Nat Hazards (2015) 75:S127–S138
DOI 10.1007/s11069-014-1071-1

ORIGINAL PAPER

# Assessment of energy supply vulnerability between China and USA

**Lan-Cui Liu · Gang Wu**

Received: 26 October 2013 / Accepted: 29 January 2014 / Published online: 12 February 2014


**Abstract** USA and China are the two largest energy-consuming countries, and energy supply vulnerability is a prior topic on energy policy. Then, we develop energy supply vulnerability assessment index including the sustainability, the stability, the reliability, and the diversification indicators to assess and compare the change of energy supply vulnerability between China and USA based on the data in 2001–2010. We found that the fluctuations of energy supply vulnerability in China are more than those of USA. In 2001–2006, the index of China's energy supply vulnerability presented a quick uptrend, but it presented a slow downtrend in 2007–2010 due to the uncertainty of some indicators; energy supply vulnerability of USA presented smaller change from 2000 to 2008 because of the stable and comprehensive energy supply system, but in 2009 and 2010, it became obviously less than those in other years due to the decline of energy consumption per capita. Additionally, Chinese energy supply also faces higher maritime transportation and geopolitical vulnerability than that of USA. The comparisons of the change of energy supply vulnerability between China and USA show that it is important to develop comprehensive energy supply system to reduce the uncertainty of main effect indicators, such as the control of energy consumption growth, and the diversification of energy supply and import.

**Keywords** Vulnerability · Energy supply · Assessment indicators · Energy supply security

L.-C. Liu (✉)
Center for Climate and Environmental Policy, Chinese Academy of Environmental Planning, Ministry of Environmental Protection of China, 701 Room, Beikechuangye Building, 10 Dayangfang, Beiyuan Road, Chaoyang District, Beijing 100012, China
e-mail: liulancui@163.com; liulc@caep.org.cn

G. Wu
Management Department of the National Natural Science Foundation of China, Beijing 100085, China

## 1 Introduction

Energy supply is vulnerable to a lot of unstable factors such as geopolitical risk, price fluctuation risk, and piracy attacks risk. Therefore, energy supply security is a priority topic on energy policy agenda worldwide, especially the oil supply security. As the two largest energy importers in the world, China and USA face with larger energy supply vulnerability because their energy consumption is huge and they import plenty of oil to meet their demand. For example, Chinese oil import depends mainly on Middle Eastern and African countries where unstable political conditions affect crude oil trade. Oil imports from these regions require long-distance tanker transportation and the crossing of a number of sea areas with high incidence of pirate attacks. In contrast, USA imported more of its crude oil from relatively low-risk countries, notably its North American neighbors Canada and Mexico, which together accounted for 34.0 % of total imports. Furthermore, oil imports and the dependence on foreign oil of China increased rapidly with economic growth, but those of USA presented a downtrend (as shown in Fig. 1). Then what are their respective energy supply vulnerabilities? What difference exists between their evolution of energy supply vulnerability? To answer these questions, we develop energy supply vulnerability index, assess, and compare the change of energy supply vulnerability between China and USA in 2000–2010.

Several previous studies assessed oil vulnerability and energy vulnerability. Ediger and Berk (2011) implemented a principal component analysis to establish an Oil Import Vulnerability Index (OIVI) based on four factors: the crude oil import dependence of primary energy consumption, the crude oil import bill as a share of GDP, non-diversification of import sources, and share of oil in total energy imports. Their study evaluated Turkish oil imports in the period 1968–2007 based on the OIVI approach. Gupta (2008) assessed the relative oil vulnerability of 26 net oil-importing countries for the year 2004,

