Net exergy flow network analysis in the international fossil energy trade

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Abstract:

It is available work, exergy, the fossil energy provided that each country need when they import fossil fuels. Therefore, it forms exergy flow network embodied in the global fossil energy trade. Therefore, we need to know the net exergy flow pattern in international fossil energy trade and what kinds of roles the countries play. We convert the import and export volume of fossil fuels into exergy. We construct global net exergy flow network of fossil energy with countries as node, the net exergy inflow or outflow relationship as the edges from 2000 to 2012. According to the indicators in complex network theory, we defined the IO index and divided countries into five types and analysed the exergy flow pattern. We find that most countries either are exergy of fossil energy supplier or demander. The exergy of fossil energy can flow directly from the original exporters to the final importers or basically through one or two countries. The financial crisis in 2007 impacts both the energy supplier and demander. In general, in the world level, there are one global source, the Middle East, of net exergy flow of fossil energy and two global destinations, USA and Europe, of net exergy flow. In the region level, there are two regional exergy flow communities. One is in the Commonwealth of Independent States and another is in the Asia-Pacific region. The exergy flow pattern reflects the geopolitics among regional countries and energy supply and demand relations between the countries.

Keywords:

Exergy, Fossil Energy, International Trade, Flow Pattern

1. Introduction

As crucial and non-replaceable material for production, energy traditionally plays a significant role in economic growth. According to the previous study, the demand of energy will expand by 45% all around the world from now to 2030 [1]. However, the distribution of fossil fuels is very uneven around the world. Therefore, besides national production, countries lacked of energy need to import fossil fuels from other counties with abundant fossil fuels. In fact, it is available work the fossil energy provided that each country need when they import fossil fuels. Nevertheless, exergy specifically is the maximum amount of work that can be recovered from a system, namely available work. It is enable consideration of the quality of energy inputs as well as the breakdown and efficiency of energy use; both important and dynamic characteristics of evolving socioeconomic systems [2]. Therefore, it forms exergy flow network embodied in the global fossil energy trade. For a variety reason, one country could both import fossil fuels from another and export them to that country at the same time. Thus there is net exergy flow between each pair of trade partners. This kind of exergy flow system just likes the streams in the physical world. The exergy flow pattern of fossil fuels maybe changes with time going by. Different kinds of countries will play different roles in the net exergy flow system.

In order to analysis the net exergy flow pattern of international fossil energy, the complex network theory provides a theoretical approach to reveal the law and features of network. The main idea of complex network theory is to consider the relationships between various parts of real complex systems as a complex network [3]. A lot of researches have used complex network to analysis the international trade. They find that it is a scale-free network with few countries control the major trade relationship. Hai Qi [4] analysed the international ferrous metal ores trade network with exergy as the weight, and he concluded that the exergy can reflect the import and export more truly.

In this paper, we adopt complex network theory to analyse the net exergy flow embodied in the international fossil fuel trade. Because coal, crude oil and natural gas are the major fossil fuels, we select them as our research objects. We convert the trade volume of these four kinds of fossil fuels into exergy and add them together. Then we construct global net exergy flow network of fossil energy with countries as node, the net exergy inflow or outflow relationship as the edges and net exergy flow volume between countries as the weight. According to the indicators in complex network theory, we defined five kinds of countries in the network and analysed the exergy flow pattern. Finally, we made discussion and drew the conclusions.

2. Methodology and Data

2.1. Method

2.1.1 exergy conversion of fossil energy

Traditionally, people value the combination of socio-economic material in terms of economic currency. However, the monetary valuations lack the type of scientific definition that is based on energetic or physical explanations. In particular, the concept of exergy provides a unified indicator of different forms of material and energy flows based on evaluating the distance from the studied system to thermodynamic equilibrium [5, 6]. That is, exergy is defined as the maximum work that can be extracted from a system when this system moves toward thermodynamic equilibrium with a reference state. Exergy can be thought of as a measure of the quality or potential of a system to cause change. Unlike energy flow, which only concerns quantity, exergy is a measure of the quantity and quality of energy resources [5, 6].

