Applied Energy 123 (2014) 415–423

Contents lists available at ScienceDirect

Applied Energy

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

A multilayered analysis of energy security research and the energy supply process

Eriko Kiriyama [a,*], Yuya Kajikawa [b]

[a] Todai Policy Alternatives Research Institute, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[b] Graduate School of Innovation Management, Tokyo Institute of Technology, 3-3-6 Shibaura, Minato-ku, Tokyo 108-0023, Japan

HIGHLIGHTS

- The analysis reveals that energy security research is highly multidisciplinary.
- Diversification is important for ensuring security in the energy supply process.
- A multilayered overview of the energy supply process is important for energy risk management.
- Consumer lifestyle innovation will be a part of energy security in the future.

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form 5 December 2013
Accepted 7 January 2014
Available online 3 February 2014

Keywords:
Energy security
Energy policy
Energy supply chain
Network analysis

ABSTRACT

After the Fukushima nuclear disaster, a reassessment of the energy system is needed in order to include such aspects as human security and resilience. More open and careful discussions are needed concerning the various risks and uncertainties of future energy options, both in Japan and globally. In this paper, we aim to offer a fundamental basis for discourse on energy security by analyzing the status and trends in academic publications on that issue. Our bibliometrics analysis indicates that research has shifted from promoting strategies for ensuring the self-sufficiency of the primary energy to diversification of the secondary energy supply chain by introducing energy networks consisting of an infrastructure established through international coordination. In the literature, the concept of *energy security* is ambiguous and allows for multiple interpretations. Our results illustrate the existence of highly multidisciplinary topics within energy security, which can be categorized into four perspectives: geopolitical, economic, policy related, and technological.

1. Introduction

Energy security has been regarded as one of the main objectives of energy policy concurrent with economic efficiency and environmental safeguards. However, because it includes a variety of connotations, energy security has been represented as a criterion with indicators selected to fit political contexts. For instance, geopolitical considerations have been fundamental in supporting renewable energy and nuclear energy in several countries, including Japan, to reduce dependence on imports of fossil fuels.

Since the Fukushima disaster in 2011, the National Policy Unit (NPU) and the Ministry of Economy, Trade, and Industry (METI) in Japan decided to abandon their existing plans and rechart a new Strategic Energy Plan [1]. With this plan, they seek to formulate a new energy mix through close coordination and cooperation with civil society; the aim is to reflect public opinion through highly transparent discussions. In particular, open and careful discussions are needed regarding the risks and uncertainties associated with energy and the place of environmental options—including matters recognized as given conditions in the past—and its place in future energy options, both in Japan and in global society [2].

Various researchers have offered ways to understand and formulate the discussion about energy security. Regarding historical and scholarly discussions of energy security, Cherp and Jewell present the knowledge mapping required for energy security through perspectives rooted in political and natural science, engineering, economics, and systems analysis [3]. As for quantification, Sovacool and Brown define and measure energy security based on four dimensions: availability, affordability, efficiency, and environmental stewardship [4]. Similarly, Jansen and Seebregts create an index for measuring the extent of long-term energy security and security externality valuation for populations in defined areas [5]. Eunju et al. also measure the costs of energy security in terms of supply disruption and price volatility and consider the degree of concentration in supply and demand in the energy market [6].

* Corresponding author. Tel.: +81 3 5841 1708; fax: +81 3 5841 1709.
E-mail address: kiriyama@pp.u-tokyo.ac.jp (E. Kiriyama).

0306-2619/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2014.01.026

Regarding the energy supply chain, Zhang et al. construct an evaluation framework for oil import security within the supply-chain process and identify the main risk factors [7]. In terms of geopolitics, Sahir and Qureshi argue that the regional and global actors in energy security should recognize that traditional geopolitical strategies destabilize regions and divert attention from the real threats [8].