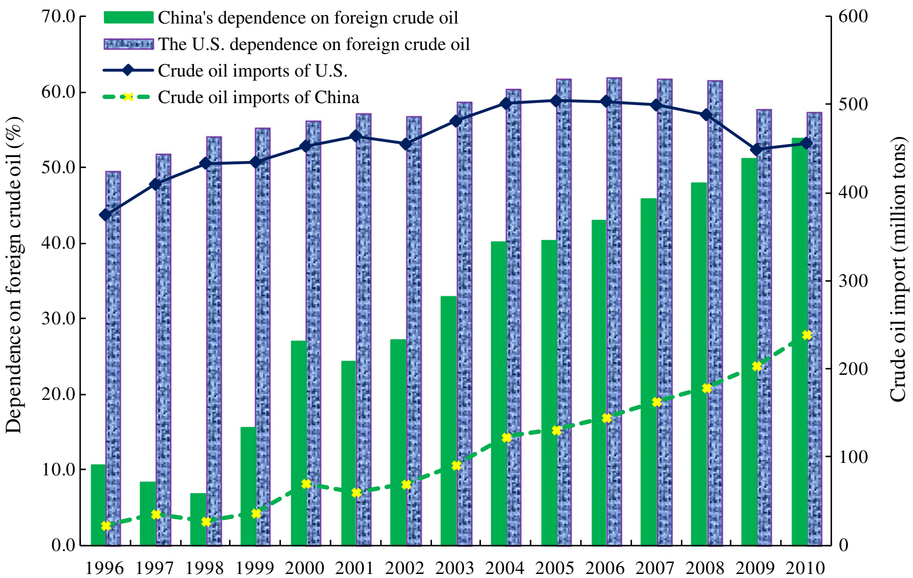


**Fig. 1** China and US crude oil imports and their dependence on foreign oil in 1996–2010

adopting a principal component approach to integrate the ratio of value of oil imports to GDP, oil consumption per unit of GDP, and other individual indicators into a composite index of oil vulnerability. The index introduced by Gupta was able to capture the relative sensitivity of various economies toward development of the international oil market, with a higher value in the index indicating higher vulnerability. Gnansounou (2008) provided a composite index of energy demand/supply weaknesses as a proxy of energy vulnerability and assessed the energy vulnerability index for some selected industrialized countries. Wu et al. (2007) developed a risk-index model using portfolio theory to characterize trends in China's oil import risks, quantified the diversification index of China's crude oil imports over 1996–2004, and explored the relationship between China's monthly import prices and Brent spot prices. Energy systems can be vulnerable to climate change, and Schaeffer et al. (2012) present a review of the impacts that climate change may have throughout the energy chain and identify current knowledge gaps and areas for future research development. Bhattacharyya (2009) analyzed the diversity of fuel mix for electricity generation in selected European countries and investigated how the fuel bill has changed as a share of GDP between 1995 and 2005. The drivers of fuel-dependence-related vulnerability are determined using Laspeyres index decomposition. They found that the gas dependence of the Dutch and Italian systems made them vulnerable but the vulnerability increased in all countries in recent years. Wu et al. (2009) compared and analyzed the supply, price, and transport risks of imports of crude oil and petroleum products using portfolio theory and a diversification index. Lucena et al. (2009) analyzed the vulnerabilities of renewable energy production in Brazil for the cases of hydropower generation and liquid biofuels production, given a set of long-term climate projections for the A2 and B2 IPCC emission scenarios.

Comparing with the above studies, the current paper focused on the assessment of energy supply vulnerability change and the comparisons of China and USA in order to identify the main factors affecting energy supply vulnerability of China. The rest of this paper is organized as follows. Section 2 describes the selected evaluation indicators and related data sources. Section 3 discusses the assessment results of the energy supply vulnerability. Finally, Section 4 gives the limitations and some conclusions.