Table 1 The exergy of fossil energy in the GNEFN /PJ

	edge weight			*node weighted out-degree*		
	maximum	*mean*	*sum*	*maximum*	*mean*	*sum*
2000	6.54E+03	4.31E+01	1.16E+05	1.25E+04	6.66E+02	1.16E+05
2001	7.60E+03	9.71E+01	1.22E+05	1.35E+04	7.06E+02	1.22E+05
2002	6.97E+03	8.83E+01	1.19E+05	1.61E+04	6.50E+02	1.19E+05
2003	8.02E+03	9.54E+01	1.26E+05	1.59E+04	7.05E+02	1.26E+05
2004	7.90E+03	9.87E+01	1.39E+05	2.00E+04	7.61E+02	1.39E+05
2005	9.50E+03	1.03E+02	1.51E+05	1.94E+04	8.32E+02	1.51E+05
2006	9.36E+03	1.04E+02	1.53E+05	1.88E+04	8.54E+02	1.53E+05
2007	1.05E+04	1.06E+02	1.58E+05	1.99E+04	8.75E+02	1.58E+05
2008	9.90E+03	1.04E+02	1.61E+05	1.91E+04	8.87E+02	1.61E+05
2009	5.07E+03	8.98E+01	1.42E+05	1.92E+04	7.53E+02	1.42E+05
2010	6.03E+03	9.52E+01	1.52E+05	2.04E+04	8.14E+02	1.52E+05
2011	6.84E+03	9.73E+01	1.55E+05	2.05E+04	8.25E+02	1.55E+05
2012	4.21E+03	9.90E+01	1.49E+05	2.00E+04	8.05E+02	1.49E+05

The weight of the GFEN is the sum of the exergy of the four kinds of selected fossil fuels. The exergy is determined by the environment it located in. For calculations of the global fossil energy exergy, it is reasonable to select a global standard environment to illustrate the series of works on the standard chemical exergy of some elements and compounds, which facilitate further exergy calculations [7].

Researchers have calculated the exergy of the metals and minerals in the standard environment [8-10]. Thermophysical exergy of the materials is ignored as negligible. With respect to a fuel, the exergy transformation factor is equal to the product of the lower heating value (LHV) on average, which is often adopted by energy statistical yearbooks, and the exergy–energy ratio [11,12].The exergy coefficient of LNG and GNG is the same as all types of natural gas. Thus, the exergy coefficient of crude oil, coal, LNG and GNG is 44.32 PJ/Mt, 22.16PJ/Mt, 4.13 PJ/108m3, and 4.13 PJ/108m3, respectively [12,13]. We use the exergy coefficient to convert the fossil energy import and export volume into exergy, and then, we sum the exergy of the four selected fossil energies into one exergy value. The result is given in Table 1. There are some very small exergy flow values from one country to another which can be ignored comparing to the maximum of exergy flow. If we use all these small value to construct the net exergy flow network, they will impact the final result.

2.1.2 Complex network theory

In this study, we construct the global net exergy flow network of fossil energy with direction and weight (GNEFN). The nodes are the countries, and the edges are the net exergy flow in the global fossil energy trade among countries. The direction of the edges represents the direction of the energy exergy flow. The net-export and net-import represents the energy exergy flow net-out and net-in. And the net exergy of fossil energy is the weight of the edges. Therefore, in the network, if there are fossil energy trade occurred between country *i* and country *j*, then v_{ij} denotes exergy of fossil energy which country *i* outflows to country *j*. v_{ji} denotes exergy of fossil energy which country j outflows to country i. If v_{ij}>vji, then a link from i to j is drawn, and aij(t)=1. If $v_{ij} < v_{ji}$, then a link from j to i is drawn, and aij(t)=0. If $v_{ij} = v_{ji}$, then there is no link between country i and country j and $a_{ij}(t)$=o. w_{ij} denotes the net exergy flow between the two countries. Therefore, there is no two-way connection between country *i* and country *j*. The weight of the GNEFN is sum of exergy of four selected kinds of fossil fuels. The weight of the GNEFN is sum of exergy of four selected kinds of fossil fuels. Therefore, the exergy flow values among countries are all bigger than 1000MJ in this paper. There are some indicators in terms of complex network theory. Firstly, we give the definitions and formulations of them.

(1) The out-degree and in-degree

The out-degree and in-degree represent the number of countries a country outflowing and inflowing in the GNEFN, which defined by Eq.(1) and Eq.(2) [14]:

$$k_i^{out}(t) = \sum_{j=1}^{n(t)} a_{ij}(t) \quad (1)$$

$$k_i^{in}(t) = \sum_{j=1}^{n(t)} a_{ji}(t) \quad (2)$$

where $k_i^{out}(t)$ and $k_i^{in}(t)$ denote the out-degree and in-degree, respectively. n(t) is the total number of countries in the network in year t.

(2) The weighted out-degree and in-degree

The weighted out-degree and weighted in-degree represent total volume of net exergy a country outflowing and inflowing in the GNEFN, which defined by Eq.(3) and Eq.(4) [14]:

$$s_i^{out}(t) = \sum_{j=1}^{n(t)} w_{ij}(t) \quad (3)$$

$$s_i^{in}(t) = \sum_{j=1}^{n(t)} w_{ji}(t) \quad (4)$$

where $s_i^{out}(t)$ and $s_i^{in}(t)$ denote the weighted out-degree and weighted in-degree, respectively. n(t) is the total number of countries in the network in year t.

