy accounts from 2000 to 2017 based on the IEA energy balances. Then, the energy accounts are further mapped to 41 countries or regions, 35 industries and 4 types of energy including coal, oil, gas and others. The decomposition and calculation are conducted for 41 countries or regions (40 countries or regions plus the rest of the world) and 35 industries. To better present the results, the 41 countries or regions were classified into 6 groups, including China (CHN), the United States (US), the European Union (UN), the BRICs except China (Brazil, Russia and India, in short BRI), Japan and the South Korea (JK), and the rest of the World (ROW).

4. Energy Decomposition along GVCs

The world has witnessed a stable growth of energy use in past 2 decades, from 7711.1 Mtoe in 2000 to 12684.01 Mtoe in 2017. The energy use through domestic channels have increased from 5645.87 Mtoe to 9767.08 Mtoe, with an annual growth rate of 3.1%; while the energy uses through world trade have increased mildly from 2065.24 Mtoe to 2916.93 Mtoe, with a growth rate of 1.9%. From 1995 to 2008, the share of energy use through world trade increased from 26.8% to 30.1%, making up nearly 30% of world total. It decreased sharply to 26.8% in 2009, due to sudden shrinkage of global trade. The share of energy use through world trade channels have slowly recovered to 28.0% in 2014, since when it started to decrease again to 23.0% in 2017. As in Figure 1, global energy uses through all 5 channels have increased, in which the energy use through return domestic channel have almost doubled and that through the complex GVCs channel have increased the second most. By looking into different types of energy, the amount of coal and oil uses embodied in trade have increased since 2000, while the amount of gas embodied has decreased recently. Energy uses embodied in trade accounted for 20.5%, 26.2% and 31.7% in world total coal, oil and gas uses respectively in 2000, which rose to 25.9%, 30.0% and 31.4% in 2008, and fell back to 20.0%, 26.1% and 24.3% in 2017. Detailed information on world energy use through GVCs by energy types are provided in Appendix B.

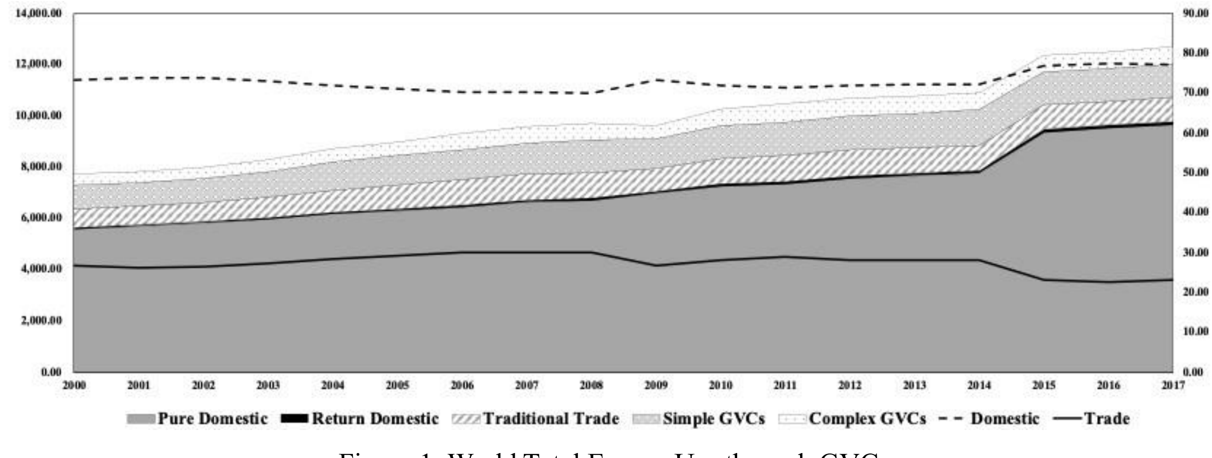


Figure 1: World Total Energy Use through GVCs

4.1. Production-based Energy Use along GVCs

The production-based energy use accounts for the energy use of each country during the production process. Table 1 reports the production-based energy use of 6 major economies listed above. The production-based energy use of the developed countries, i.e. the United States, the European Union, Japan and Korean stayed relatively stable, while that of the developing countries has grown rapidly. In 2000, the total production-based of China was roughly half of the United States, while it reached 3171.24 Mtoe in 2017, not only exceeded the United States to be the world's largest energy user, but also made up 25% of world's total production-based energy use. The production-based energy use of three other BRICs countries has also increased from 917.57 Mtoe in 2000 to 1713.87 Mtoe in 2017, which is nearly doubled. In total production-based energy use of China, 602.74 Mtoe is induced by world trade in 2017. That is, 19.0% of the energy use in China during production are created by the demand of other countries. A striking fact is that the European Union, Japan and Korean, as developed countries, also have a high share of production-based energy use created by world demand.

Table 1. Production-based Energy Use of Major Economies

	2000			2017		
	Total	By trade	Trade (%)	Total	By trade	Trade (%)
CHN	829.11	185.82	22.4	3171.24	602.74	19.0
USA	1962.06	213.11	10.9	1943.69	193.27	9.9
EU	1359.64	462.39	34.0	1315.91	513.93	39.1
BRI	917.57	297.28	32.4	1713.87	376.54	22.0
JK	633.69	122.72	19.4	714.77	179.05	25.1
ROW	2009.05	783.92	39.0	3824.52	1051.40	27.5
WORLD	7711.11	2065.24	26.8	12684.01	2916.93	23.0

Table 2 decomposes the production-based energy use induced by trade down to different global value chains. During 2000 to 2017, the production-based energy use of developed economies induced by trade have increased slightly from 798.2 Mtoe to 886.3 Mtoe, while that of the developing economies have increased from 1267.0 Mtoe to 2030.7 Mtoe, with an increase of 763.7 Mtoe. Considering the total increase of world's energy use is 4972.90 Mtoe from 2000 to 2017, 15.4% of it has been the increase of production-based energy use induced by trade in developing economies. That is, a considerable part of global energy use increase is due to the production-based energy use induced by international trade in developing countries.

Table 2. Production-based Energy Use of Major Economies Induced by Trade

	traditional trade		simples GVCs		Complex GVCs		Total	
	2000	2017	2000	2017	2000	2017	2000	2017
World	713.2	956.8	935.4	1300.0	416.6	660.1	2065.2	2916.9
Developed Economies	291.4	307.9	328.6	358.1	178.2	220.2	798.2	886.3
Developing Economies	421.8	648.9	606.8	941.9	238.5	439.9	1267.0	2030.7
in which:								
CHN	100.6	287.9	55.8	211.2	29.5	103.7	185.8	602.7
BRI	51.1	73.3	157.2	188.1	89.0	115.2	297.3	376.5
ROW	270.1	287.8	393.8	542.7	120.0	221.0	783.9	1051.4

Figure 2 provides total production-based energy use embodied in trade for major economies and decomposes it into three channels: traditional trade, simples GVCs and complex GVCs. Detailed decomposition results by energy types, that is, coal, oil, gas and other energy types are included in appendix C. The increase of energy use embodied in simple GVCs and complex GVCs has been faster than that embodied in traditional trade, which is in line with the pattern of world trade. It also indicates that future energy use might be more deeply embodied in global value chains and global production networks. The total production-based energy use embodied in trade grows most rapidly in China during its participation in the World trade organization (WTO). China is the economy with largest production-based energy use induced through traditional trade and simple GVCs, while the European Union is the economy with largest production-based energy use induced through complex GVCs.

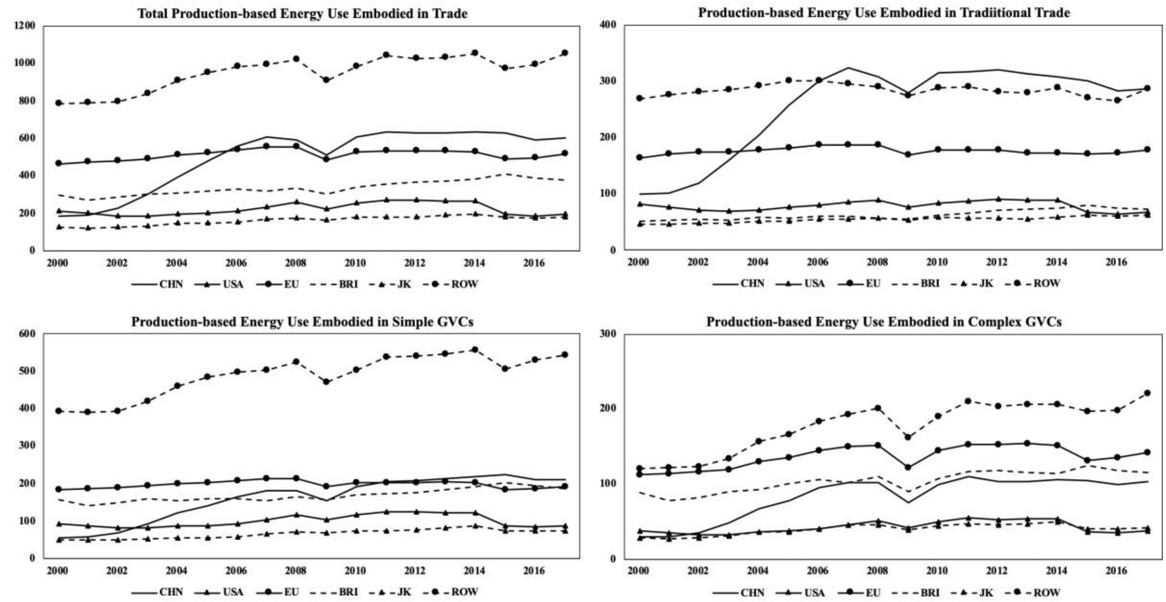


Figure 2: Production-based Energy Use through GVCs

Figure 3 further breaks down total production-based energy use embodied in GVCs according to energy types for China, the United States, and the Europe Union. The production-based energy uses of China, the US and the EU show very different patterns. As a heavily coal-dependent country, China’s production-based coal use embodied in GVCs is much larger than that of the US and the EU, although it has experienced a decrease since 2014 due to the air pollution control action plan, the installment of renewable energy, and energy intensity changes. On the contrary, the oil uses embodied in GVCs of the EU and the US are much larger than that of China. It is also worth noting that gas and other energy uses embodied in GVCs are also increasing rapidly, with a large part contributed by China’s installment and enlargement of renewable energies, including wind energy and solar energy.

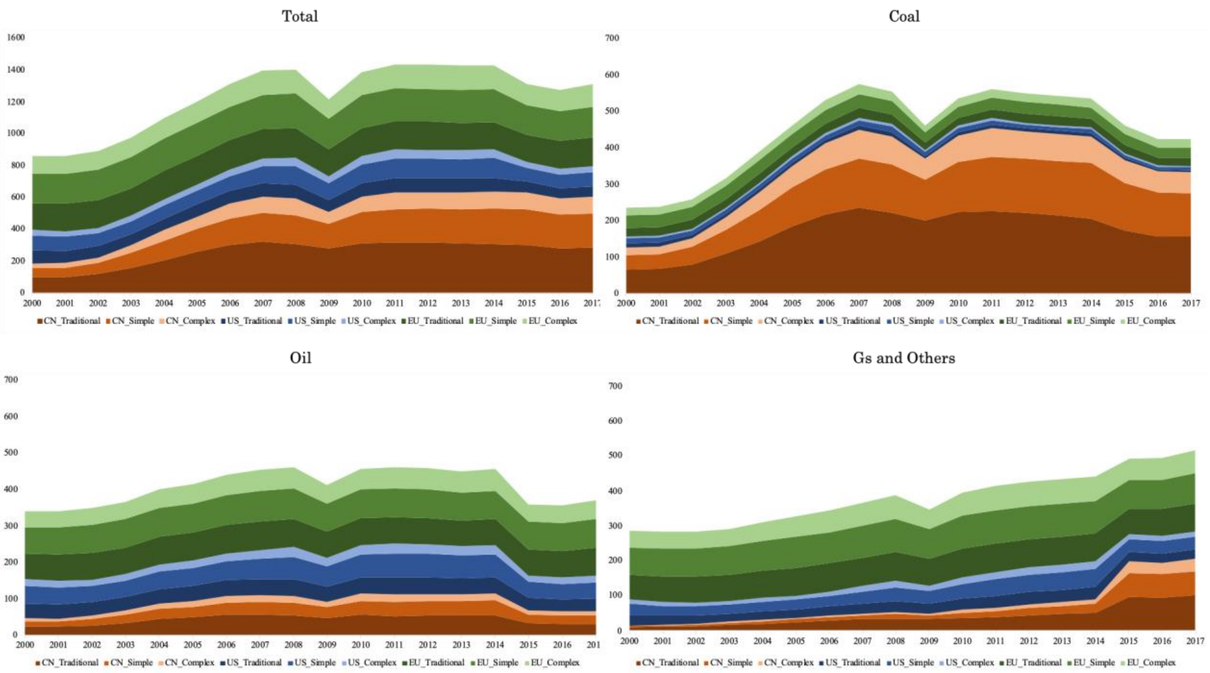


Figure 3: Production-based Energy Use Embodied in Trade by Energy Type

4.2. Consumption-based Energy Use along GVCs

The consumption-based energy use represents the total energy use to fulfill each country's final demand of consumption. Table 3 reports the consumption-based energy use of 6 major economies. The United States and China are the top two economies with the largest consumption-based energy use in 2017. The consumption-based energy use of China in 2017 is over 4 times of that in 2000. The European Union is the economy whose consumption-based energy is deeply embodied in world trade. Almost 50% of consumption-based energy of the European Union is fulfilled by world trade. On the contrary, China and the other 3 BRICs countries have rather low share of consumption-based energy fulfilled by world trade, which is 10.6% and 10.8% in 2017 respectively.