Concerning the increasing importance of energy security in energy policy, many studies have reevaluated energy security; such studies are expected to offer intellectual and evidential bases for making decisions about science and energy policy. Because of the large volume of academic publications, however, there is no comprehensive research offering an essential and objective picture of energy security.

Our aim is to illustrate the overall structure of energy research using bibliometric analysis, which is useful for efficiently and effectively generating a holistic perspective on a given research domain. Over the last few years, several papers have used citation analysis for energy research. Namely, Kostoff et al. analyze the structure of energy research through textual analysis [9,10]. Konur highlights the importance of scientometrics in gaining valuable insights into the use of algae and other sources of bioenergy [11]. Lastly, Liping measures international cooperation in energy R&D in China using bibliometric analysis to determine the frequency of copublication [12]. Similarly, this paper aims to provide a comprehensive perspective on energy security research by applying bibliometric analysis to academic publications.

2. Methodology

Our data was collected from the Science Citation Index-Expanded (SCI-E) and the Social Sciences Citation Index (SSCI) compiled by Thomson Reuters, which maintains citation databases covering thousands of academic journals and offers bibliographic database services. SCI-E and SSCI include papers published since 1948.

We retrieved papers to obtain coverage of citation data using the query "energy and security" and found records that contained these terms in the abstract, title, and/or keywords fields of a record. In the retrieval, we used the web-based user interface Web of Science (Thomson Reuters) for the citation database. As a result, we obtained data from 1157 papers published before January 2012 as shown in Table 1. The collected data were analyzed using citation network analysis wherein a citation network is created in which a node is a paper and a link is a citation. Since this paper focuses on relationships among papers, only the data for the largest graph components were used. Hence, we eliminated papers with no citations to or from any other papers. After extracting the largest connected component, we divided the network into clusters using the topological clustering method [13], which does not require heuristic input parameters. This method revealed tightly knit clusters with a high density of links within each cluster, enabling the creation of a nonweighted graph consisting of many nodes. By arranging the citation network into clusters, we could identify research topics consisting of groups of related papers. Co-citation and bibliographic coupling were used in the citation network analysis. In such couplings, however, core papers are sometimes not included in the largest component, especially immediately after those papers are published [14]. Therefore, we regarded direct citations as links in the citation network.

After clustering the network, we analyzed the characteristics of each cluster by the titles and abstracts of papers frequently cited by other papers in the cluster, as well as the journals in which the papers in the cluster were published. We named each cluster and listed the keywords for each from the titles and abstracts of the most-cited papers in the cluster. The average publication year of the papers in each cluster was calculated to discern trends in the research field.

Next, we visualized the citation network using the large graph layout (LGL) algorithm developed by Adai et al. [15], which dynamically visualizes large networks of hundreds of thousands of nodes and millions of links. This algorithm also applies a force-directed iterative layout, guided by the minimal spanning tree of the network, to generate coordinates for the nodes in two or three dimensions. We visualized the citation network by expressing intracluster links in the same color so that the clusters could be understood intuitively.

Table 1
Data on energy security.

Period	1948–2012
Average year of published papers	2008.06
Number of papers	1157
Number of nodes	336
Number of links	496
Number of clusters	16

3. Results and discussion

Fig. 1 shows the number of publications by authors in different countries. As seen in this figure, in 2011 the United States was first in the number of papers published related to energy security. Then in descending order came England, China, Canada, India, Japan, and Germany. Since 2005, the growth rate in the number of papers has increased, especially in the United States. Energy security is considered one of the main objectives of energy policy along with economic efficiency and environmental protection. However, because *energy security* has varied connotations, it is expressed through different indicators selected to fit existing political contexts. One example is the energy self-sufficiency ratio. Since the oil crises of 1973 and 1979, the United States has used this ratio to legitimate and promote policy initiatives for a stable supply of resources and to diversify energy by introducing alternative sources (e.g., nuclear, wind, and photovoltaic power).