## 2 Indicators and data sources

### 2.1 Assessment indicators for energy supply vulnerability

The vulnerability of a system is the degree to which that system is unable to cope with selected adverse events. When applying to energy security in long term, a formal definition is difficult to implement due to the number of possible harsh events and the epistemic nature of their uncertainty (Gnansounou 2008). Actually, several factors contribute to raise the concerns about the growing energy supply insecurity, including the current trends in the evolution of global economy and geopolitical changes; the risk of import (for example, price risk and transport risk); the strain on oil and natural gas reserves; the concentration of most of these reserves in unstable regions; local armed conflicts; and so on. Assessing national energy supply vulnerability is mainly to measure its ability to response emergencies. Therefore, it is helpful to reduce energy supply vulnerability with high supply capacity (for example, high energy R/P ratio, self-support ratio, storage ratio, and diversification)and low demand pressures (for example, low energy intensity, consumption per capita, price fluctuation ratio), to a certain extent. In order to assess national energy supply

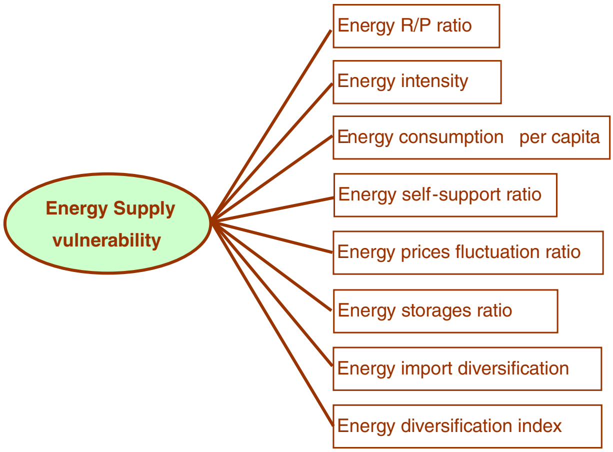


**Fig. 2** The evaluation index of energy supply vulnerability

vulnerability, we selected four kinds of indicators from two aspects of supply capacity and demand pressure, which is shown in Fig. 2.

1. Evaluation indicators for the sustainability of energy supply: energy reserve and production ratio, energy intensity, energy consumption per capita.
2. Evaluation indicators for the stability of energy supply: self-sufficiency ratio, price fluctuation ratio.
3. Evaluation indicators for the reliability of energy supply: energy reserve ratio, the diversification index of energy imports.
4. Evaluation indicators of the diversification of energy supply: energy diversification index.

Firstly, we normalize all the selected indicators and make them positively related to energy supply vulnerability in the following manner.

The normalization equation of benefit-type indicator is as follows:

$$X = {(X_i - X_{\min})}/{(X_{\max} - X_{\min})} \quad (1)$$

The normalization equation of cost-type indicator is as follows:

$$X = {(X_{\max} - X_i)}/{(X_{\max} - X_{\min})} \quad (2)$$

Secondly, the composite index for energy supply vulnerability is computed as the root square of eight relative indicators:

$$I_v = 1 - \left( \frac{\sum_{i=1}^{8} X_i^2}{8} \right)^{0.5} \quad (3)$$

The equations and explanation of evaluation indicators of energy supply vulnerability are shown in Table 1.

See Table 2 for the variables and explanation of evaluation indicators of energy supply vulnerability.