(3) The shortest distance and Average path length

The average path length represents the average steps for each pair of countries to net-inflow or net-outflow exergy of fossil energy. Thus, the average path length is defined as Eq.(5) [15]:

$$\mathrm{l} = 1/\mathrm{n}(\mathrm{n}-1) * \sum_{\mathrm{i,j}} \mathrm{d_{ij}} \quad (5)$$

where dij denotes the shortest distance between node i and j. If node i and j can't reach each other or i=j, then the shortest distance dij is 0.

2.2. Data

The fossil energy refers to crude oil, coal and natural gas in this paper. And the natural gas is further divided into liquefied natural gas (LNG) and gaseous natural gas (GNG). The import and export data from countries to countries come from The United Nations Statistics Division from 2000 to 2012 which include 185 countries and areas. Each kind of fossil energy has a code in terms of HS code. Thus the HS code of crude oil, coal, LNS and GNG in the database we used are 270900, 270100, 271111 and 271121, respectively.

3. Empirical analysis of global net exergy flow network

3.1 The role of countries in the GNEFN

In this paper, we define five kinds of countries in the global net exergy flow network of fossil energy, which are main net exporter, main net importer, export-oriented mediator, import-oriented mediator and mediator. To get these five types countries, we defined the in-out index at first which denoted as IO.

$$\mathrm{IO} = \frac{s_i^{in} - s_i^{out}}{s_i^{in} + s_i^{out}} \quad (6)$$

where s_i^{in} and s_i^{out} represent the total volume of exergy inflowing and outflowing of country i, and the value of IO range from -1 to 1. It more close to -1, the country outflows much more exergy of fossil energy than inflows. It means this country is major exergy exporter like supplier. The role of this kind of country is to supply exergy to others. It more close to 1, the country inflows much more exergy of fossil energy than outflows. It means this country is major exergy importer like demander. The role of this kind of country is to import fossil energy to consume exergy. It more close to 0, the country inflow exergy more close to outflow. It means this country is mediator. The role of this kind of country is to transfer the exergy from the exergy exporter to the exergy importer like agency.

We calculated the IO of each country and some results are shown in figure 1. As we can see from figure 1, about 55% of the countries' IO value is between 0.8 and 1. 27% of the countries' IO value is between -0.8 and -0.1. And only 5% of countries' IO value is between -0.2 and 0.2. It indicates that most countries either are exergy of fossil energy supplier or demander and there are more demanders than suppliers. With the time going by, the number of different kinds of countries didn't change basically.

Besides the IO index, we also need to consider the actual exergy inflow volume and outflow volume. Thus, we divide all the countries into five types according to eq.(7) and the main results are given in Table 2 and Table 3.

$$\begin{cases} s_i^{in} - s_i^{out} \le -1 * 10^2 PJ, \mathrm{IO} \le -0.8 & \mathrm{NO} \\ s_i^{in} - s_i^{out} \ge 1 * 10^2 PJ, \mathrm{IO} \ge 0.8 & \mathrm{NI} \\ s_i^{in} - s_i^{out} \le -1 * 10^2 PJ, -0.8 < \mathrm{IO} < -0.2 & \mathrm{OT} \\ s_i^{in} - s_i^{out} \ge 1 * 10^2 PJ, 0.2 < \mathrm{IO} < 0.8 & \mathrm{IT} \\ s_i^{in} \ge 1 * 10^2 PJ, s_i^{out} \ge 1 * 10^2 PJ, \mathrm{IO} \le -0.8 & \mathrm{TR} \end{cases} \quad (7)$$

where NO denotes the main net exergy of fossil energy exporter; NI denotes the main net exergy of fossil energy importer; OT denotes the main exergy of fossil energy export-oriented mediator; IT denotes the main exergy of fossil energy import-oriented mediator and TR denotes the mediator.