Table 3. Consumption-based Energy Use of Major Economies

	2000			2017		
	Total	By trade	Trade (%)	Total	By trade	Trade (%)
CHN	715.25	71.97	10.1	2873.15	304.65	10.6
USA	2229.20	480.25	21.5	2202.23	451.81	20.5
EU	1570.41	673.16	42.9	1519.47	717.49	47.2
BRI	688.91	68.62	10.0	1499.30	161.96	10.8
JK	722.39	211.43	29.3	762.36	226.65	29.7
ROW	1784.95	559.82	31.4	3827.50	1054.38	27.5
WORLD	7711.11	2065.24	26.8	12684.01	2916.93	23.0

Table 4 reports the consumption-based energy use of major economies fulfilled by trade through different global value chains. The consumption-based energy use of developed economies driven by trade increased slightly from 2000 to 2017, while that of the developing economies increased from 700.4 Mtoe to 1521.0 Mtoe. The consumption-based energy of developing economies embodied in trade has not only doubled from 2000 to 2017, but also exceeded that of the developed economies. The consumption-based energy of developing economies has witnessed an increase of 820.6 Mtoe, making up 96.3% of world's total increase in energy use embodied in trade. The countries of ROW, including the most underdeveloped countries and regions, have played an important role in global consumption-based energy use increase.

Table 4. Consumption-based Energy Use of Major Economies Induced by Trade

	traditional trade		simples GVCs		Complex GVCs		Total	
	2000	2017	2000	2017	2000	2017	2000	2017
World	713.2	956.8	935.4	1300.0	416.6	660.1	2065.2	2916.9
Developed Economies	483.1	469.5	589.0	548.3	292.7	378.2	1364.8	1395.9
Developing Economies	230.1	487.3	346.4	751.8	124.0	281.9	700.4	1521.0
in which:								
CHN	13.1	58.0	41.4	181.5	17.5	65.1	72.0	304.6
BRI	18.1	46.2	36.5	77.5	13.9	38.3	68.6	162.0
ROW	198.9	383.1	268.4	492.8	92.5	178.5	559.8	1054.4

Figure 4 provides total consumption-based energy use embodied in trade for major economies and decomposes it into three channels: traditional trade, simples GVCs and complex GVCs. Detailed decomposition results by energy types, that is, coal, oil, gas and other energy types are provided as appendix D. The European Union and the United States are the economies with the largest consumption-based energy use fulfilled by world trade. This is especially evident for consumption-based energy use through traditional trade, of which the scales of European Union and the United States are several times larger than that of other economies. It is in line with the fact that developing countries fulfill a large part of their demand by direct import of final products, for instance clothes and low-tech machineries. China's consumption-based energy has increased rapidly through simples GVCs, which is also consistent with its pattern of world trade participation.

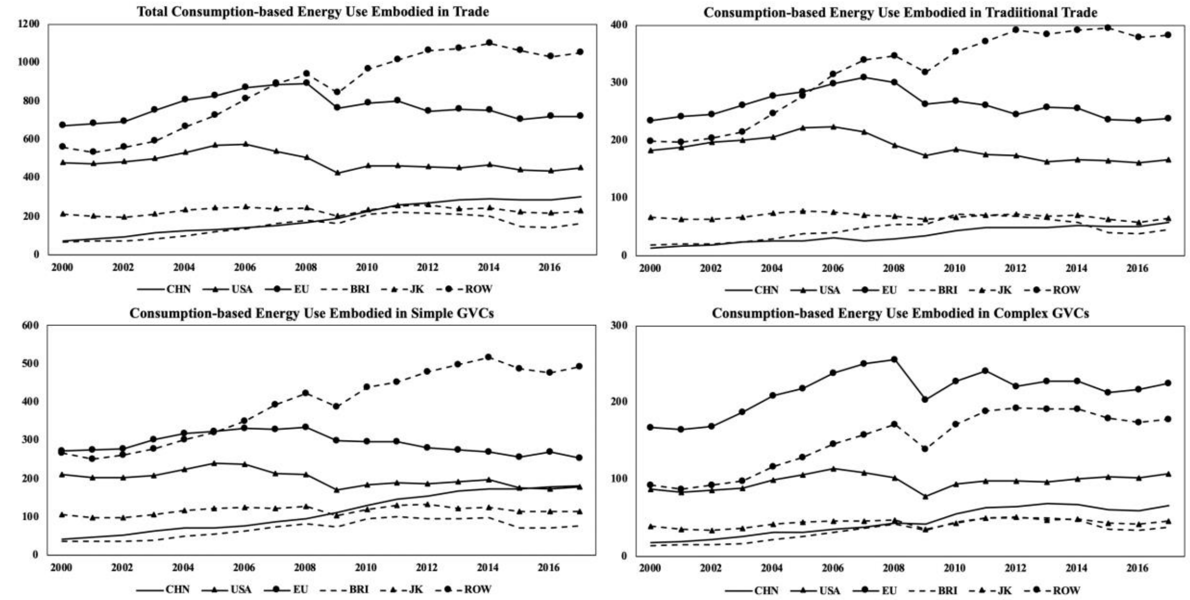


Figure 4: Consumption-based Energy Use through GVCs

Similarly, Figure 5 breaks down total consumption-based energy use embodied in GVCs according to 4 energy types for China, the United States, and the Europe Union. Different from production-based energy uses, the US and the EU's consumption-based energy use on coal, oil, gas and other types of energy all exceeded that of China. Although China is the country with the most production-based coal use embodied in GVCs, its consumption-based coal use is far less than that of the US and the EU.

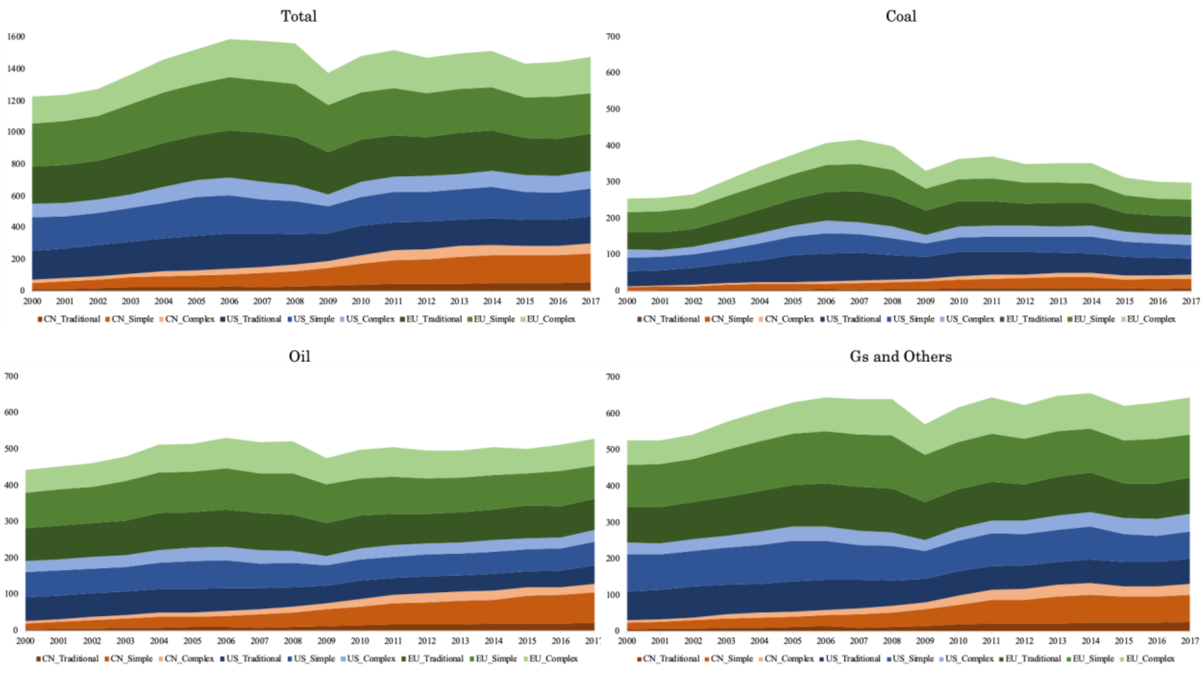


Figure 5: Consumption-based Energy Use Embodied in Trade by Energy Type

4.3. Net Energy Transfer along GVCs

The net energy transfer refers to the difference between the consumption-based and the production-based energy use of each country. It measures how much of the energy use is net "outsourced" to other countries, or fulfilled by other countries. On world level, the net energy transfer always adds up to zero; however, its distribution among different countries can be dispersed. As in Table 5, developed economies have positive net energy transfer while developing economies' is negative. Although the production-based energy use of developing countries is growing rapidly, a considerable amount of growth is induced by the demand of developed countries.

Table 5. Consumption-based Energy Use of Major Economies Induced by Trade

	traditional trade		simples GVCs		Complex GVCs		Total	
	2000	2017	2000	2017	2000	2017	2000	2017
Developed Economies	191.7	161.6	260.4	190.2	114.5	158.0	566.6	509.7
in which:								
US	101.6	98.3	116.5	90.3	49.1	70.0	267.1	258.5
EU	69.5	60.0	86.2	59.5	55.0	84.1	210.8	203.6
JK	20.6	3.3	57.7	40.4	10.4	3.9	88.7	47.6
Developing Economies	-191.7	-161.6	-260.4	-190.2	-114.5	-158.0	-566.6	-509.7
in which:								
CHN	-87.5	-229.8	-14.4	-29.7	-12.0	-38.5	-113.9	-298.1
BRI	-33.0	-27.1	-120.7	-110.6	-75.0	-76.9	-228.7	-214.6
ROW	-71.2	95.3	-125.3	-49.9	-27.5	-42.5	-224.1	3.0

Figure 6 decomposes the net energy transfer embodied in trade down to three channels. China, India and other developing countries in the rest of the world have negative net energy transfer. China is the country with the largest negative net energy transfer, of which that through traditional trade accounts for the most.

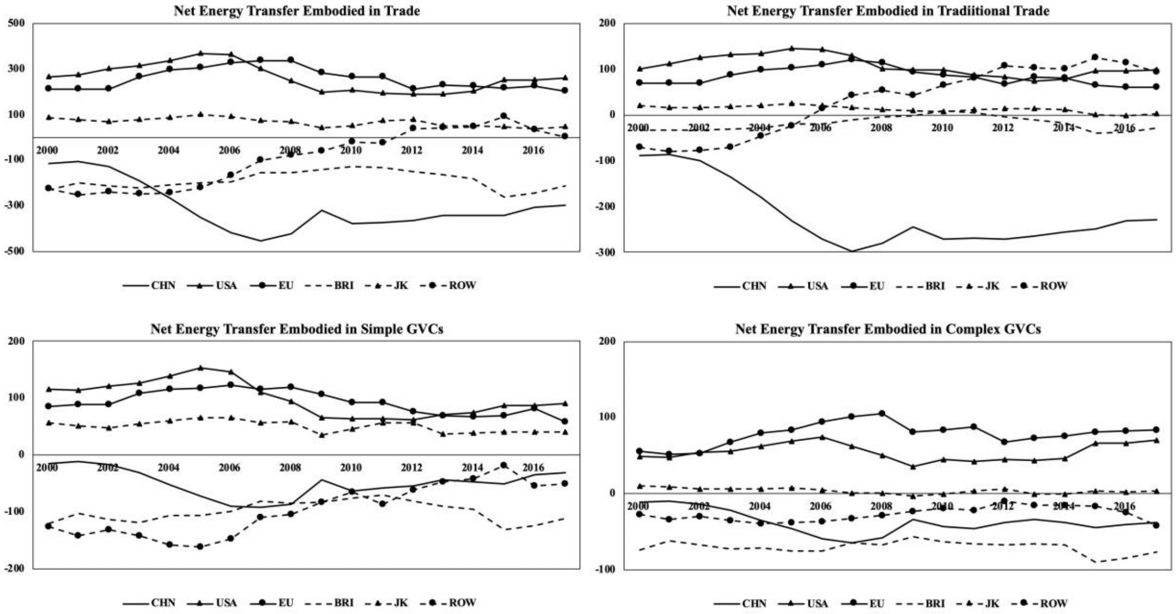
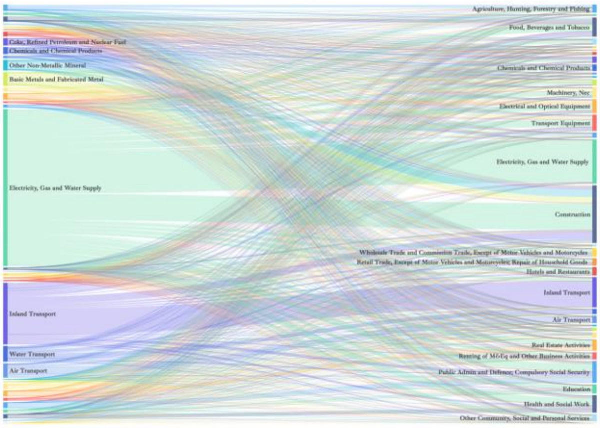


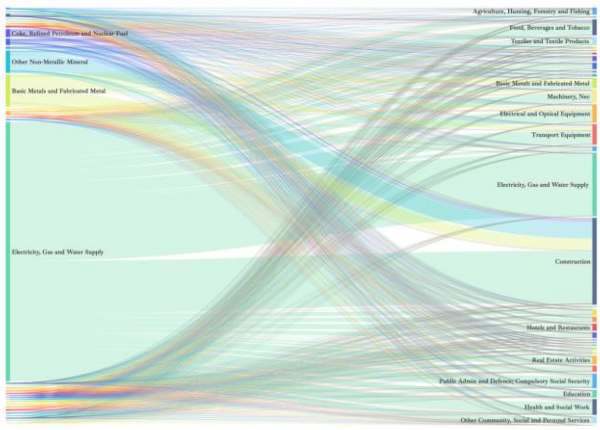
Figure 6: Net Energy Transfer through GVCs