**Table 1** Equation and explanation of indicator of energy supply vulnerability

| Evaluation index | Equation | Indicator explanation |
|---|---|---|
| Energy reserve/production ratio | $R_{\mathrm{R/P}} = \sum_{i=1}^{n} r_i \omega_i$ | Reserve/production ratio for coal, petroleum and natural gas, a benefit-type indicator |
| Energy intensity | $\mathrm{EI}_{\mathrm{int.}} = E_{\mathrm{con.}} / \mathrm{GDP}$ | Energy consumption per unit GDP, a cost-type indicator |
| Energy consumption per capita | $P_{\mathrm{con.}} = E_{\mathrm{con.}} / \mathrm{population}$ | Energy consumption per capita, a cost-type indicator |
| Energy self-sufficiency ratio | $R_{\mathrm{sup.}} = \sum_{i=1}^{n} s_i \omega_i$ <br> $s_i = \frac{i_{\mathrm{con}} + i_{\mathrm{exp}} - i_{\mathrm{imp}}}{i_{\mathrm{con}}} \times 100\,\%$ | To measure the self-sufficiency of energy consumption, mainly fossil energy, a benefit-type indicator |
| Energy price fluctuation ratio | $R_{\sigma} = \sum_{i=1}^{n} \omega_i \sigma_i$ | To measure the fluctuation degree of energy prices (international crude oil prices adopted in this paper), a cost-type indicator |
| Energy storages ratio | $R_{\mathrm{ser.}} = \sum_{i=1}^{n} \mathrm{ser}_i \omega_i$ | To measure the scale of energy strategic reserves (national SPR adopted in this paper), a benefit-type indicator |
| Diversification ratio of energy imports | $\mathrm{I}_{div.} = 1 - \sum_{i=1}^{n} \omega_i \sqrt{\sum_{j=1}^{m} d_{ij}^2}$ | To measure the diversified degree of energy import (index of crude oil import adopted in this paper), a benefit-type indicator |
| Energy diversification index | $C = \sqrt{\sum_{i=1}^{n} c_i^2}$ | To measure the diversification degree of energy supply, a cost-type indicator |

**Table 2** Variables and explanation of indicators of energy supply vulnerability

| Variables | Explanation of variables |
|---|---|
| $I_v$ | Index of energy supply vulnerability |
| $X_i$ | Feature value of indicator $i$ |
| $r_i$ | Reserve/production ratio of the "$i$" fossil energy |
| $\omega_i$ | Share of the "$i$" fossil energy |
| $E_{con.}$ | Energy consumption |
| $s_i$ | Self-sufficiency ratio of the "$i$" energy |
| $i_{con.}, i_{exp.}, i_{imp.}$ | The consumption, export and import amounts of the "$i$" fossil energy |
| $\sigma_i$ | Variance of the "$i$" energy price |
| $ser_i$ | Strategic reserves ratio of the "$i$" fossil energy |
| $d_{ij}$ | Share of the "$j$" import source for the "$i$" fossil energy |
| $C_i$ | Share of the "$i$" energy in primary energy consumption |

### 2.2 Data sources

The data of reserves production ratio of coal, oil, and gas, and the data of primary energy production, imports, exports, and consumption in 2000–2010 are taken from the BP Statistical Review of World Energy (2001–2011) (BP 2011), China Custom Statistical Yearbook 1997–2010 (GACC 2010) and China Statistical Yearbook 2011 (State Statistical Bureau 2011). The data of national strategic petroleum reserves are taken from the news and reports of energy administration. China's oil imports of every supply origins in 2000–2002 are taken from the China's Foreign Economic Relations and Trade Yearbook (Commerce Department 2001, 2002, 2003), and the data in 2003–2010 are taken from China Commerce Yearbook (Commerce Department 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011). The energy intensity and energy consumption per capita data are taken from the China energy report (2010): energy efficiency research (Wei et al. 2010). The data of USA are taken from the Energy Information Administration of the US Department of Energy (EIA 2011).

## 3 Empirical results discussion and analysis

### 3.1 The index of China's energy supply vulnerability presents an uptrend and then downtrend

The proposed energy supply vulnerability indicators were estimated for the year 2000–2010 to compare the energy supply vulnerability between China and USA. There is huge difference with the changes of energy supply vulnerability between China and USA due to the gap of economic development stage and energy supply capacity. The change in China's energy supply vulnerability presents on a roller coaster; however, the change in USA presents a step-by-step downtrend (as shown in Figs. 3, 4). We will discuss and analyze the detailed reasons leading to the differences, respectively.