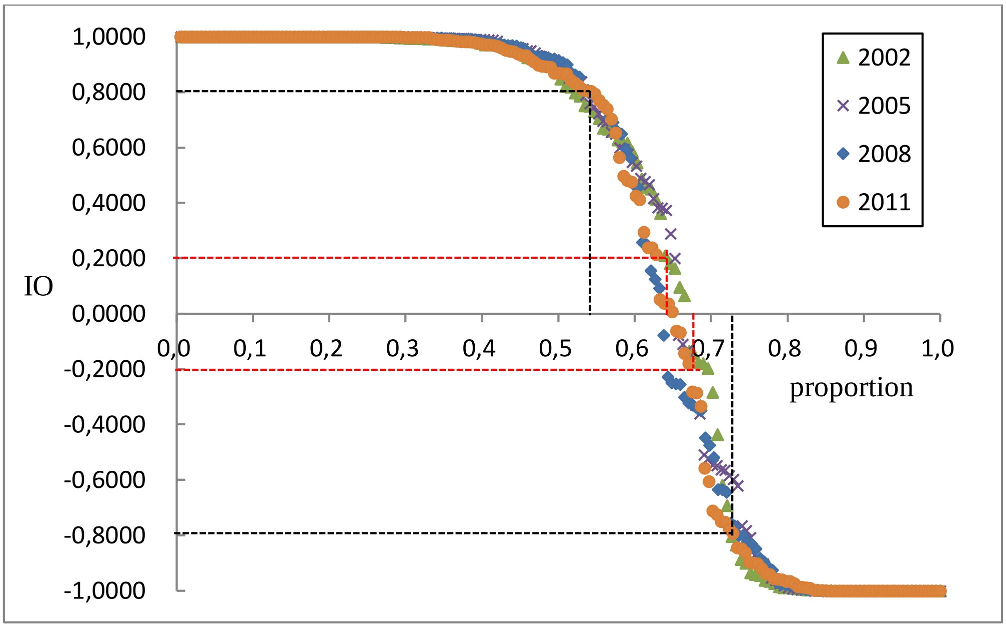


Fig. 1. The distribution of countries' IO value

Table 2 country list in different types

Type	*country*
NO	United Arab Emirates, Viet Nam, Mexico, Algeria, Angola, Colombia, Iran, Iraq, Kuwait, Libya, Nigeria, Norway, Oman, Qatar, Russian Federation, Saudi Arabia, Venezuela
NI	France, Thailand, Greece, Switzerland, Sweden, Spain, Singapore, Rep. of Korea, Portugal, Japan, Italy, Ireland, India, Hungary, Finland, Germany, Chile, Ukraine, Turkey
OT	Australia, Malaysia, Canada
IT	Czech Rep., Poland, Netherlands

Countries in table 2 basically don't change their country type in this study period. According to our definition, we can see that the main net exergy of fossil energy exporter mainly are Mexico, Russian Federation, Viet Nam, Colombia and OPEC members like United Arab Emirates, Iran, Libya and Venezuela. As our former paper analyzed that the exergy of crude oil and natural gas occupies about 80 percent in the exergy of fossil energy. These countries both have large reserves and output of oil and natural gas especially the OPEC members. The main net exergy of fossil energy importer mainly are Asian and European countries like Japan, India, France and Greece. These countries' economy grows at a relatively high speed. Thus, they need much more energy to ensure the economic development. Australia, Malaysia and Canada are the three main exergy of fossil energy export-oriented mediator. It indicates that these three countries not only import large amount of fossil energy but also export more. Czech Rep., Poland and Netherlands are three main exergy of fossil energy import-oriented mediator. It indicates that these three countries not only export large amount of fossil energy but also import more. These two kinds of countries occupy a small percentage all over the world. They consume the fossil energy to develop their own economy as well as get more money through the energy trade with other countries. Don't like the four type countries in table 2, the mediators in the GNEFN change their type in this study period (Table 3). Different with what we all know that China became net oil importer since 1993, China was main exergy of fossil energy import-oriented mediator before 2007 and became main net exergy of fossil energy importer since 2008 after the crisis.

Table 3 Countries' type evolution from 2000 to 2012

	USA	*Brazil*	*Austria*	*China*	*Egypt*	*United Kingdom*	*Denmark*	*Indonesia*
2000	NI	NI	NI	IT	NO	OT	OT	NO
2001	IT	IT	NI	TR	OT	TR	OT	OT
2002	NI	IT	NI	IT	OT	TR	OT	OT
2003	NI	IT	NI	IT	TR	TR	OT	OT
2004	IT	IT	NI	IT	OT	TR	OT	OT
2005	NI	IT	NI	IT	OT	TR	OT	NO
2006	NI	IT	NI	IT	OT	IT	OT	NO
2007	NI	IT	NI	IT	NO	TR	OT	NO
2008	NI	IT	NI	NI	NO	IT	OT	NO
2009	NI	TR	IT	NI	OT	IT	TR	NO
2010	NI	TR	IT	NI	OT	IT	TR	NO
2011	NI	TR	IT	NI	OT	IT	TR	NO
2012	IT	TR	IT	NI	OT	IT	TR	NO