Our results from the clustering of citation networks yielded 16 clusters: cluster 1 (40 papers), energy policy; cluster 2 (38 papers), biofuel; cluster 3 (34 papers), oil import; cluster 4 (28 papers), natural gas; cluster 5 (28 papers), climate change, low-carbon; cluster 6 (25 papers), economy, cost; cluster 7 (24 papers), biodiesel; cluster 8 (18 papers), governance; cluster 9 (17 papers), the EU; cluster 10 (17 papers), bioenergy; cluster 11 (16 papers), Markal model; cluster 12 (15 papers), strategies; cluster 13 (12 papers), China; cluster 14 (10 papers), the Middle East; cluster 15 (7 papers), batteries; and cluster 16 (7 papers), hydrogen. In addition, we calculated the simple average publication year for the papers in each

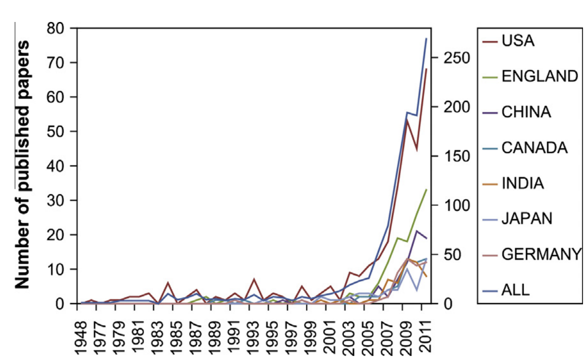

Fig. 1. Number of papers published annually on energy security research.

cluster (Table 2). As shown in Fig. 1, the number of all published papers significantly increased each year. Hence, the average year for each cluster in Table 2 is quite recent.

Cluster 1, energy policy, is located at the core of the energy security research papers; thus, its role is the most significant. Yergin said energy security would be the number-one topic on the agenda for energy policy and that concerns over energy security would not be limited to oil [16,17] According to Jansen and Seebregts, energy security gets political attention in emergencies involving physical shortages at oil or natural gas stations, or following blackouts in the electricity supply system [18]. In addition, Sovacool suggests that energy security is a multidimensional phenomenon; the technical energy supply and the demand-side aspects of energy security exist simultaneously with social, political, and economic factors across a variety of sectors, including electricity and transport [19].

Regarding cluster 2, biofuel, Demirbas points out that biofuels have been regarded as relevant technologies by both developing and industrialized countries because of energy security concerns, environmental issues, foreign exchange savings, and socioeconomic factors related to the rural sector [20]. Moreover, Hammond et al. explain that biofuel technology in the transport sector has received support on the grounds of energy security [21]. Further, Zhou and Thomson argue that the main driving forces for the development of biofuel technology in Asia are energy security for improving trade balances and expansion of the agricultural sector [22].

Oil import (cluster 3) has been a primary focus of energy security policy. Vivoda examined the importance of diversification policy for oil importers, explained why oil importers implement oil diversification policies, and contextualized oil import diversification strategies within the overall energy security policy of oil importers [23]. Using LEAP (long-range energy alternatives planning) modeling, Hippel presents the attributes of energy security through multiple dimensions: energy supply (oil imports, etc.), economics, technology, environment, society, culture, and the military [24]. Similarly, Wu et al. quantify the diversification index of China's crude oil imports and suggest that diversification can enhance energy security by reducing the risk of market disruptions [25].

Next, cluster 4 deals with natural gas, which was formerly a national or regional fuel but has now assumed an important role for energy security owing to the development of long-distance pipelines, shale gas, and liquefied natural gas. Bambawale and Sovacool discuss seven hypotheses pertaining to the following: the security of the energy supply, geopolitics, climate change, decentralization, energy efficiency, research and innovation in new energy technologies, and self-sufficiency and trade. Because the security of fossil fuels is a top energy security priority, China is investing in unconventional sources of gas such as coal-bed methane and shale gas [26]. Bilgin addresses the rising demand for gas among the EU27, elaborating on the alleged risks of dependence on Russia, such as Gazprom's disagreement with the Ukraine, which triggered international gas crises in 2006 and 2009 [27]. Bilgin also examines the incentives for and barriers to Europe's further cooperation with selected Caspian and Middle Eastern countries for ensuring European energy security. Similarly, Correlje and Linde examine the consequences of geopolitical developments for the stable supply of oil and natural gas and argue that energy security issues have become integral to EU policy regarding external trade and foreign relations [28].