In 2001–2006, the index of China's energy supply vulnerability presented a quick uptrend, as shown in Fig. 3, mainly due to:

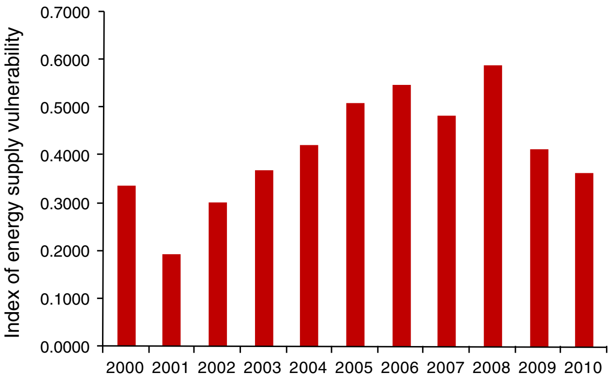


**Fig. 3** The index of China's energy supply vulnerability in 2000–2010

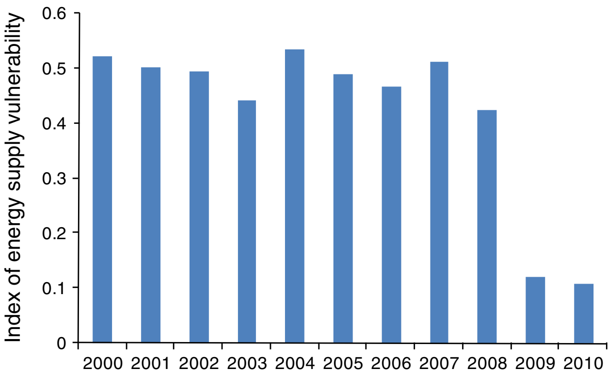


**Fig. 4** The index of US energy supply vulnerability in 2000–2010

1. Energy consumption quickly grew. With the rapid economic growth, China's energy consumption increased by average annual speed of 12 %, bringing huge pressure on energy supply vulnerability. Some southern regions even experienced electricity and oil supply shortages to some extents.
2. Energy supply sustainability decreased. During this period, the energy reserves/production ratio rapidly reduced. The reserves/production ratio of coal decreased by 50 %, and the reserves/production ratio of oil decreased by 40 % compared with that of 2001.
3. The energy imports risk rise. As oil imports kept a rapid increase, the dependence of import exceeded 42 %. However, China's oil imports were still overly dependent on instable Middle East regions, occupying a share of as high as 47 %. The diversification index of oil imports presents a downtrend. In addition, the international oil price had a fluctuating increase, intensifying price risk in oil trades.
4. Energy intensity rebounded and the energy consumption per capita rapidly increased. Before 2000, China's energy intensity presented a downtrend. But in 2003–2005, it rebounded, up 10 % compared with that of 2002. Moreover, energy consumption per capita also increased by 40 % over the same period.

Except for 2008, the index of China's energy supply vulnerability presented a slow downtrend in 2007–2010, mainly due to:

1. The growth of energy consumption was less than those in 2001–2006, with an average annual growth of about 6.7 %.
2. The sustainability of energy supply weakened and the energy reserves/production ratio declined slightly.
3. The energy import risk was further rising. The international energy price soared with sharp fluctuation, especially the case in 2008, causing a higher price risk. For this reason, the vulnerability index in 2008 largely increased (as shown in Fig. 3). Additionally, the diversification index of China's oil imports did not increase simultaneously, which was basically kept at the level of 2005.
4. The energy intensity quickly declined, but the energy consumption per capita increased rapidly. In 2010, the energy intensity dropped by 16.76 % compared with that of 2005.
5. At the end of 2008, the Phase 1 of China's strategic petroleum reserves project was finished and put into operation, significantly uplifting the energy reserves ratio in 2010 and decreasing the index of energy supply vulnerability to some extent.