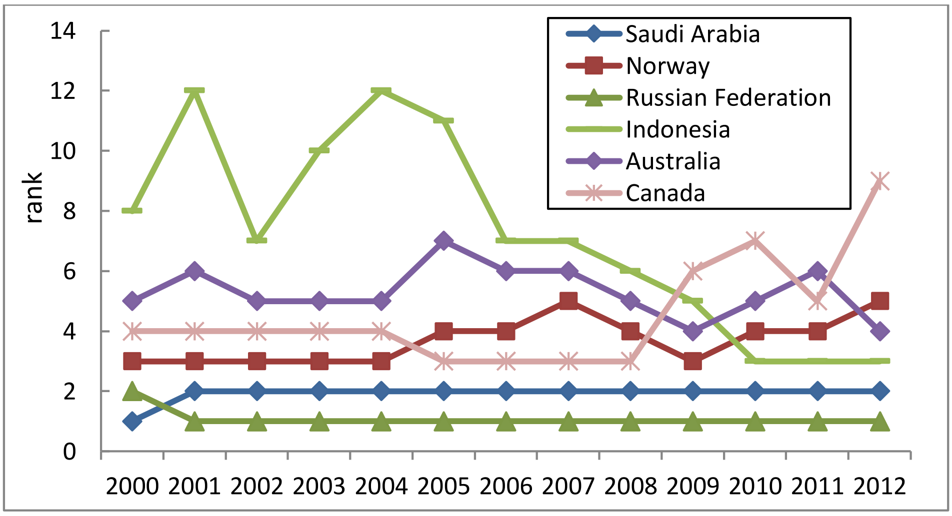


Fig. 2 the main country's rank about the total exergy export volume

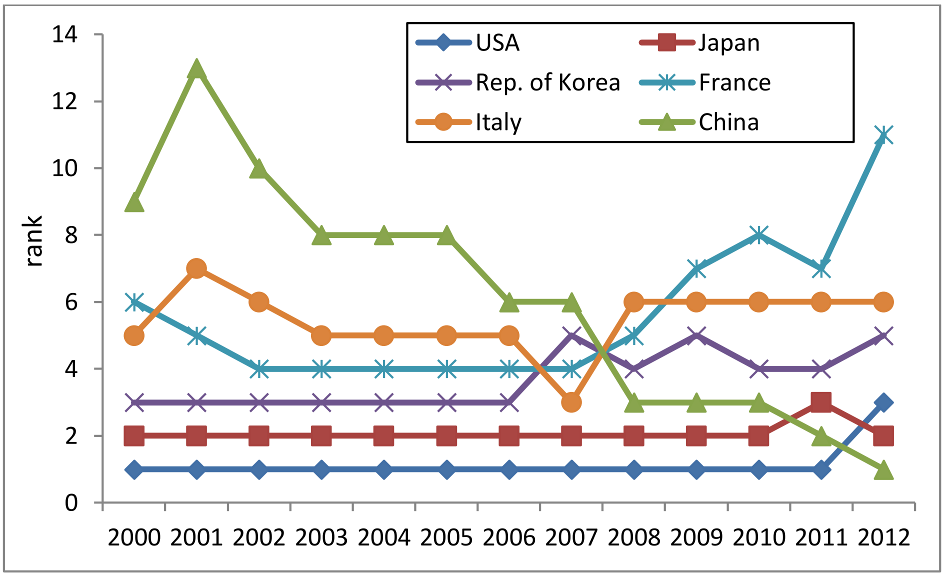


Fig. 3 the main country's rank about the total exergy import volume

We rank all the counties based on their weighted out-degree and weighted in-degree that are the total volume of exergy of fossil energy export and import, and then get the top 6 countries (Figure 2 and Figure 3). We can see that Saudi Arabia and Russian Federation are basically the first and second one from 2000 to 2012. Before 2004, Norway, Canada and Australia are basically top five countries. Indonesia fluctuated between 7th and 12th before 2006. However, after the subprime crisis in 2007, the ranking of Norway, Indonesia, Australia and Canada changed a lot. Indonesia becomes a more important exergy exporter while Canada becomes less important.

As for the main exergy importers, USA and Japan are basically the first and second one from 2000 to 2012. This is in accordance with their ranking of gross domestic product in the world. Since 2008, after the subprime crisis, China imported more and more fossil energy and had become the first exergy of fossil energy importer in 2012. Before 2006, Rep. of Korea is the third exergy importer. As China became top 3, Rep. of Korea dropped to the forth one. Italy is basically the fifth or sixth one, and it became the third one only 2007. France was the fourth before 2007 and dropped to eleventh all the time after that. We can draw a conclusion that the subprime crisis impacts these countries a lot.