4.4. Sector Level Results

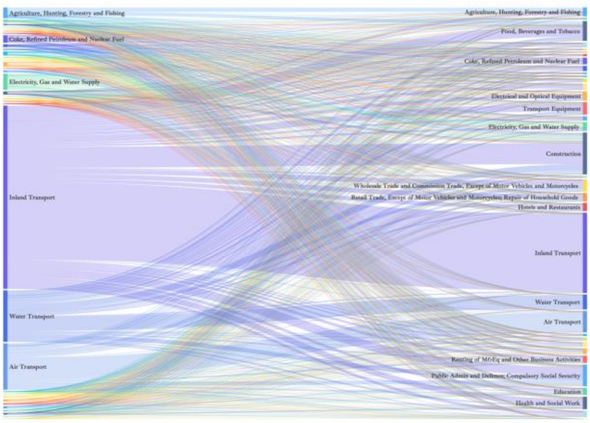
This section also presents the sector level results to shed lights on the redistribution of energy across industries and provide information on how much energy use is induced by "clean" sectors downstream. Figure 7 shows energy is embodied in Global Value Chains and redistributed across sectors. Figure 7a, representing the total energy flow, shows that though a large share of primary energy are direct inputs of energy sectors (e.g., "Electricity, Gas, and Water Supply"), transport sectors (e.g., "Inland Transport", "Water Transport", and "Air Transport"), and material sectors (e.g., "Basic Metals and Fabricated Metal" and "Other Non-Metallic Mineral"). However, the distribution is largely different in final demand sectors, in which manufacturing industries and service sectors have increased a lot ("Construction", "Public Administration", "Health and Social Work", and "Education"). With very little direct energy input, the "clean" sectors rely more on energy contained in intermediate products from upstream industries. The energy types are heterogeneous, more coal is used as a direct input for the electricity sector (e.g., "Electricity, Gas, and Water Supply") and more oil is used as a direct input for the transportation sector (e.g., "Inland Transport," "Water Transport," and "Air Transport"). Specifically, we investigate how the energy finally consumed by the ICT industry were transmitted through Global Value Chains. Figure 8 show the upstream sectors of the ICT industry by energy types. The graphs in Figure 8 show that the largest embodied energy flows to the ICT industry are from upstream sectors like: (1) energy sector like "Electricity, Gas, and Water Supply"; (2) transport sectors like "Inland Transport", "Air Transport", and "Water Transport"; (3) and sectors of components and parts like "Post and Telecommunication", "Electrical and Optical Equipment", "Basic Metal and Fabricated Metal".



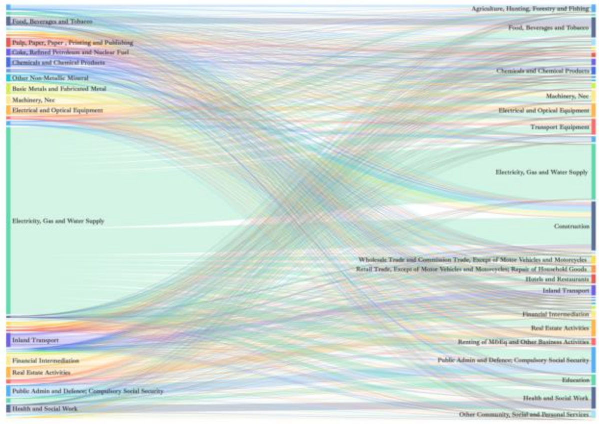
(a)



(b)

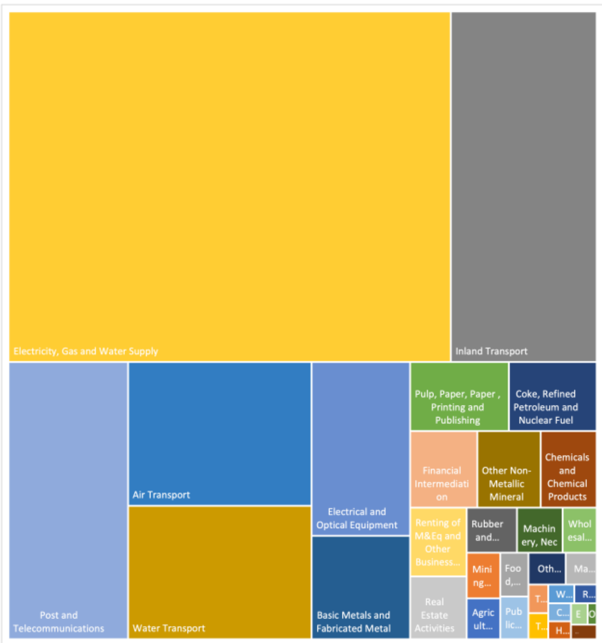


(c)

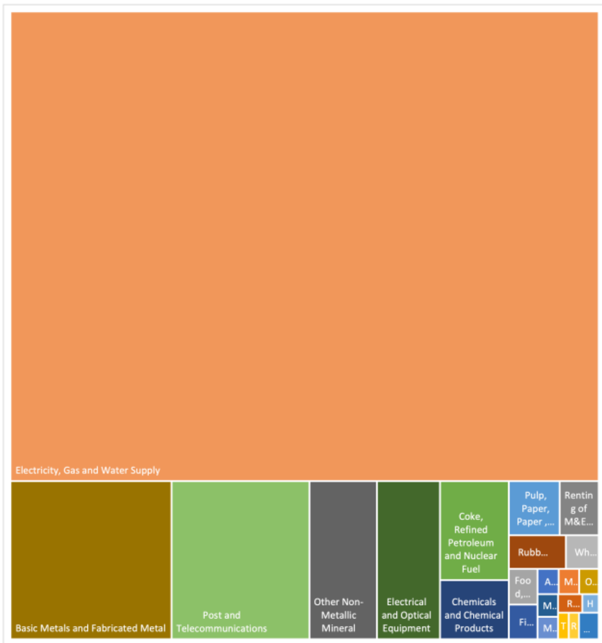


(d)

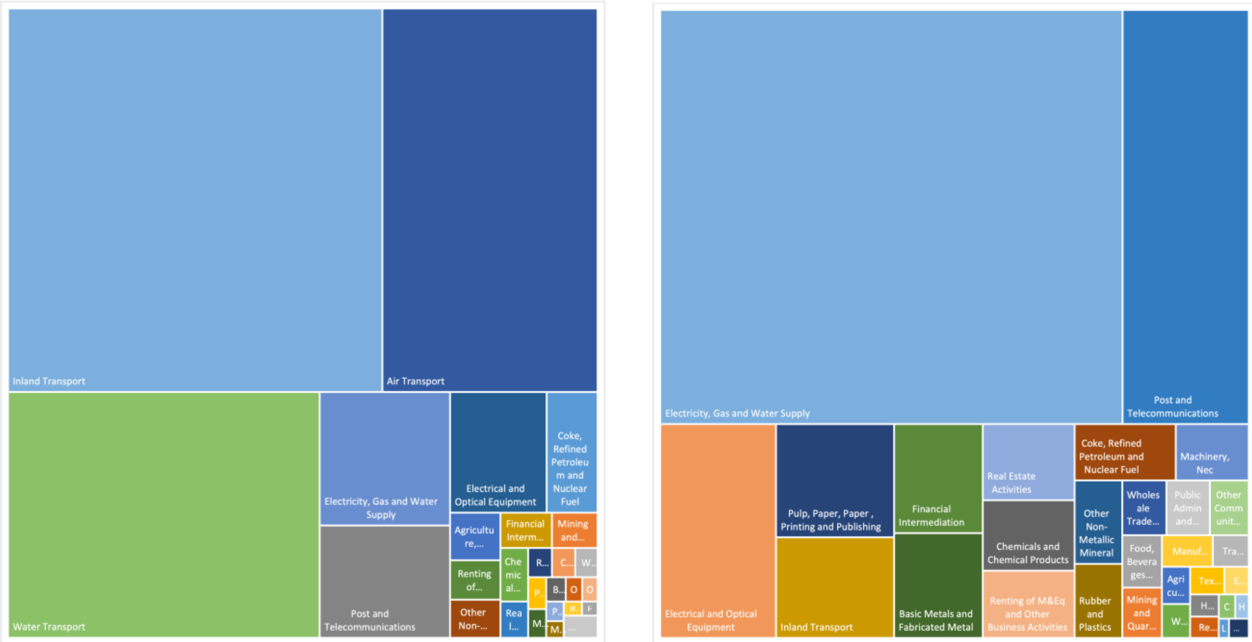
Figure 7: Energy Transfer through Sectors. a, Total Energy. b, Coal. c, Oil. d, Gas and Other Energy Types.



(a)



(b)



(c) (d)

Figure 8: Energy Consumed by ICT Industry: by Energy Types. a, Total Energy. b, Coal. c, Oil. d, Gas and Other Energy Types.

5. Empirical Results

Energy transference between countries is embodied in trade activities and influenced by social and economic patterns. In this section, empirical research is conducted to analyze the key factors affecting energy flows between countries. First, the empirical strategy is outlined based on the gravity model. Second, the empirical results on total energy use embodied in trade are presented. Thirdly, the results on energy use decomposed by global value chains are reported. Not only the results of total energy use, but also that of coal, oil, gas as well as other energies are reported in Appendix E.

5.1. Model Specification

In this study, we analyze the energy transfer between countries based on gravity model, which is often used to examine the factors influencing trade flows or FDI flows. Since the introduction of gravity model into economics (Tinbergen, 1962[50]), the explanary power and the robustness of gravity model has been widely recognized (Leamer and Levinsohn, 1995[51]). A large number of studies have applied gravity model to study bilateral trade in goods (Anderson and van Wincoop, 2003[52], trade in services (Kimura and Lee, 2008[53]), the migration of population (Ravenstein, 1885[54]), as well as transnational FDI (Blonigen, 2005[55]). The gravity model establishes the relationship between bilateral trade flows and its dependent factors, including the economic scale of and trade cost between the two countries. It has been proved that the trade flows are positively correlated with economic scale and negatively correlated with trade cost, which is often measured by geographic distance or cultural distance (Shepherd, 2016[56]).

The sample used in this study is the energy transfer flows between each pair of entities in 40 economies covered by the WIOD database and ADB-MRIO database from 1995 to 2017. For each pair, the home country is the consumption side of the energy, namely whose consumption-based energy use is accounted for; the host country is the production side of the energy, namely whose production-based energy use is accounted for. The dependent variables are the total energy flows between countries and its decomposition into traditional trade, simple GVCs and complex GVCs, which are obtained from the decomposition of energy use in section 4. The independent variables include the economy scale of the home and host country, geographical and cultural distances between the two countries, and fixed effects. The specification of the model is expressed as follows.

$$E_{ijt} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnGDP_{jt} + \beta_3 lnDIS_{ij} + \beta_4 Con_{ij} + \beta_5 Lan_{ij} + \beta_6 Law_{ij} + \mu_i + \nu_j + \upsilon_t + \varepsilon_{ijt} \qquad 7$$

The economy scale of the home country and host country is the logarithm of GDP, which is reported in constant 2010 U.S. dollars. The GDP data is from the World Bank. The geographical distance between the home and host country includes the distance between the most populated cities, the distance between capitals, and the distance weighted by population density, are obtained from CEPII. According to previous empirical research on trade flows and FDI flows between countries, this study also includes other control variables. First, whether the home country and the host country are contiguous. If the two countries are contiguous, the variable contiguity takes the value of 1, otherwise it is 0. The data on contiguity comes from CEPII. A common border between the two countries is likely to reduce trade costs and promote energy use transference. Second, whether the home country and host country use the same official language. If the two countries have the same official language, the variable of language is 1, otherwise the value is 0. The data of official language also comes from CEPII. The same language system between the two countries helps to reduce the communication cost and transaction cost, enhance trust and encourage production outsourcing, thus promotes trade and energy transfer. Third, whether the home country and the host country use similar legal systems. If the two countries have similar legal systems, the variable law takes the value of 1, otherwise the value is 0. The data of law system comes from the World Legal System Report of Ottawa University, Canada. Being in the same legal system can deepen the trust between the two countries, reduce the friction of interaction, and reduce transaction costs, so as to improve the trade and product outsourcing between the two countries, and promote the energy transfer between the two countries. Table 6 presents the summary statistics of the main variables included.

Table 6. Summary Statistics

Variable	Definition	Mean	Std. Dev.	Min	Max
Energy Flow					
total	ln energy use in total	4.81	2.33	-3.41	14.76
tradition	ln energy use through traditional trade	3.15	2.49	-7.75	11.32
simple	ln energy use through simple GVC	3.29	2.52	-8.78	10.82
complex	ln energy use through complex GVC	3.65	2.04	-4.21	10.07
GDP					

lngdp	ln GDP in constant 2010 US $	26.73	1.73	22.69	30.48
Distances and other dummy variables					
dist (10^4 km)	distance between most populated cities	0.52	0.45	0.01	1.88
distcap	distance between capitals	0.51	0.44	0.01	1.85
distw	ln weighted distance	0.52	0.44	0.02	1.83
lndist (ln of km)	ln distance between most populated cities	7.98	1.19	1.90	9.84
lndistcap	ln distance between capitals	7.98	1.18	1.90	9.83
lndistw	ln population intensity weighted distance	8.03	1.14	2.13	9.81
law	1 for similar law system	0.50	0.50	0	1
contiguity	1 for contiguity	0.06	0.23	0	1
language	1 for common official language	0.05	0.22	0	1

5.2. Energy Embodied in Trade

In this section, the results on total energy use embodied in trade are presented. Table 7 reports the results on total energy use embodied in trade. Detailed information for coal, oil, gas as well as other energy use are also provided in Appendix F as Table F1-F4. First of all, the energy flow between the home and host countries increase as the GDP of both countries increases. As the demand side, the home country plays a more important role in the energy transfer between the two countries. A 1% increase of the GDP of the home country and the host country, increases the energy flow between the two countries by 1.312% and 0.649% respectively. Larger economic scale and demand of the home country increases its total trade with foreign countries and its outsourcing of energy-intensive goods, while larger economic scale of the host country increases its capacity to fulfill the demand of other countries and to participate in global production networks.