## 3.2 The index of US energy supply vulnerability presents a downtrend

The USA developed the most comprehensive of energy supply system. Based on the statistical data, US energy resources reserves are richer than China. In 2010, proven recoverable coal resources reserve was 237.3 billion tons and ranked the top one. Reserve/production ratio of coal was 241 and can account for 27.6 % of the world. For crude oil, proven recoverable resources reserve was 309 billion barrels and ranked twelfth in the world. Reserve/production ratio was 11.3 and can account for 2.2 % of the world. For natural gas, proven recoverable resources reserve was 7,700 billion cubic meter and ranked fourth in the world. Reserve/production ratio of coal was 12.6 and can account for 4.1 % of the world. However, USA is still the biggest energy importing country due to the higher energy consumption per capita. In 2010, energy consumption per capita was 7.23 toe, which was almost four times as much as the average energy consumption per capita in the world.

Figure 4 shows that energy supply vulnerability of USA presented smaller change from 2000 to 2008, but in 2009 and 2010, it became obviously less than those in other years. The main reasons are as follows:

1. Energy consumption per capita of USA in 2009 and 2010 decreased by 12.56 and 10.24 %, respectively, compared with that in 2000 due to the effects of global financial crisis since 2008.
2. Energy intensity in 2009 and 2010 also declined obviously, compared with that in 2000, drop by 16.36 and 16.11 %, respectively.
3. Energy self-sufficiency ratio and energy reserve ratio had been improved greatly. In 2000, they were 71.61 and 7.52 %, and increased to 76.56 and 10.61 % in 2009, and 76.05 and 10.40 % in 2010.
4. Energy supply types and energy import sources became more diversified, and the international oil prices fluctuated less, which can ensure the supply security.

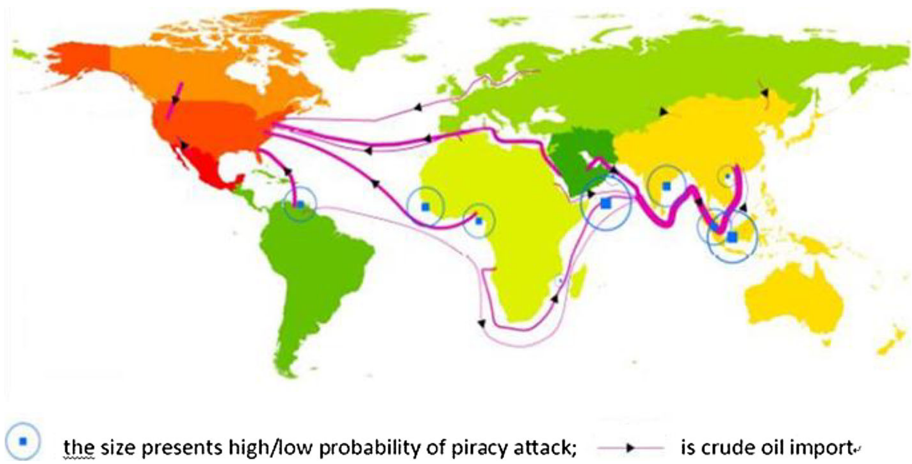


**Fig. 5** Trade flow of oil imports of China and USA and distribution of piracy attacks

## 3.3 The effect of geopolitical risk and transport risk on energy supply vulnerability between China and USA

Due to data limitation, we have not considered the geopolitical risk and transport risk among the evaluation indicators. In fact, the geopolitical risk is one of the important factors affecting energy supply vulnerability, but it is very difficult to quantitative evaluation. Although China and USA are the two largest crude oil importers in the world, they differ substantially with regard to their crude oil import sources and geopolitical risks. For example, China depends mainly on Middle Eastern and African countries where unstable political conditions affect crude oil trade. Importing from these regions requires long-distance tanker transportation and the crossing of a number of sea areas with high incidence of pirate attacks (as shown in Fig. 5). In 2010, China's imported crude oil was obtained largely from the relatively high-risk Middle East, accounting for 47.1 % of total imports (as shown in Table 3 and Fig. 5). In contrast, the USA imported more of its crude oil from relatively low-risk countries, notably its North American neighbors Canada and Mexico, which together accounted for 34.0 % of total imports (GACC 2011; EIA 2011). It is clear that China faces much greater geopolitical risks and supplies vulnerability than USA in its sources for crude oil imports.