3.2 Exergy flow pattern in the international fossil energy trade

We calculated the shortest distance and average path length in the GNEFN (Figure 4). The average path length ranges between 2.23 and 2.42 in the study period. The distances between each two countries range from one to five. The proportion of distance changes little. The exergy of fossil energy can flow directly from the original exporters to the final importers or basically through one or two countries. It indicates that the distance between the importer and exporter is very short. The importers can easily get the exergy they needed from exporters.

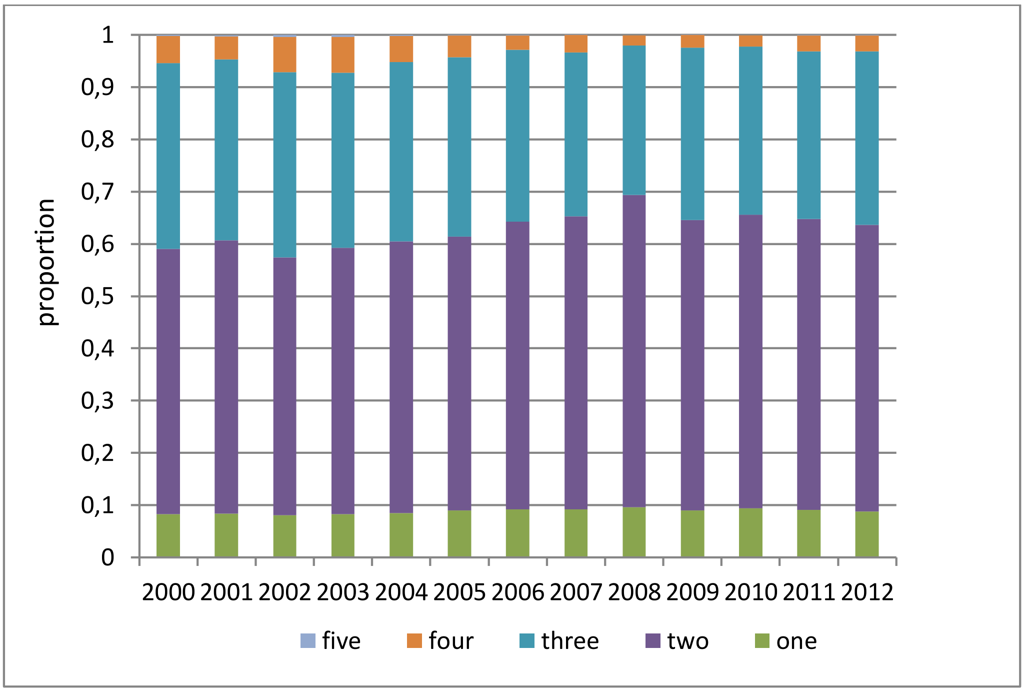
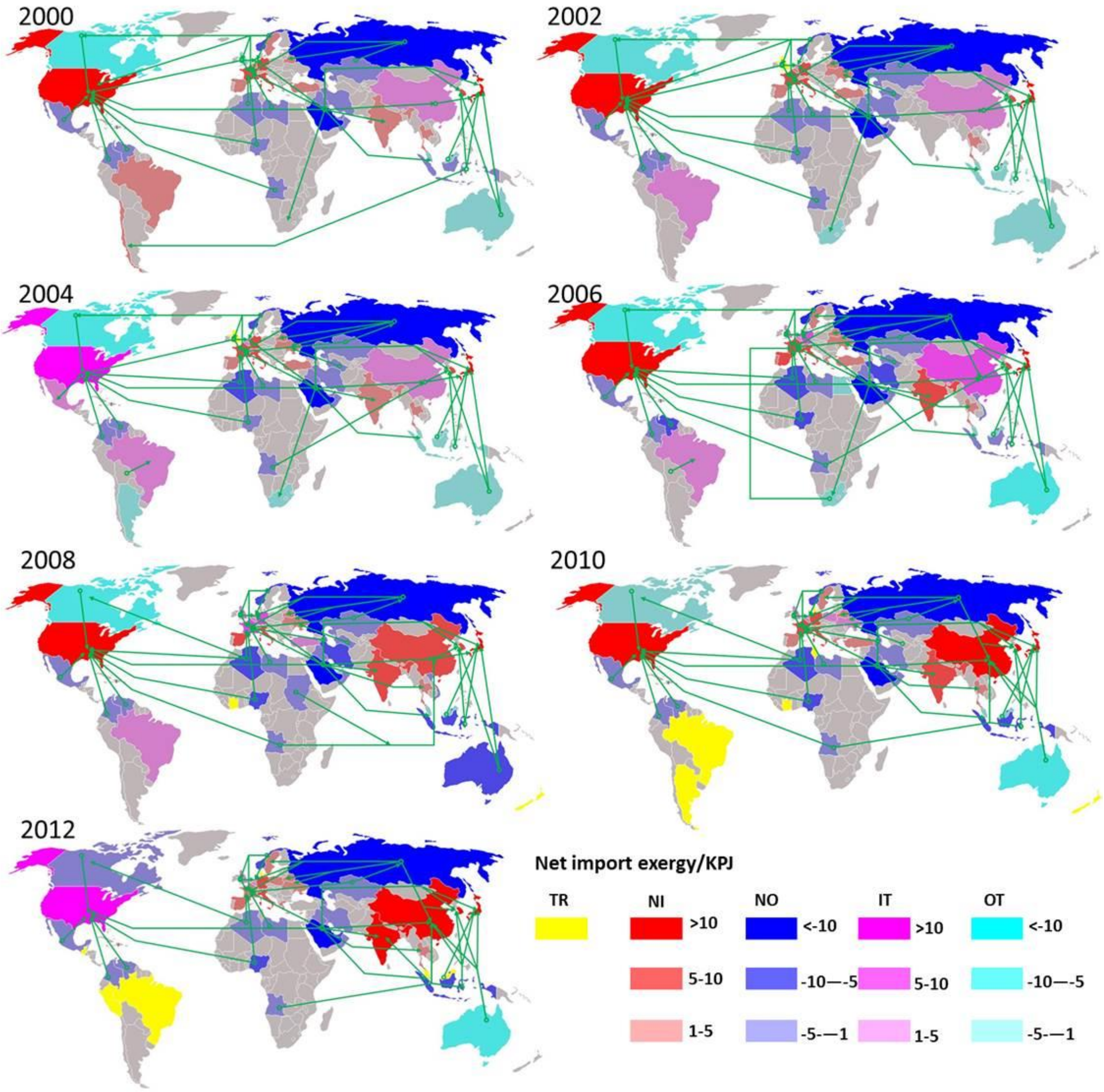