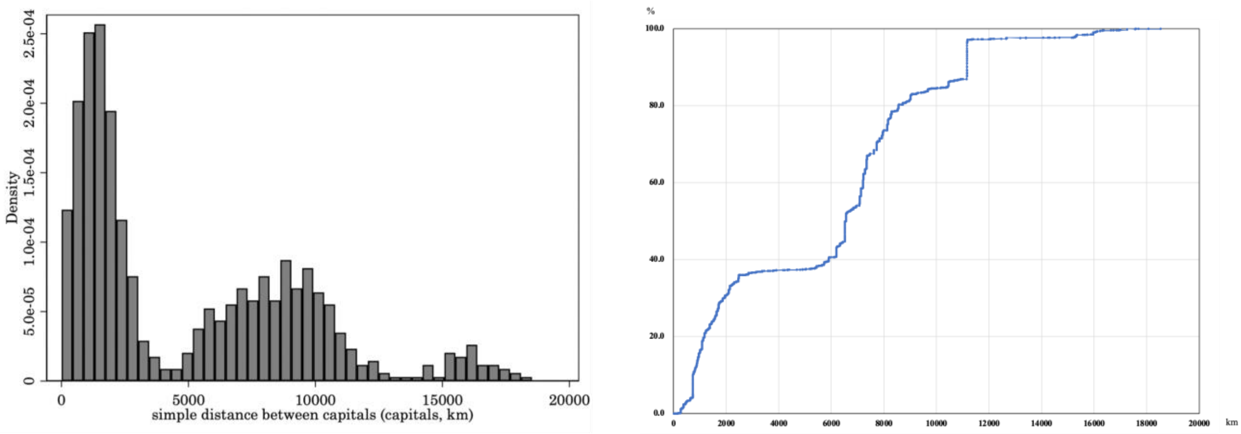
Table 7. Energy embodied in trade: Total

	(1) total	(2) total	(3) total	(4) total	(5) total	(6) total
lngdp_con	1.312***	1.312***	1.312***	1.312***	1.312***	1.312***
	(41.87)	(41.69)	(41.88)	(41.79)	(42.28)	(42.24)
lngdp_pro	0.649***	0.649***	0.649***	0.649***	0.649***	0.649***
	(20.08)	(20.22)	(20.06)	(20.25)	(20.00)	(20.23)
lndist	-0.991***	-0.917***				
	(-134.26)	(-118.14)				
lndistcap			-1.016***	-0.936***		
			(-134.79)	(-115.96)		
lndistw					-1.074***	-0.993***
					(-138.35)	(-117.79)
contiguity		0.345***		0.386***		0.408***

		(15.23)		(17.56)		(19.51)
language		0.0811^{***}		0.0931^{***}		0.0906^{***}
		(3.13)		(3.60)		(3.49)
law		0.0503^{***}		0.0453^{***}		0.0214
		(3.86)		(3.44)		(1.63)
cons	-38.32^{***}	-39.13^{***}	-38.05^{***}	-38.93^{***}	-37.51^{***}	-38.41^{***}
	(-29.52)	(-30.10)	(-29.43)	(-30.10)	(-29.19)	(-29.89)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	28080	28080	28080	28080	28080	28080
R^2	0.937	0.939	0.938	0.940	0.940	0.942

*Note: The significance levels of 1%, 5%, and 10% are denoted by ***, ** and * respectively. All columns include country fixed effects and year fixed effects. t statistics are reported in parentheses.*

In line with traditional gravity model, there is a robust negative correlation between two countries' energy flow and their geographical distance. As presented in columns (2), (4) and (6), a 1% increase in geographic distance leads to a 0.917%, 0.936% and 0.993% decrease of energy flow after controlling for other variables and fixed effects. Figure 9 presents the histogram of simple distance between country/region capitals and shows the cumulative share of embodied energy against the geographical distances. Figure 9 shows that over 30% of energy is redistributed to countries/regions within 2000km (e.g., the geographical distances between capital cities are 1911km between FIN and FRA, 2098km from China to Japan). From 2000 km to 6000 km, the cumulative share increases considerably more slowly, and from 6000 km to 10 000 km, it climbs steadily. Several big energy pairs occur within such range, for instance, it is 9018km from Australia to China and 5795 from China to Russia. There is a steep increase near 11000km, which includes several country pairs like China-the United States, Brazil-Russia, Canada-India. If the two countries are adjacent, use the same official language, or are under the same legal system, the energy flow between them increases. This is because these similarities between the two countries can enhance trust, reduce the cost of communication, promote the trade of goods and services, encourage the outsourcing of production, and ultimately promote the energy flow between them. When using weighted geographical distance in column (6), a common border of the two countries, the same official language, and a same legal system can increase energy flow by 0.408%, 0.0906% and 0.0214%, respectively. This finding indicates that proximity and similarity between countries can decrease the frictions between countries and lower transaction costs, thus a world with more similar cultures and lower trade barriers might have even more energy use embodied in trade.



(a) (b)

Figure 9: Energy Embodied in GVCs-Geographical Distances. a, Histogram of Simple Distance between Capital (km). b, Energy Embodied in GVCs-Geographical Distances (Measured by Capital Distance).

5.3. Energy Embodied in Traditional, Simple and Complex GVCs

The pattern of energy flow might be different according to global value chains. To examine the characteristics of each global value chain, we further conduct the empirical analysis on the energy flow through traditional trade, simple GVCs and complex GVCs. Table 8 reports the effects of concerned variables on total energy use embodied in each global value chain. Detailed information for coal, oil, gas as well as other energy use are also provided in Appendix F as Table F5-F8.

In Table 8 columns (1) and (2) presents the results for traditional trade, columns (3) and (4) for simple GVCs, and (5) and (6) for complex GVCs. Consistent with findings in 5.2, the energy flow between the home and host countries increase as the GDP of both countries increases for all three global value chains. A 1% increase of the GDP of the home country, increases the energy flow between the two countries through traditional trade, simple GVCs and complex GVCs by 1.517%, 1.345%, and 1.233% respectively. By comparing the scale of the coefficients, the economy scale of the home country plays a more important role in traditional trade than in simple and complex GVCs. This might be driven by the direct import of final products of developed countries, as outlined in section 4.

We have found negative correlation between two countries' energy flow and their geographical distance in all three channels. The distance in Table 8 is measured by the weighted distance based on population density. As presented in columns (2), (4) and (6), a 1% increase in geographic distance is correlated with about a 1.320%, 1.509% and 0.407% decrease of energy flow through traditional trade, simple GVCs and complex GVCs respectively. The complex GVCs channel is the least affected by the distance. This is because the products and the energy embodied in products have crossed national borders for multiple times and the "real distance" should be a complex measurement weighted by the production process, rather than a simple geographical distance. For instance, when Japan imports iron and steel from China which is produced by iron ore from Australia, the distance between Japan and Australia along the complex GVCs is a distance weighted by the production networks, rather than their geographical distance.

A striking fact is that contiguity, same official language and same legal system have different impacts on energy flows across GVC channels. As for tradition trade presented in column (2), a common border and the same official language increase energy flow by 0.369% and 0.236% respectively; however, the same legal system has no significant effect. As for simple GVCs presented in column (4), a common border increases energy flow by 0.332%; however, the same language or legal system both have positive but not significant effect. The complex GVCs show different characteristics. Being adjacent to each other or using the same official language decreases the energy flow through complex GVCs. This is easy to understand because contiguity and same language enhances the possibility of direct trade between the two countries through traditional trade or simple GVCs, which cause a substitution effect to the complex GVCs. It is worth noting that the effect of a same law system is still positive for complex GVCs. The energy flow increase caused by the same law system exceeds its substitution effect. It also reveals the importance of building a general law system for world trade.

Table 8. Energy embodied in Global Value Chains: Traditional, Simple and Complex GVCs

	(1)	(2)	(3)	(4)	(5)	(6)
	tradition	tradition	simple	simple	complex	complex
lngdp_con	1.517***	1.517***	1.345***	1.345***	1.233***	1.233***
	(27.09)	(27.07)	(23.42)	(23.38)	(58.04)	(58.39)
lngdp_pro	0.707***	0.707***	0.741***	0.741***	0.626***	0.626***
	(14.34)	(14.41)	(15.34)	(15.42)	(30.97)	(30.94)
lndistw	-1.399***	-1.320***	-1.573***	-1.509***	-0.374***	-0.407***
	(-126.15)	(-102.64)	(-144.14)	(-117.71)	(-91.74)	(-84.95)
contiguity		0.369***		0.332***		-0.194***
		(11.94)		(11.76)		(-17.87)
language		0.236***		0.0310		-0.0770***
		(5.78)		(0.72)		(-6.78)
law		-0.0154		0.0178		0.0353***
		(-0.71)		(0.75)		(5.09)
cons	-43.55***	-44.46***	-37.51***	-38.19***	-42.89***	-42.50***
	(-20.91)	(-21.39)	(-17.98)	(-18.30)	(-51.22)	(-50.99)
Origin	Y	Y	Y	Y	Y	Y
Destination	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	28074	28074	28080	28080	28080	28080
R^2	0.872	0.874	0.875	0.876	0.976	0.976

*Note: The significance levels of 1%, 5%, and 10% are denoted by ***, ** and * respectively. All columns include country fixed effects and year fixed effects. t statistics are reported in parentheses.*

Table 9. Energy embodied in trade: Total

	(1) Coal	(2) Oil	(3) Gas	(4) Other
lngdp_con	1.370***	1.246***	1.288***	1.429***
	(35.97)	(37.50)	(39.96)	(32.88)
lngdp_pro	1.045***	0.352***	0.488***	0.821***
	(29.51)	(10.66)	(13.29)	(19.18)
lndistw	-1.009***	-0.951***	-1.012***	-1.034***
	(-110.09)	(-109.90)	(-117.81)	(-98.14)
contiguity	0.387***	0.453***	0.383***	0.413***
	(15.69)	(21.15)	(17.67)	(15.72)
language	0.157***	0.0770***	0.137***	0.0730**
	(5.66)	(2.92)	(5.69)	(2.31)
law	0.0234*	0.0258*	0.0383***	0.0207
	(1.71)	(1.83)	(3.05)	(1.19)
cons	-51.95***	-29.67***	-34.81***	-48.30***
	(-34.95)	(-22.13)	(-24.21)	(-27.46)
Consumption	Y	Y	Y	Y
Production	Y	Y	Y	Y
Year	Y	Y	Y	Y
N	27260	27984	26637	27454
R^2	0.948	0.932	0.941	0.912

*Note: The significance levels of 1%, 5%, and 10% are denoted by ***, ** and * respectively. All columns include country fixed effects and year fixed effects. t statistics are reported in parentheses.*

5.4. Heterogeneity between Different Energy Types

As different types of energy flow could show heterogeneous patterns across GVCs, this study further researches into how factors influence energy flows embodied in various GVCs for each energy type. Table 9 reports the effects of concerned variables on total energy use for coal, oil, gas and other types of energy. It shows that a 1% increase of the GDP of the home country, increases the energy flow between the two countries by 1.370%, 1.246%, 1.288% and 1.429% for coal, oil, gas and other energy types respectively, which are of the similar size. However, the effect of host country is heterogeneous for different energy types. A 1% increase of the GDP of the host country, increases the energy flow between the two countries by 1.045%, 1.352 %, 0.488 % and 0.821% for coal, oil, gas and other energy types respectively, in which the impact on coal is significantly larger than that on all other types of energies. In line with previous findings, the longer is the distance between the home and the host country, the less is the energy flow for all 4 types of energy. If the two countries are adjacent, use the same official language, or are under the same legal system, the energy flow between them increases for each type of energy.

Table 10 reports the effects of concerned variables on bilateral energy flows through each GVC for coal, oil, gas and other types of energy. While the GDP of both countries and the distance between them are still controlled, Table 10 mainly focus on the impact of contiguity, same official language, and same legal system. Panel A shows that if the two countries are adjacent, use the same official language, or are under the same legal system, their energy flows through traditional trade increases for each type of energy. Panel B presents similar findings for energy flows through simple GVCs, while the coefficients of the same official language are smaller than those estimated for energy flows through traditional trade. Although some of the effects are not statistically significant, all coefficients in Panel A and Panel B are positive. Panel C reports the impacts on energy flows through complex GVCs. In line with results in column (6) of Table 8, being adjacent to each other or using the same official language decreases the energy flow through complex GVCs, while the same law system increases relevant energy flows. This result is robust for coal, oil, gas and other types of energy.