From the data of International Maritime Bureau (IMB), there were 443 piracy attacks incidents in 2010, relative to the 2008 and 2009 increased 51 and 9 %, respectively. We calculated the average incidence of global piracy attacks over 2005–2010 based on the data from the IMB and International Maritime Organization (in Fig. 6). Firstly, the statistical results show that the incidence of piracy attacks in Somalia waters was the highest instead of the Malacca Straits, because many countries were paying great attention to the Malacca Straits, and there were more frequent maritime patrols, which forced the pirates to transfer their activities to other areas. And global piracy attacks present diversified trends and focused almost exclusively on Somalia waters, Indonesian waters, Malacca Straits, Persian Gulf, Gulf of Guinea, and Caribbean Sea (in Fig. 6). Secondly, unlike the USA, the vital ship routes for China's crude oil imports must traverse the waters of higher incidence of piracy attacks, for example, Somalia waters, Indonesian waters, and Malacca Straits (as shown in Fig. 5). Thirdly, in recent years, the incidence of piracy attacks in East Africa and

**Table 3** Share of major crude oil import sources of China and USA in 2010

| USA | | | | | | China | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Share of major oil import source nations (%) | | | Share of major source regions (%) | | | Share of major oil import source nations (%) | | | Share of major source regions (%) | |
| Canada | Mexico | Saudi Arabia | North America | Central and South America | Africa | Saudi Arabia | Angola | Iran | Middle East | Africa |
| 21.52 | 12.44 | 11.78 | 33.96 | 19.72 | 21.77 | 18.61 | 16.52 | 8.89 | 47.12 | 29.60 |

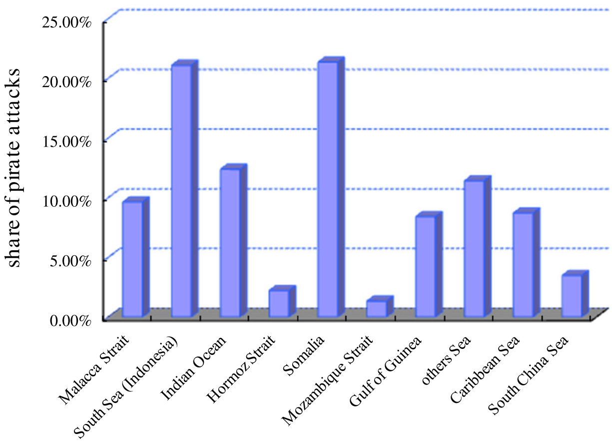


**Fig. 6** Distribution probability of global piracy attacks during the period of 2005–2010

West Africa has also increased considerably, especially in the Somalia waters and Gulf of Guinea. For example, the Saudi Arabia-owned supertanker "Sirius Star" hijacked by Somalia pirates in a raid 450 miles southeast of Mombasa, Kenya, on November 15, 2008. There were two piracy attacks on Chinese ship in Somalia waters and Gulf of Aden on November and December 2008, respectively. In order to ensure the transportation security, the Chinese navy fleet arrived in the Gulf of Aden off Somalia to carry out the first escort mission against pirates on January 7, 2009. Therefore, Chinese crude oil imports face higher energy supply vulnerability than that of USA from the perspective of maritime transportation risk and geopolitics.

## 4 Conclusions

Based on the assessment for energy supply vulnerability index in China and USA, we found that the fluctuations of energy supply vulnerability in China are more than those of USA. In 2001–2006, the index of China's energy supply vulnerability presented a quick uptrend, but it presented a slow downtrend in 2007–2010 due to the uncertainty of some indicators; energy supply vulnerability of USA presented smaller change from 2000 to 2008 because of the stable and comprehensive energy supply system, but in 2009 and 2010, it became obviously less than those in other years due to the decline of energy consumption per capita. The comparisons of the change of energy supply vulnerability between China and USA present us that it is important to develop comprehensive energy supply system to reduce the uncertainty of main effect indicators, such as the control of energy consumption growth, and the diversification of energy supply and import.