Fig. 4. The proportion of different distances among countries

Based on the analysis above, we select the main five kinds of countries and the exergy flow volume among two countries larger than 700PJ to draw the exergy flow pattern world map in several years (Figure 5). Because the United Kingdom and Netherlands, Czech Rep. and Poland are the mediator and IT, we put all exergy volume inflowing to the European aggregated together as one trade flows other than these four countries. From the exporter perspective, there are seven main exergy flow resources. The Middle East area is the first resource. Its exergy of fossil energy basically outflows to every continents and important regions, which showing its critical position in the international oil and gas trade. The second large exporter is Russian Federation. The Europe and Commonwealth of Independent States are its main export market. The third one is African countries. Their exergy of fossil energy basically outflows to USA. The fourth one is Norway whose main export market is Europe. The fifth one is Canada who basically exports exergy to USA. The sixth one is South American countries like Venezuela and Colombia who mainly outflows exergy to USA. The last one is Oceania countries whose export markets are Asian countries like Japan, China and South Korea. From the importer perspective, there are three main exergy flow destination. The first one is USA which imports exergy of fossil energy from all over the world. We can infer that the import channel diversity makes it can effectively avoid sanctions against its energy suppliers. And it also make USA can use the large amount of exergy of fossil energy to develop its economy. The second one is Asian countries like China, Japan, South Korea and India, especially China's import volume gets more in recent years. Its main energy suppliers are the Middle East, Oceania countries and Russian Federation. The third one is European countries whose main fossil energy suppliers are Norway, Russian Federation and African countries. Because of the complexity of exergy flow pattern in Europe, we draw a more detail diagram in figure 6. We can see that within Europe, Norway is the source of the exergy flow, the middle after United Kingdom, Netherlands, Belgium and Denmark a few intermediary countries eventually into France, Germany and other European countries. In general, in the world level, there are one global source, the Middle East, of net exergy flow of fossil energy and two global destinations, USA and Europe, of net exergy flow. In the region level, there are two regional exergy flow communities. One is in the Commonwealth of Independent States and another is in the Asia-Pacific region.



Notes: In the world map, TR countries are yellow color. NI countries are different depth of red. NO countries are different depth of blue. IT countries are different depth of pink. NT countries are different depth of cyan. The total net import exergy of countries decides the depth of colors. The links denotes the exergy flow direction from the exporter to importer.