Table 10. Energy embodied in trade: Three Channels

	Coal	Oil	Gas	Other
Panel A: Traditional				
contiguity	0.365***	0.381***	0.361***	0.383***
	(11.02)	(11.69)	(11.53)	(11.84)
language	0.299***	0.237***	0.288***	0.220***
	(7.51)	(5.55)	(8.57)	(5.17)
law	0.00139	0.00405	0.0467**	0.0469**
	(0.06)	(0.17)	(2.49)	(2.02)
Panel B: Simple GVC				
contiguity	0.337***	0.346***	0.327***	0.335***
	(10.72)	(11.56)	(12.04)	(10.01)
language	0.183***	0.00782	0.136***	0.0403
	(4.27)	(0.18)	(4.08)	(0.84)
law	0.0471**	0.0256	0.0919***	0.0518*
	(2.02)	(1.04)	(4.88)	(1.93)
Panel C: Complex GVC				
contiguity	-0.209***	-0.176***	-0.225***	-0.234***
	(-13.15)	(-15.23)	(-19.24)	(-12.53)
language	-0.0874***	-0.0757***	-0.0665***	-0.0602***
	(-6.10)	(-6.43)	(-5.42)	(-3.76)
law	0.0447***	0.0312***	0.0400***	0.0291**
	(5.63)	(3.75)	(5.07)	(2.49)

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively. The GDP of both countries and distance are still controlled.*

6. Conclusions and Discussions

This study decomposes the world's energy use on bilateral country-sector-global value chain level, measures countries' energy use according to production-based principle and consumption-based principle, traces the energy flows according to global value chains, and characterizes the pattern of energy flows by empirical analysis. In specific, it decomposes global energy use according to five global value chains: domestic energy use can be divided into (1) purely domestic and (2) returned domestic through trade; energy use embodied in trade can be further divided into (3) energy use through traditional trade (4) energy use through simple global value chains and (5) energy use through complex global value chains. The main findings of this study are as follows.

First, the energy use through world trade account for over 20% of world total energy use, with fluctuations during global finance crisis. The share of energy use happened through world trade increased from 26.8% in 1995, reached its highest point of 30.1% in 2008, decreased sharply to 26.8% in 2009 due to global financial crisis, slowly recovered to 28.0% in 2014 and decreased to 23.0% again in 2017. The energy use through global value chains has increased rapidly, especially for that embodied in the simple GVCs and complex GVCs. All economies are highly embodied in world energy network. Not only about 20% of the production-based energy use in China is created by overseas demand, but the developed economies like the European Union, Japan and Korea also have a high share of production-based energy use created by world demand.

Second, the distribution of production-based and consumption-based energy use is considerably different. The developing countries have large production-based energy use driven by global value chains, while the developed countries rank top in terms of consumption-based energy use through global value chains. The net energy transfer of developed economies is positive, while that of developing economies is negative. Although the energy use of developing countries is growing rapidly, part of this growth is actually induced to fulfill the demand of developed countries.

Third, empirical analysis reveals that the energy flow between the home and host countries increases with larger GDP of both countries, decreases with longer geographical distance, and increases with a common border, a common language as well as a similar law system. The patterns of energy flow are different across various global value chains. The distance is less important in complex GVCs. The three channels also act differently in terms of contiguity, same official language and same legal system. As for complex GVCs, there is a substitution effect toward traditional trade or simple GVCs if the two countries share a common border or uses the same language.

The world is deeply embodied in global value chains, and the global production networks have been more complex than ever before. Trade in products and services not only represents exchange in value, but also represents trade in energies, water resources, soil, emissions, pollutions as well as more aspects beyond. The growth of global value chains, especially complex GVCs, has restructured and reshaped the distribution of world energy uses. Any further policies targeting at sustainable development, equality, and energy saving need to take into account the role of global value chains.

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Appendix A. The concordance of countries, regions, and sectors

The 41 countries and regions, the 35 sectors, and the concordance of the WIOD and ADB-MRIO countries are listed as Table A1, Table A2, and Table A3.

Table A1: List of 41 countries or regions

No.	ISO	Country
1	AUS	Australia
2	AUT	Austria
3	BEL	Belgium
4	BGR	Bulgaria
5	BRA	Brazil
6	CAN	Canada
7	CHN	China
8	CYP	Cyprus
9	CZE	Czech Republic
10	DEU	Germany
11	DNK	Denmark
12	ESP	Spain
13	EST	Estonia
14	FIN	Finland
15	FRA	France
16	GBR	United Kingdom
17	GRC	Greece
18	HUN	Hungary
19	IDN	Indonesia
20	IND	India
21	IRL	Ireland
22	ITA	Italy
23	JPN	Japan
24	KOR	Korea
25	LTU	Lithuania

26	LUX	Luxembourg
27	LVA	Latvia
28	MEX	Mexico
29	MLT	Malta
30	NLD	Netherlands
31	POL	Poland
32	PRT	Portugal
33	ROM	Romania
34	RUS	Russia
35	SVK	Slovak Republic
36	SVN	Slovenia
37	SWE	Sweden
38	TUR	Turkey
39	TWN	Taiwan Region
40	USA	United States
41	RoW	Rest of the World

Table A2: List of 35 sectors

No.	Sectors
1	Agriculture, Hunting, Forestry and Fishing
2	Mining and Quarrying
3	Food, Beverages and Tobacco
4	Textiles and Textile Products
5	Leather, Leather and Footwear
6	Wood and Products of Wood and Cork
7	Pulp, Paper, Paper, Printing and Publishing
8	Coke, Refined Petroleum and Nuclear Fuel
9	Chemicals and Chemical Products
10	Rubber and Plastics

11	Other Non-Metallic Mineral
12	Basic Metals and Fabricated Metal
13	Machinery, Nec
14	Electrical and Optical Equipment
15	Transport Equipment
16	Manufacturing, Nec; Recycling
17	Electricity, Gas and Water Supply
18	Construction
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
22	Hotels and Restaurants
23	Inland Transport
24	Water Transport
25	Air Transport
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
27	Post and Telecommunications
28	Financial Intermediation
29	Real Estate Activities
30	Renting of M&Eq and Other Business Activities
31	Public Admin and Defense; Compulsory Social Security
32	Education
33	Health and Social Work
34	Other Community, Social and Personal Services
35	Private Households with Employed Persons

Table A3. Concordance Table of WIOD and ADB Countries/Regions

WIOD			ADB MRIO			
	Code	Name			Code	Name

1	AUS	Australia	1	1	AUS	Australia
2	AUT	Austria	2	2	AUT	Austria
3	BEL	Belgium	3	3	BEL	Belgium
4	BGR	Bulgaria	4	4	BGR	Bulgaria
5	BRA	Brazil	5	5	BRA	Brazil
6	CAN	Canada	6	6	CAN	Canada
7	CHN	China	7	8	CHN	China
8	CYP	Cyprus	8	9	CYP	Cyprus
9	CZE	Czech Republic	9	10	CZE	Czech Republic
10	DEU	Germany	10	11	DEU	Germany
11	DNK	Denmark	11	12	DNK	Denmark
12	ESP	Spain	12	13	ESP	Spain
13	EST	Estonia	13	14	EST	Estonia
14	FIN	Finland	14	15	FIN	Finland
15	FRA	France	15	16	FRA	France
16	GBR	United Kingdom	16	17	GBR	United Kingdom
17	GRC	Greece	17	18	GRC	Greece
18	HUN	Hungary	18	20	HUN	Hungary
19	IDN	Indonesia	19	21	IDN	Indonesia
20	IND	India	20	22	IND	India
21	IRL	Ireland	21	23	IRL	Ireland
22	ITA	Italy	22	24	ITA	Italy
23	JPN	Japan	23	25	JPN	Japan
24	KOR	Korea	24	26	KOR	Korea
25	LTU	Lithuania	25	27	LTU	Lithuania
26	LUX	Luxembourg	26	28	LUX	Luxembourg
27	LVA	Latvia	27	29	LVA	Latvia
28	MEX	Mexico	28	30	MEX	Mexico
29	MLT	Malta	29	31	MLT	Malta
30	NLD	Netherlands	30	32	NLD	Netherlands
31	POL	Poland	31	34	POL	Poland
32	PRT	Portugal	32	35	PRT	Portugal
33	ROM	Romania	33	36	ROM	Romania
34	RUS	Russia	34	37	RUS	Russia
35	SVK	Slovak Republic	35	38	SVK	Slovak Republic

36	SVN	Slovenia	36	39	SVN	Slovenia
37	SWE	Sweden	37	40	SWE	Sweden
38	TUR	Turkey	38	41	TUR	Turkey
39	TWN	Taiwan Region	39	42	TAP	Taipei,China
40	USA	United States	40	43	USA	United States
41	RoW	Rest of the World	41	44	BAN	Bangladesh
			41	45	MAL	Malaysia
			41	46	PHI	Philippines
			41	47	THA	Thailand
			41	48	VIE	Viet Nam
			41	49	KAZ	Kazakhstan
			41	50	MON	Mongolia
			41	51	SRI	Sri Lanka
			41	52	PAK	Pakistan
			41	53	FIJ	Fiji
			41	54	LAO	Lao People's Democratic Republic
			41	55	BRN	Brunei Darussalam
			41	56	BTN	Bhutan
			41	57	KGZ	Kyrgyz Republic
			41	58	CAM	Cambodia
			41	59	MDV	Maldives
			41	60	NPL	Nepal
			41	61	SIN	Singapore
			41	62	HKG	Hong Kong
			41	63	RoW	Rest of the World
			41	7	CHE	Switzerland
			41	19	HRV	Croatia
			41	33	NOR	Norway

Appendix B. Decomposition of Energy Use

This study analyzes transnational energy use through the Environmentally-extended Input Output Model. Based on the decomposition of value added and carbon emissions along the global value chains by Koopman, Wang and Wei (2014), Wang et al. (2017), Meng et al. (2018a, 2018b), it employs an Environmentally-extended Input Output Model of m countries and n sectors to decompose energy supply and use between countries along the global value chains. In a general input-output model, the equilibrium between product supply and demand can be expressed in the following matrix form:

$$AX + Y = X \qquad 1$$

where, A is the direct input coefficient matrix, X is the total output matrix, and Y is the final demand matrix. Put the final demand Y on the right side of the equation, equation 1 can be rewritten as follows:

$$(I - A)X = Y \qquad 2\text{-}1$$

$$\begin{bmatrix} I - A^{11} & \cdots & -A^{1m} \\ \vdots & \ddots & \vdots \\ -A^{m1} & \cdots & I - A^{mm} \end{bmatrix} \begin{bmatrix} X^{11} & \cdots & X^{1m} \\ \vdots & \ddots & \vdots \\ X^{m1} & \cdots & X^{mm} \end{bmatrix} = \begin{bmatrix} Y^{11} & \cdots & Y^{1m} \\ \vdots & \ddots & \vdots \\ Y^{m1} & \cdots & Y^{mm} \end{bmatrix} \qquad 2\text{-}2$$

where Y^{sr}, any submatrix on the right side of equation 2-2, refers to the part of final demand of country r imported from country s. So that Y^{sr} can be expressed as follows:

$$(I - A^{ss})X^{sr} - \sum_{t \neq s}^{m} A^{st}X^{tr} = Y^{sr} \qquad 3\text{-}1$$

$$(I - A^{ss})X^{sr} = \sum_{t \neq s}^{m} A^{st}X^{tr} + Y^{sr} \qquad 3\text{-}2$$

Denote the Leontief inverse matrix of country s as $L^{ss} = (I - A^{ss})^{-1}$. Pre-multiply equation 3-2 with L^{ss}, the general expression of X^{sr} and its special form X^{ss} can be expressed as follows:

$$X^{sr} = L^{ss} \sum_{t \neq s}^{m} A^{st}X^{tr} + L^{ss}Y^{sr} \qquad 3\text{-}3$$

$$X^{ss} = L^{ss} \sum_{t \neq s}^{m} A^{st}X^{ts} + L^{ss}Y^{ss} \qquad 3\text{-}4$$

Similarly, put the total output X on the left side of the equation, equation 1 can be rewritten as follows:

$$X = (I - A)^{-1}Y = BY \qquad 4\text{-}1$$

$$\begin{bmatrix} X^{11} & \cdots & X^{1m} \\ \vdots & \ddots & \vdots \\ X^{m1} & \cdots & X^{mm} \end{bmatrix} = \begin{bmatrix} B^{11} & \cdots & B^{1m} \\ \vdots & \ddots & \vdots \\ B^{m1} & \cdots & B^{mm} \end{bmatrix} \begin{bmatrix} Y^{11} & \cdots & Y^{1m} \\ \vdots & \ddots & \vdots \\ Y^{m1} & \cdots & Y^{mm} \end{bmatrix} \qquad 4\text{-}2$$

where X^{sr}, any submatrix on the right side of equation 4-2, refers to the part of output of country s to fulfill the demand of country r. So that X^{sr} can be expressed as follows:

$$X^{sr} = \sum_{t}^{m} B^{st}Y^{tr} \qquad 5$$

Clearly, one country's output is either used or consumed in its own country, or elsewhere in other countries. Therefore, the total output of country s can be written as follows:

$$X^s = \sum_r^m X^{sr} = X^{ss} + \sum_{r\neq s}^m X^{sr} \qquad 6$$

Replace the X^{sr} and X^{ss} in equation 6 with their expressions in equation 3-3 and 3-4, the total output of country s can be written as follows:

$$X^s = L^{ss}Y^{ss} + L^{ss}\sum_{r\neq s}^m Y^{sr} + L^{ss}\sum_{t\neq s}^m A^{st}X^{ts} + L^{ss}\sum_{r\neq s}^m \sum_{t\neq s}^m A^{st}X^{tr} \qquad 7$$

The target of this study is to decompose energy use by its country of production and consumption. Noted that the left side of equation 7 is the production of country s, the right side of equation 7 should decompose the outputs of country s according to its consumption countries. That is, each item on the right side of equation 7 should be mapped to the final demand of certain country. For this purpose, equation 5 is further introduced into equation 7, which is rewritten as follows:

$$X^s = L^{ss}Y^{ss} + L^{ss}\sum_{r\neq s}^m Y^{sr} + L^{ss}\sum_{t\neq s}^m A^{st}\sum_u^m B^{tu}Y^{us} + L^{ss}\sum_{r\neq s}^m \sum_{t\neq s}^m A^{st}\sum_u^m B^{tu}Y^{ur} \qquad 8$$