While the above assessment results and analysis have provided us with interesting insights, it also has some limitations. Due to data limitations, we do not assess quantitatively the impacts of the geopolitical factor, transport factor, and piracy attacks in the evaluation indicators on energy supply vulnerability, but we compared the share of major crude oil import sources of China and USA in 2010 and analyzed the trade flows of oil imports and piracy attacks incidents, which show clearly that energy supply vulnerability of China is also higher than that of USA. From the perspective of assessment indicators and method, there are quite a few areas in which improvements in data and methods are desirable.

**Acknowledgments** The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China under Grant Nos. 71173207, 70903028, and 71373099. And we would like to sincerely thank for the reviewers helpful suggestions and feedback on an early draft of this paper.

## References

Bhattacharyya SC (2009) Fossil-fuel dependence and vulnerability of electricity generation: case of selected European countries. Energy Policy 37:2411–2420

BP (2011) BP Statistical Review of World Energy 2011. British Petroleum (BP), London

Commerce Department (2001) China's Foreign Economic Relations and Trade Yearbook 2001. China Foreign Economic Relations and Trade Press, Beijing

Commerce Department (2002) China's Foreign Economic Relations and Trade Yearbook 2002. China Foreign Economic Relations and Trade Press, Beijing

Commerce Department (2003) China's Foreign Economic Relations and Trade Yearbook 2003. China Foreign Economic Relations and Trade Press, Beijing

Commerce Department (2004) China Commerce Yearbook 2004. China Commerce Press, Beijing

Commerce Department (2005) China Commerce Yearbook 2005. China Commerce Press, Beijing

Commerce Department (2006) China Commerce Yearbook 2006. China Commerce Press, Beijing

Commerce Department (2007) China Commerce Yearbook 2007. China Commerce Press, Beijing

Commerce Department (2008) China Commerce Yearbook 2008. China Commerce Press, Beijing

Commerce Department (2009) China Commerce Yearbook 2009. China Commerce Press, Beijing

Commerce Department (2010) China Commerce Yearbook 2010. China Commerce Press, Beijing

Commerce Department (2011) China Commerce Yearbook 2011. China Commerce Press, Beijing

Ediger VS, Berk I (2011) Crude oil import policy of Turkey: historical analysis of determinants and implications since 1968. Energy Policy 39:2132–2142

EIA (2011) Spot prices for crude oil and petroleum products. Energy Information Administration of Department of Energy, U.S. http://www.eia.doe.gov/

General Administration of Customs of China (2011) The statistical data of customs of China. www.customs.gov.cn/

General Administration of Customs of China (GACC) (2010) China Custom Statistical Yearbook 1997–2010. General Administration of Customs of the People's Republic of China Press, Beijing

Gnansounou E (2008) Assessing the energy vulnerability: case of industrialized countries. Energy Policy 36:3734–3744

Gupta E (2008) Oil vulnerability index of oil-importing countries. Energy Policy 36:1195–1211

Lucena AFP, Szklo AS et al (2009) The vulnerability of renewable energy to climate change in Brazil. Energy Policy 37:879–889

Schaeffer R, Szklo AS et al (2012) Energy sector vulnerability to climate change: a review. Energy 38:1–12

State Statistical Bureau (2011) China Statistical Yearbook 2011. China Statistical Press, Beijing

Wei YM, Liao H et al (2010) China energy report (2010): energy efficiency research. Science Press. (in Chinese)

Wu G, Wei YM, Fan Y, Liu LC (2007) An empirical analysis of the risk of crude oil imports in China using improved portfolio approach. Energy Policy 35:4190–4199

Wu G, Liu LC, Wei YM (2009) Comparison of China's oil import risk: results based on portfolio theory and a diversification index approach. Energy Policy 37:3557–3565