Fig. 5 The main exergy of fossil energy flow pattern

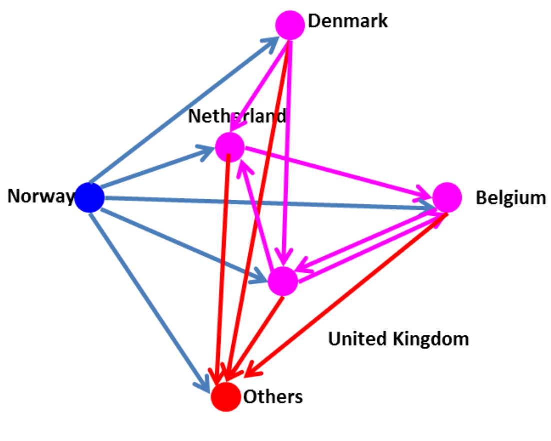


Fig. 6 The main exergy of fossil energy flow in Europe

4. Discussion and Conclusion

The result of the IO index shows that most countries either are exergy of fossil energy supplier or demander and their country type didn't change much in the study period. There is more demander than supplier and this situation didn't change much in the study period either. It verifies that the distribution of fossil energy is very uneven all over the world in exergy perspective. As non-renewable energy resource, we can deduce that unless it found new reserve bases or produce renewable energy, the situation cannot change easily and quickly in the future. However, it is not benefit for the countries' energy safety if a country depends much on the import from other countries to ensure the supply of energy to develop economy. If there were war or financial crisis in those energy suppliers or all over the world, the demander will have energy supply disruptions and impact the economy. Therefore, in order to get rid of the dependency of exporter, the energy importer needs to actively explore new reserve or develop renewable energy industry.

According to the analysis of the ranking evolution of total exergy export volume and total exergy import volume, it infers that the financial crisis in 2007 impact both the energy supplier and demander. Different made different energy policy to deal with the crisis. During this period, China took a series economic policy including energy trade policy. China signed a series of oil trade agreement with Russia, South Africa, Iran and other countries. Financial crisis makes the international oil, coal prices decline sharply, and although China's coal prices fell, but the price is still higher than the international coal market, which makes China's coal market supply and demand pattern further change. On the one hand, due to the low international market price of coal, it stimulates the economically developed coastal areas in southern China to give up purchasing domestic coal, to purchase the international coal market. Thus it will reduce the demand for domestic coal. On the other hand, due to the range of the decline in the international coal market is bigger, faster, and then increased the pressure of the domestic coal market supply exceeds demand. The contrast of domestic and international coal market price, plus the effect of coal export tax, increased China's coal imports and reduced exports. On December 18, 2008, the New York mercantile exchange on January delivery of light crude oil futures prices fell to $36 per barrel. In half a year, international oil prices slumped from $147 a barrel to $36 per barrel, down about 75%. China seized the opportunity to speed up the strategic oil reserve and increased the imports volume. At the same time, in 2008 China's crude oil and gas production continue to grow slowed modestly.

From the shortest distance among countries and the exergy flow global pattern we can know that the geographic distance among countries cannot hinder their fossil energy trade. No matter how far is the physical distance between two countries, the exergy of fossil energy can outflow from sources to the destination directly or indirectly through one or two mediators. However, it is because of the geographic distance between countries, transportation cost between far away countries is higher than closer countries. Thus, the closer countries prefer to make fossil energy trade like the Asian-Pacific region and Norway and other European countries. Other than the geographic distance, the political union is the main reason for the close energy trade relationship between countries like Commonwealth of Independent States and Norway and other European countries.

In this paper, we analyze the net exergy flow embodied in the international fossil fuels trade according to the complex network theory. We select the major fossil fuels, coal, crude oil, liquid natural gas and gaseous natural gas as our research objects. We convert the trade volume of these four kinds of fossil fuels into exergy and add the exergy flow volume of these four types' fossil fuels between countries. Then we construct global net exergy flow network of fossil energy with countries as node, the net exergy inflow or outflow relationship as the edges and net exergy flow volume between countries as the weight from 2000 to 2012. According to the indicators in complex network theory, we defined the IO index and divided countries into five types which are main net exporter, main net importer, export-oriented mediator, import-oriented mediator and mediator. We also analyzed the exergy flow pattern. We find that most countries either are exergy of fossil energy supplier or demander and there are more demanders than suppliers. The exergy of fossil energy can flow directly from the original exporters to the final importers or basically through one or two countries. It indicates that the distance between the importer and exporter is very short. The importers can easily get the exergy they needed from exporters. The financial crisis in 2007 impacts both the energy supplier and demander. In general, in the world level, there are one global source, the Middle East, of net exergy flow of fossil energy and two global destinations, USA and Europe, of net exergy flow. In the region level, there are two regional exergy flow communities. One is in the Commonwealth of Independent States and another is in the Asia-Pacific region. The exergy flow pattern reflects the geopolitics among regional countries and energy supply and demand relations between the countries.

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