This provides a general form of decomposition method along the value chains, which is suitable for bilateral decomposition of value added, carbon emissions, energy use and so on. The total outputs of a country can be divided into five global value chain channels according to the types of products and the number of border crossings. First, the pure domestic channel that the production and consumption of the products happens in the same country and there is no international trade involved. Second, the returned domestic channels in which products involved in international trade still return to the source country of production, thus the original production and final consumption of the products still remain in the same country. Third, the traditional trade channels that the production and consumption of the products happens in two different countries, in which the products are exported to another country as final products and directly consumed by that country, with single border-crossing. Forth, the simple value chain channels that the production and consumption of the products happens in two different countries, in which the products are exported to another country as intermediate products and then processed by that country before consumption, with single border-crossing. Five, the complex value chain channels that the production and consumption of the products involved more than two countries, in which the products cross national borders for multiple times as intermediate inputs and finally consumed by another country.

$$X^s = \underbrace{L^{ss}Y^{ss}}_{1.Pure\ domestic} + \underbrace{L^{ss}\sum_{r\neq s}^G A^{sr}\sum_u^m B^{ru}Y^{us}}_{2.Returned\ domestic}$$

$$+ \underbrace{L^{ss}\sum_{r\neq s}^m Y^{sr}}_{3.Traditional\ trade} + \underbrace{L^{ss}\sum_{r\neq s}^m A^{sr}L^{rr}Y^{rr}}_{4.Simple\ GVCs}$$

$$+ \underbrace{L^{ss}\left(\sum_{r\neq s}^{m}\sum_{t\neq s}^{m}A^{st}\sum_{u}^{m}B^{tu}Y^{ur}-\sum_{r\neq s}^{m}A^{sr}L^{rr}Y^{rr}\right)}_{5.Complex\ GVCs} \quad 9$$

Similar to the decomposition of value added and carbon emissions, pre-multiply equation 9 with the diagonal matrix of energy intensity coefficient of country s, $\widehat{EI}^s$, the total energy use of countries s can be decomposed into its final consuming countries along the five global value chains above. Then, the production-based energy use of country s can be divided into:

$$E^s_{production} = \widehat{EI}^s X^s = \underbrace{\widehat{EI}^s L^{ss} Y^{ss}}_{1.Pure\ domestic} + \underbrace{\widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}A^{sr}\sum_{u}^{m}B^{ru}Y^{us}}_{2.Returned\ domestic} + \underbrace{\widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}Y^{sr}}_{3.Traditional\ trade} + \underbrace{\widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}A^{sr}L^{rr}Y^{rr}}_{4.Simple\ GVCs} + \underbrace{\widehat{EI}^s L^{ss}\left(\sum_{r\neq s}^{m}\sum_{t\neq s}^{m}A^{st}\sum_{u}^{m}B^{tu}Y^{ur}-\sum_{r\neq s}^{m}A^{sr}L^{rr}Y^{rr}\right)}_{5.Complex\ GVCs} \quad 10$$

According to equation 10, the total production-based energy use of country s induced by country s is $\widehat{EI}^s L^{ss} Y^{ss} + \widehat{EI}^s L^{ss}\sum_{r\neq s}^{G}A^{sr}\sum_{u}^{m}B^{ru}Y^{us}$, in which $\widehat{EI}^s L^{ss} Y^{ss}$ is the energy use directly induced by the final demand of country s itself, and $\widehat{EI}^s L^{ss}\sum_{r\neq s}^{G}A^{sr}\sum_{u}^{m}B^{ru}Y^{us}$ is the energy use induced by the final demand of country s through products returned domestic. The total production-based energy use of country s induced by other countries is $\widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}Y^{sr} + \widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}A^{sr}L^{rr}Y^{rr} + \widehat{EI}^s L^{ss}\left(\sum_{r\neq s}^{m}\sum_{t\neq s}^{m}A^{st}\sum_{u}^{m}B^{tu}Y^{ur}-\sum_{r\neq s}^{m}A^{sr}L^{rr}Y^{rr}\right)$. In specific, without loss of generality, the production-based energy use of country s induced by country r can be expressed as $\widehat{EI}^s L^{ss} Y^{sr} + \widehat{EI}^s L^{ss} A^{sr} L^{rr} Y^{rr} + \widehat{EI}^s L^{ss}\left(\sum_{t\neq s}^{m}A^{st}\sum_{u}^{m}B^{tu}Y^{ur} - A^{sr}L^{rr}Y^{rr}\right)$. Further, the production-based energy use of country s induced by country r through traditional trade, simple GVCs and Complex GVCs are respectively $\widehat{EI}^s L^{ss} Y^{sr}$, $\widehat{EI}^s L^{ss} A^{sr} L^{rr} Y^{rr}$ and $\widehat{EI}^s L^{ss}\left(\sum_{t\neq s}^{m}A^{st}\sum_{u}^{m}B^{tu}Y^{ur} - A^{sr}L^{rr}Y^{rr}\right)$.

Then, the consumption-based energy use of country s, which is either produced by itself or by other countries through global value chains, can be expressed as follows:

$$E^s_{consumption} = \underbrace{\widehat{EI}^s L^{ss} Y^{ss}}_{1.Pure\ domestic} + \underbrace{\widehat{EI}^s L^{ss}\sum_{r\neq s}^{m}A^{sr}\sum_{u}^{m}B^{ru}Y^{us}}_{2.Returned\ domestic} + \underbrace{\sum_{r\neq s}^{m}\widehat{EI}^r L^{rr} Y^{rs}}_{3.Traditional\ trade} + \underbrace{\sum_{r\neq s}^{m}\widehat{EI}^r L^{rr} A^{rs} L^{ss} Y^{ss}}_{4.Simple\ GVCs} + \underbrace{\sum_{r\neq s}^{m}\widehat{EI}^r L^{rr}\left(\sum_{t\neq r}^{m}A^{rt}\sum_{u}^{m}B^{tu}Y^{us} - A^{rs}L^{ss}Y^{ss}\right)}_{5.Complex\ GVCs} \quad 11$$

Further, the net energy use transfer of country s, namely the net energy use it "outsourced" to other countries, which is the difference between its production-based energy use and consumption-based energy use, can be expressed as follows:

$$E_n^s = E_c^s - E_p^s \quad 12$$

By replacing the energy intensity matrix in above decompositions with that of coal, oil, gas and other energy types, we can further decompose the energy use of coal, oil, gas and other energies along the GVCs.

Appendix C. World Energy Use Through GVCs by Energy Types

The decomposition of world energy use by various global value chains of different energy types is shown in table C1, and figures C1, C2, C3.

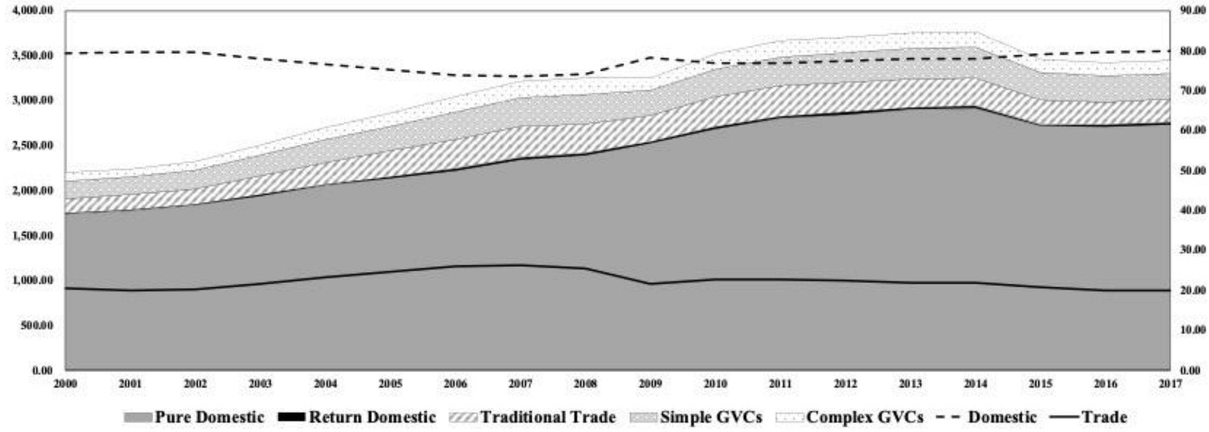

Figure C1: World Total Energy Use through GVCs: Coal

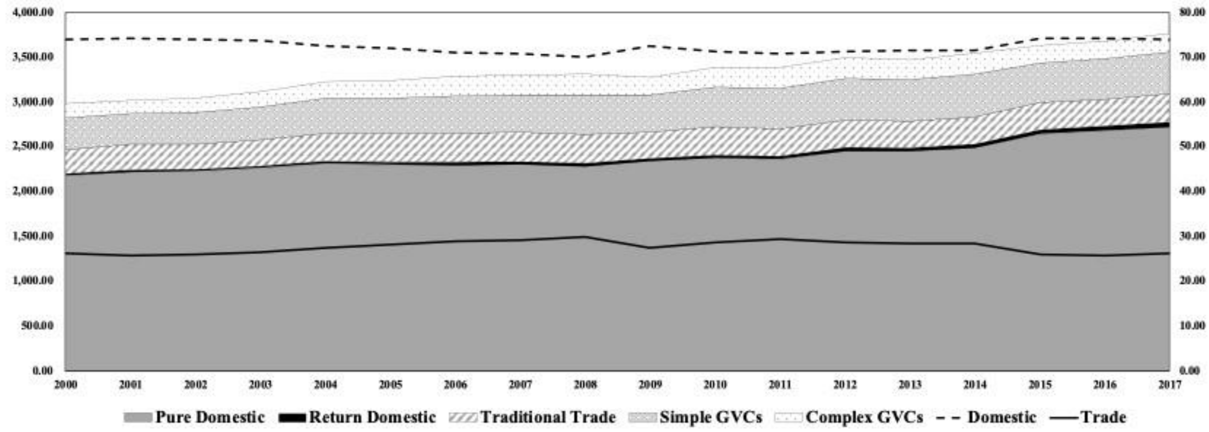

Figure C2: World Total Energy Use through GVCs: Oil

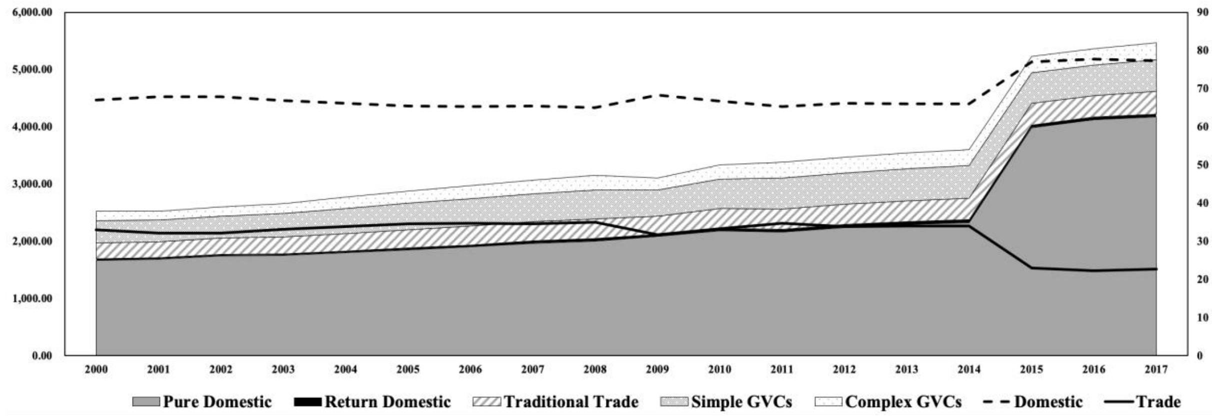

Figure C3: World Total Energy Use through GVCs: Gas and Others

Appendix D. Production-based Energy Use along GVCs for coal, oil, gas and other energy

The production-based energy use for coal, oil, gas and other energy types is shown in figures D1, D2, D3.

Table D1: World Energy Use by Energy Types

	Coal			Oil			Gas		
	sum	domestic	trade	sum	domestic	trade	sum	domestic	trade
2000	2209.2	79.5	20.5	2979.4	73.8	26.2	1689.9	68.3	31.7
2001	2247.8	79.9	20.1	3022.8	74.2	25.8	1702.5	69.4	30.6
2002	2326.7	79.6	20.4	3040.6	74.0	26.0	1762.5	70.1	29.9
2003	2508.1	78.2	21.8	3110.8	73.6	26.4	1824.2	69.4	30.6
2004	2708.9	76.7	23.3	3230.5	72.5	27.5	1881.2	69.0	31.0
2005	2871.1	75.3	24.7	3244.5	71.9	28.1	1950.0	68.4	31.6
2006	3044.7	73.9	26.1	3283.0	71.0	29.0	2015.9	68.5	31.5
2007	3217.8	73.7	26.3	3302.9	70.8	29.2	2113.0	69.0	31.0
2008	3253.6	74.4	25.6	3310.8	70.1	29.9	2165.0	68.6	31.4
2009	3255.7	78.4	21.6	3273.3	72.5	27.5	2115.1	71.9	28.1
2010	3524.5	77.1	22.9	3388.4	71.2	28.8	2298.4	70.4	29.6
2011	3677.2	77.1	22.9	3391.2	70.7	29.3	2362.1	69.4	30.6
2012	3712.7	77.6	22.4	3494.5	71.3	28.7	2427.0	70.5	29.5
2013	3760.3	78.0	22.0	3476.1	71.6	28.4	2464.4	70.4	29.6
2014	3777.6	78.1	21.9	3538.4	71.6	28.4	2469.8	70.4	29.6
2015	3469.6	79.1	20.9	3633.9	74.1	25.9	1840.0	75.9	24.1
2016	3428.2	79.9	20.1	3679.2	74.2	25.8	1896.8	76.7	23.3
2017	3455.7	80.0	20.0	3762.5	73.9	26.1	1946.0	75.7	24.3

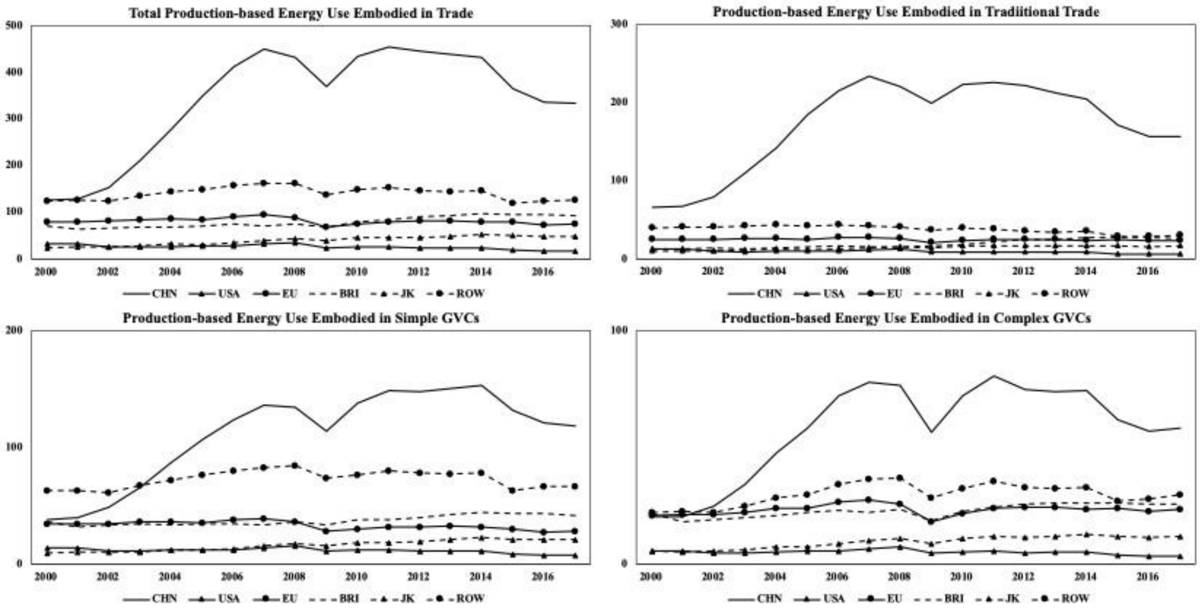

Figure D1: Production-based Energy Use through GVCs: Coal

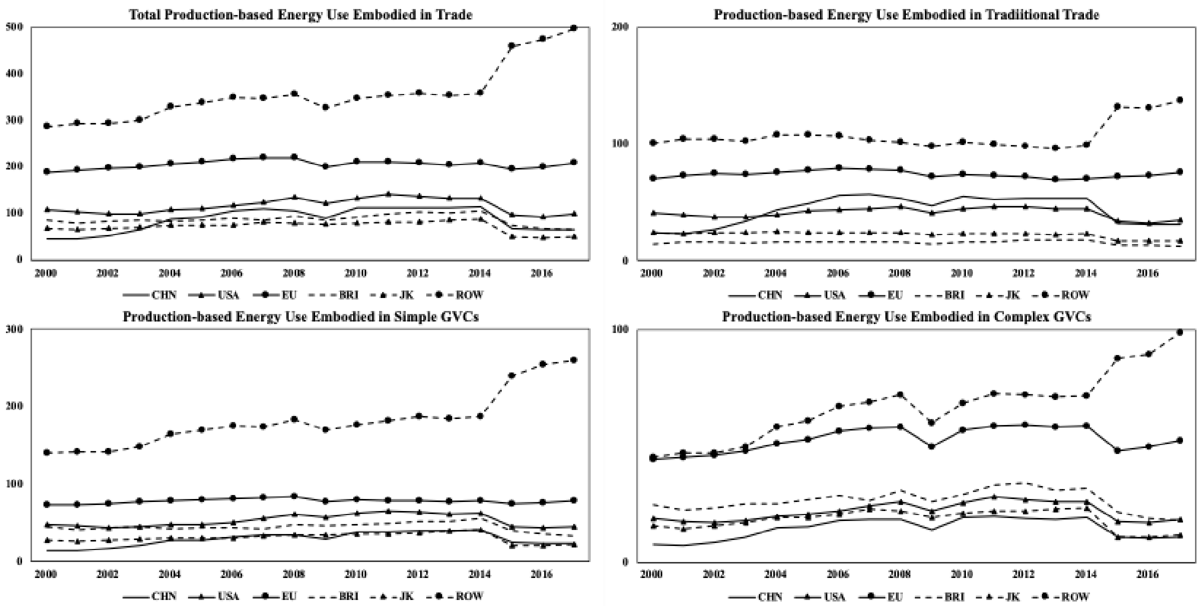

Figure D2: Production-based Energy Use through GVCs: Oil

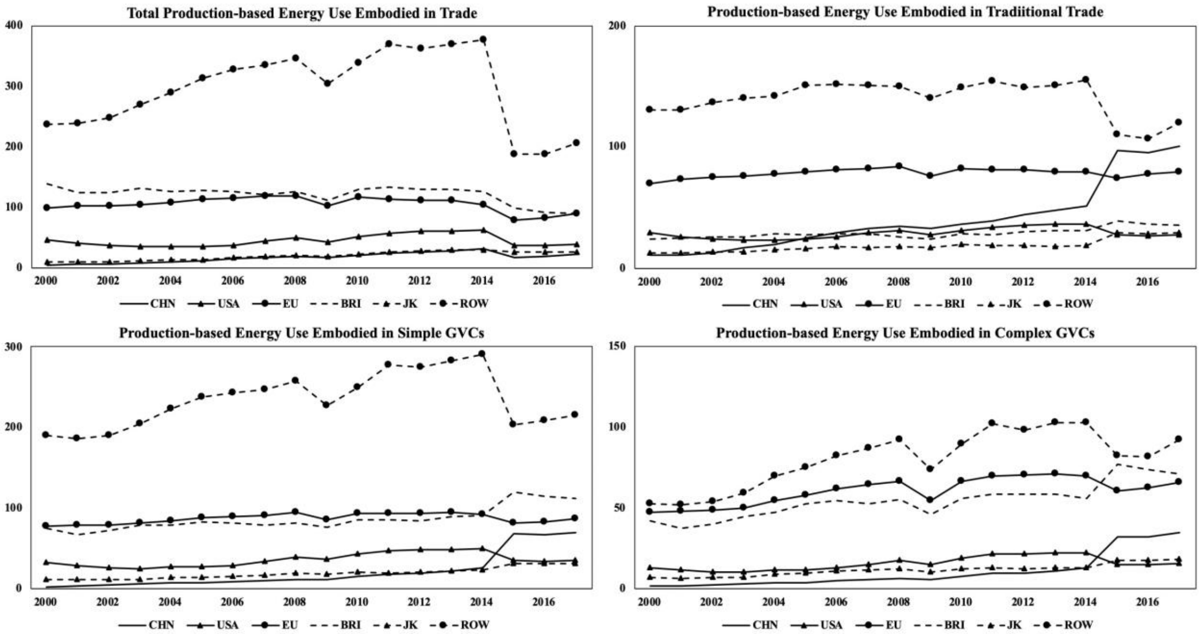

Figure D3: Production-based Energy Use through GVCs: Gas and Others

Appendix E. Consumption-based Energy Use along GVCs for coal, oil, gas and other energy

The consumption-based energy use for coal, oil, gas and other energy types is shown in figures E1, E2, E3.

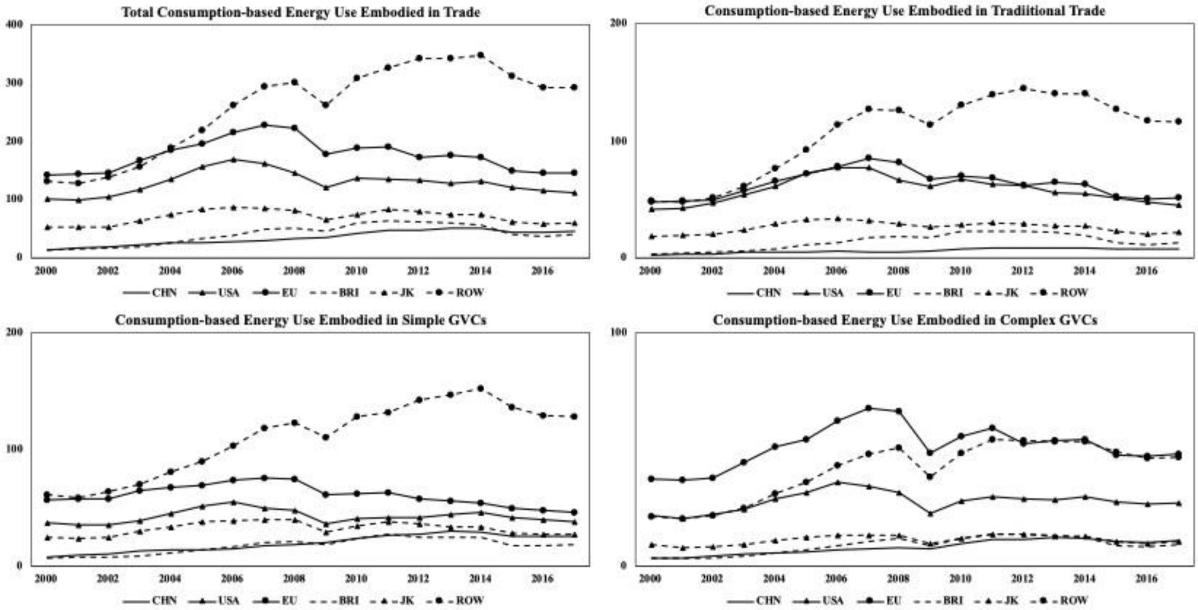

Figure E1: Consumption-based Energy Use through GVCs: Coal

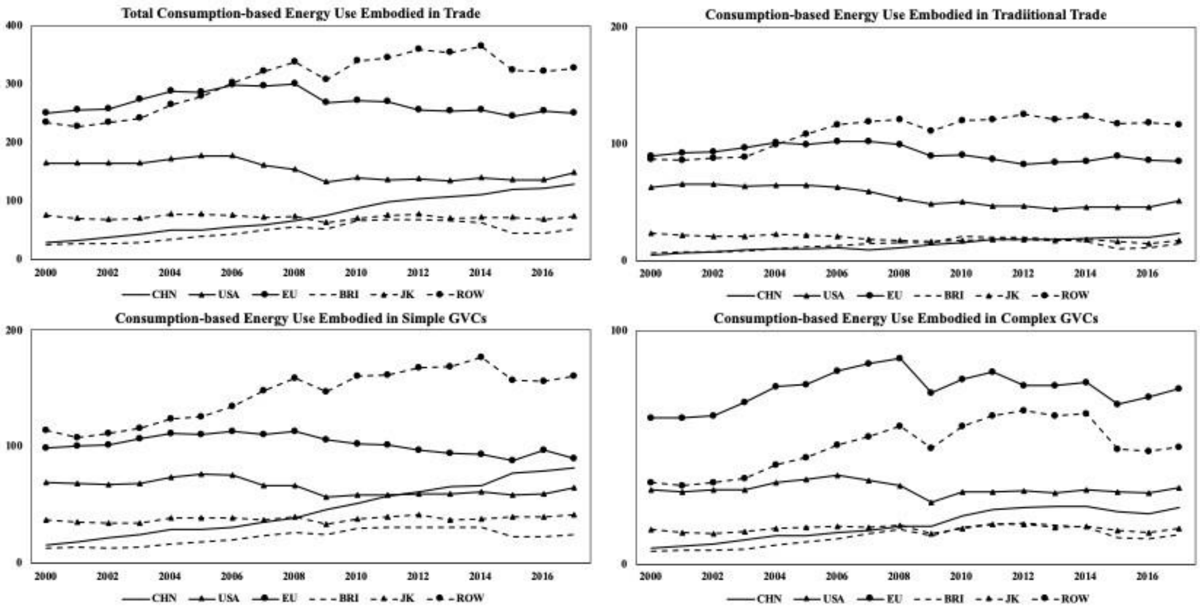

Figure E2: Consumption-based Energy Use through GVCs: Oil

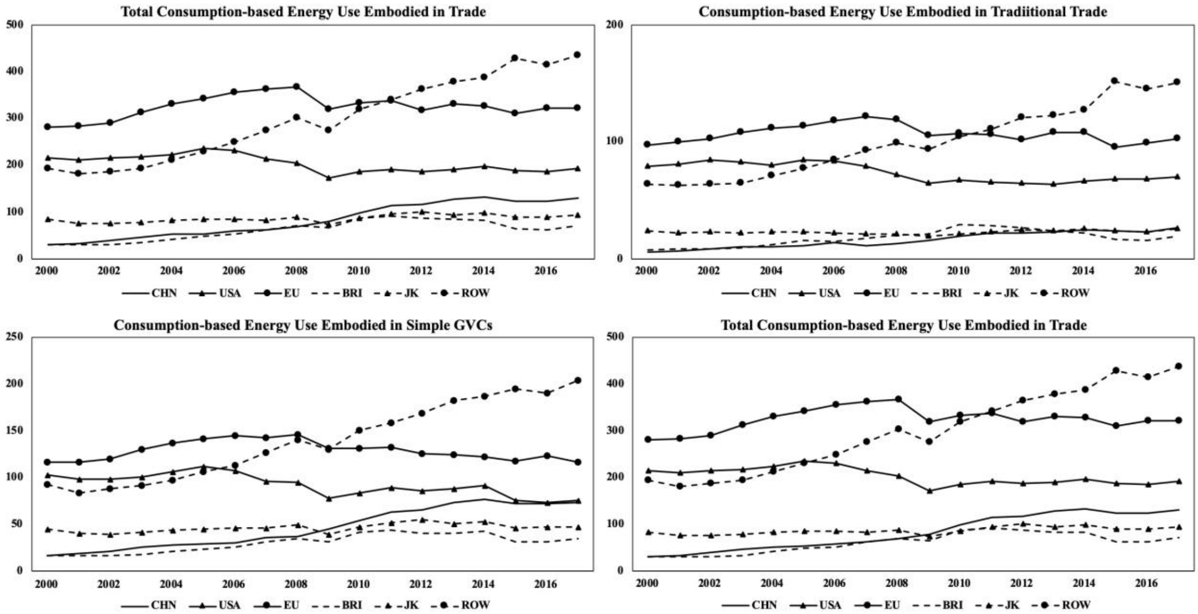

Figure E3: Consumption-based Energy Use through GVCs: Gas and Others

Appendix F. Empirical Research on Energy Embodied in Trade

Table F1. Energy embodied in trade: Coal

	(1)	(2)	(3)	(4)	(5)	(6)
	total	total	total	total	total	total
lngdp_con	1.370***	1.370***	1.370***	1.371***	1.370***	1.370***
	(35.77)	(35.73)	(35.75)	(35.77)	(35.94)	(35.97)
lngdp_pro	1.045***	1.045***	1.045***	1.045***	1.045***	1.045***
	(29.31)	(29.48)	(29.28)	(29.52)	(29.25)	(29.51)
lndist	-1.008***	-0.931***				
	(-126.83)	(-110.34)				
lndistcap			-1.033***	-0.950***		
			(-127.06)	(-109.20)		
lndistw					-1.093***	-1.009***
					(-130.52)	(-110.09)
contiguity		0.326***		0.367***		0.387***
		(12.33)		(14.28)		(15.69)
language		0.147***		0.162***		0.157***
		(5.31)		(5.87)		(5.66)
law		0.0580***		0.0518***		0.0234*
		(4.29)		(3.79)		(1.71)
cons	-51.84***	-52.70***	-51.58***	-52.51***	-51.02***	-51.95***
	(-34.63)	(-35.17)	(-34.52)	(-35.16)	(-34.30)	(-34.95)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27260	27260	27260	27260	27260	27260
R^2	0.945	0.945	0.945	0.946	0.947	0.948

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F2. Energy embodied in trade: Oil

	(1)	(2)	(3)	(4)	(5)	(6)
	total	total	total	total	total	total
lngdp_con	1.245***	1.246***	1.245***	1.246***	1.246***	1.246***
	(37.41)	(37.27)	(37.36)	(37.31)	(37.52)	(37.50)
lngdp_pro	0.352***	0.352***	0.352***	0.352***	0.352***	0.352***

	(10.61)	(10.68)	(10.58)	(10.69)	(10.54)	(10.66)
lndist	-0.963***	-0.882***				
	(-126.06)	(-106.60)				
lndistcap			-0.988***	-0.901***		
			(-127.14)	(-105.27)		
lndistw					-1.041***	-0.951***
					(-132.71)	(-109.90)
contiguity		0.391***		0.429***		0.453***
		(17.01)		(19.19)		(21.15)
language		0.0678**		0.0792***		0.0770***
		(2.57)		(3.02)		(2.92)
law		0.0526***		0.0473***		0.0258*
		(3.74)		(3.34)		(1.83)
cons	-29.41***	-30.31***	-29.13***	-30.10***	-28.68***	-29.67***
	(-21.89)	(-22.49)	(-21.75)	(-22.43)	(-21.44)	(-22.13)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27984	27984	27984	27984	27984	27984
R^2	0.927	0.929	0.928	0.930	0.930	0.932

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F3. Energy embodied in trade: Gas

	(1)	(2)	(3)	(4)	(5)	(6)
	total	total	total	total	total	total
lngdp_con	1.289***	1.287***	1.290***	1.288***	1.290***	1.288***
	(39.27)	(39.15)	(39.55)	(39.51)	(40.01)	(39.96)
lngdp_pro	0.488***	0.488***	0.488***	0.488***	0.488***	0.488***
	(13.22)	(13.27)	(13.23)	(13.32)	(13.18)	(13.29)
lndist	-1.008***	-0.929***				
	(-131.33)	(-116.96)				
lndistcap			-1.037***	-0.953***		
			(-133.87)	(-118.03)		
lndistw					-1.096***	-1.012***
					(-136.28)	(-117.81)

contiguity		0.329***		0.362***		0.383***
		(13.88)		(15.83)		(17.67)
language		0.115***		0.141***		0.137***
		(4.66)		(6.00)		(5.69)
law		0.0802***		0.0684***		0.0383***
		(6.41)		(5.51)		(3.05)
cons	-34.75***	-35.57***	-34.47***	-35.34***	-33.92***	-34.81***
	(-23.95)	(-24.43)	(-23.86)	(-24.43)	(-23.62)	(-24.21)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	26637	26637	26637	26637	26637	26637
R^2	0.935	0.936	0.937	0.938	0.939	0.941

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F4. Energy embodied in trade: Other

	(1)	(2)	(3)	(4)	(5)	(6)
	total	total	total	total	total	total
lngdp_con	1.432***	1.429***	1.432***	1.429***	1.431***	1.429***
	(32.78)	(32.51)	(32.80)	(32.57)	(33.08)	(32.88)
lngdp_pro	0.818***	0.819***	0.819***	0.820***	0.820***	0.821***
	(19.04)	(19.16)	(19.05)	(19.21)	(19.00)	(19.18)
lndist	-1.028***	-0.954***				
	(-115.60)	(-97.88)				
lndistcap			-1.055***	-0.975***		
			(-116.24)	(-96.80)		
lndistw					-1.115***	-1.034***
					(-118.65)	(-98.14)
contiguity		0.354***		0.397***		0.413***
		(12.70)		(14.60)		(15.72)
language		0.0602*		0.0739**		0.0730**
		(1.91)		(2.36)		(2.31)
law		0.0550***		0.0484***		0.0207
		(3.19)		(2.80)		(1.19)
cons	-48.28***	-49.03***	-48.02***	-48.85***	-47.45***	-48.30***

	(-27.36)	(-27.68)	(-27.27)	(-27.66)	(-27.04)	(-27.46)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27454	27454	27454	27454	27454	27454
R^2	0.908	0.909	0.909	0.910	0.911	0.912

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F5. Energy embodied in trade along Global Value Chains: Coal

	(1)	(2)	(3)	(4)	(5)	(6)
	tradition	tradition	simple	simple	complex	complex
lngdp_o	1.476***	1.476***	1.415***	1.415***	1.298***	1.298***
	(24.90)	(24.87)	(23.36)	(23.32)	(43.89)	(44.08)
lngdp_d	1.054***	1.054***	1.218***	1.218***	1.056***	1.056***
	(20.55)	(20.64)	(23.95)	(24.05)	(41.52)	(41.50)
lndistw	-1.384***	-1.297***	-1.624***	-1.543***	-0.402***	-0.438***
	(-121.54)	(-98.73)	(-144.03)	(-115.35)	(-79.66)	(-74.86)
contiguity		0.365***		0.337***		-0.209***
		(11.02)		(10.72)		(-13.15)
language		0.299***		0.183***		-0.0874***
		(7.51)		(4.27)		(-6.10)
law		0.00139		0.0471**		0.0447***
		(0.06)		(2.02)		(5.63)
cons	-53.47***	-54.46***	-53.19***	-54.10***	-57.39***	-56.99***
	(-24.33)	(-24.81)	(-24.09)	(-24.48)	(-52.43)	(-52.19)
Origin	Y	Y	Y	Y	Y	Y
Destination	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27248	27248	27261	27261	27261	27261
R^2	0.904	0.905	0.898	0.899	0.970	0.971

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F6. Energy embodied in trade along Global Value Chains: Oil

	(1)	(2)	(3)	(4)	(5)	(6)

	tradition	tradition	simple	simple	complex	complex
lngdp_o	1.471***	1.470***	1.295***	1.295***	1.190***	1.190***
	(24.47)	(24.42)	(20.97)	(20.94)	(50.52)	(50.75)
lngdp_d	0.435***	0.435***	0.396***	0.396***	0.337***	0.337***
	(8.54)	(8.58)	(7.80)	(7.84)	(15.76)	(15.75)
lndistw	-1.421***	-1.336***	-1.572***	-1.506***	-0.344***	-0.375***
	(-123.44)	(-99.03)	(-139.40)	(-113.29)	(-80.47)	(-72.22)
contiguity		0.381***		0.346***		-0.176***
		(11.69)		(11.56)		(-15.23)
language		0.237***		0.00782		-0.0757***
		(5.55)		(0.18)		(-6.43)
law		0.00405		0.0256		0.0312***
		(0.17)		(1.04)		(3.75)
cons	-35.28***	-36.25***	-27.41***	-28.12***	-34.88***	-34.51***
	(-16.16)	(-16.61)	(-12.37)	(-12.68)	(-38.83)	(-38.55)
Origin	Y	Y	Y	Y	Y	Y
Destination	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27796	27796	27955	27955	28065	28065
R^2	0.854	0.856	0.859	0.860	0.969	0.969

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F7. Energy embodied in trade along Global Value Chains: Gas

	(1)	(2)	(3)	(4)	(5)	(6)
	tradition	tradition	simple	simple	complex	complex
lngdp_o	1.485***	1.484***	1.284***	1.282***	1.267***	1.267***
	(28.17)	(28.05)	(25.17)	(25.08)	(53.91)	(54.20)
lngdp_d	0.566***	0.566***	0.565***	0.565***	0.468***	0.468***
	(11.13)	(11.17)	(11.42)	(11.45)	(17.16)	(17.15)
lndistw	-1.398***	-1.306***	-1.582***	-1.498***	-0.402***	-0.440***
	(-127.30)	(-105.35)	(-151.64)	(-126.12)	(-87.93)	(-82.18)
contiguity		0.361***		0.327***		-0.225***
		(11.53)		(12.04)		(-19.24)
language		0.288***		0.136***		-0.0665***
		(8.57)		(4.08)		(-5.42)

law		0.0467**		0.0919***		0.0400***
		(2.49)		(4.88)		(5.07)
cons	-40.54***	-41.54***	-32.49***	-33.34***	-40.90***	-40.47***
	(-19.26)	(-19.68)	(-15.82)	(-16.18)	(-39.69)	(-39.37)
Origin	Y	Y	Y	Y	Y	Y
Destination	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	26630	26630	26637	26637	26637	26637
R^2	0.877	0.879	0.891	0.892	0.969	0.970

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Table F8. Energy embodied in trade along Global Value Chains: Other

	(1)	(2)	(3)	(4)	(5)	(6)
	tradition	tradition	simple	simple	complex	complex
lngdp_o	1.624***	1.621***	1.326***	1.323***	1.247***	1.248***
	(27.12)	(27.06)	(21.24)	(21.07)	(35.68)	(35.82)
lngdp_d	0.893***	0.894***	1.218***	1.217***	0.961***	0.961***
	(15.49)	(15.56)	(20.88)	(20.94)	(29.48)	(29.46)
lndistw	-1.412***	-1.321***	-1.598***	-1.528***	-0.406***	-0.446***
	(-117.21)	(-94.02)	(-127.42)	(-104.13)	(-70.19)	(-63.58)
contiguity		0.383***		0.335***		-0.234***
		(11.84)		(10.01)		(-12.53)
language		0.220***		0.0403		-0.0602***
		(5.17)		(0.84)		(-3.76)
law		0.0469**		0.0518*		0.0291**
		(2.02)		(1.93)		(2.49)
cons	-53.79***	-54.75***	-52.39***	-53.04***	-54.55***	-54.14***
	(-22.58)	(-23.00)	(-21.72)	(-21.90)	(-40.69)	(-40.48)
Origin	Y	Y	Y	Y	Y	Y
Destination	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	27681	27681	27195	27195	26920	26920
R^2	0.858	0.859	0.853	0.854	0.945	0.946

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*

Appendix G. Energy Embodied in GVCs Regional Trade Agreement

Table G1. Energy embodied in trade along Global Value Chains: Regional Trade Agreement

	(1)	(2)	(3)	(4)	(5)	(6)
	total	total	total	total	total	total
lngdp_con	1.201***	1.199***	1.201***	1.199***	1.208***	1.205***
	(39.20)	(39.03)	(39.30)	(39.22)	(39.61)	(39.52)
lngdp_pro	0.454***	0.452***	0.455***	0.453***	0.461***	0.458***
	(13.82)	(13.85)	(13.82)	(13.89)	(13.98)	(14.04)
lndist	-0.907***	-0.818***				
	(-109.67)	(-96.14)				
lndistcap			-0.932***	-0.838***		
			(-109.06)	(-94.16)		
lndistw					-1.011***	-0.912***
					(-108.36)	(-92.81)
RTA	0.205***	0.240***	0.192***	0.228***	0.0774***	0.124***
	(15.02)	(17.20)	(13.84)	(16.18)	(5.28)	(8.47)
contiguity		0.378***		0.411***		0.420***
		(16.78)		(18.70)		(19.94)
language		0.142***		0.151***		0.139***
		(5.41)		(5.78)		(5.29)
law		0.0364***		0.0330**		0.0242*
		(2.85)		(2.57)		(1.88)
cons	-30.46***	-31.33***	-30.22***	-31.15***	-29.87***	-30.80***
	(-23.48)	(-24.11)	(-23.41)	(-24.13)	(-23.22)	(-23.93)
Consumption	Y	Y	Y	Y	Y	Y
Production	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
N	28080	28080	28080	28080	28080	28080
R^2	0.938	0.939	0.939	0.941	0.940	0.942

*Note: t statistics in parentheses. All columns include country fixed effects and year fixed effects. *, **, *** indicate statistical significance at 90%, 95%, and 99% confidence levels, respectively.*