Cluster 5 concerns climate change and low-carbon issues. Turton and Barreto studied the role of several policy instruments in managing energy security and climate risks and in stimulating technological change toward a more secure and climate-benign long-term global energy system [29]. Brown and Huntington discuss the tradeoff between abating greenhouse gases and improving energy security in choosing a mix of individual technologies [30]. Cai et al. studied optimal strategies for planning energy management systems under multiple uncertainties through developing efficient and environmentally friendly energy management systems for maximized energy security [31].

In cluster 6, economy and cost, Brathwaite et al. compared the energy security implications of two competing policies designed to reduce price fluctuations and dependence on foreign oil by extending the use of coal based on economic and environmental factors [32]. Stern offers the first estimate of US military costs for its Persian Gulf force and mentions an important detail about regional cost information that seems critical to energy and national security policy [33]. Frondel et al. argue that Germany's principal mechanism of supporting renewable technologies through feed-in tariffs imposes high costs without any of the alleged positive impacts on emission reduction, employment, energy security, or technological innovation. They arrived at this conclusion by focusing on costs and the associated implications for job creation and climate protection [34].

Regarding cluster 7, biodiesel, Koh and Ghazoul suggest that some environmental and societal costs could be ameliorated through the development and use of biodiesel technologies; such a move is critical for energy security and reducing reliance on foreign oil [35]. Phalan also provides a broad overview of the social and environmental costs and benefits of biodiesel by applying comprehensive assessment and mapping [36]. Singh and Olsen argue that the major factors that would determine the impact of

Table 2
Energy security research clusters and perspectives.

Cluster no.	Main issue	Number of papers	Average publication year	Perspective
1	Energy policy	40	2008.01	G, P
2	Biofuel	38	2009.01	T
3	Oil import	34	2008.07	E, P
4	Natural gas	28	2009.09	T
5	Climate change, low carbon	28	2008.07	P
6	Economy, cost	25	2009.02	E, P, T
7	Biodiesel	24	2008.08	T
8	Governance	18	2009.06	P
9	EU	17	2009.04	G, P
10	Bioenergy	17	2008.04	T
11	Markal model	16	2008.09	E, P
12	Strategy	15	2006.01	P
13	China	12	2007.06	G, P
14	Middle East	10	2007.06	G, P
15	Battery	7	2009.07	T
16	Hydrogen	7	2006.10	T

biofuels include their contributions to land-use change, the feedstock used, and issues pertaining to technology and scale [37].

In cluster 8, governance, Goldthau and Witte provide recommendations for policy makers on how the existing architecture of global energy governance might be reformed by looking closely at the security dimension of energy politics [38]. Nagy summarizes the findings for establishing the Energy Security Center (by the Hungarian Ministry of Defense, the Ministry of Economy and Transport, the Ministry of Foreign Affairs, the National Office for Research and Technology, and the Prime Minister's Office) and creating the conditions required for its operation [39]. Florini and Sovacool argue that global energy governance is a sustained research agenda needed to handle humanity's daunting energy challenges. It requires simultaneous attention to issues such as geopolitical stability, the security of energy infrastructure, transboundary environmental externalities, the proliferation of nuclear technology, investment and trade rules, and economic development [40].

Cluster 9 concerns the EU, which is currently working toward achieving a target of 20% renewable energy by 2020. Its policy framework relies primarily on individual member states implementing their own policy instruments for renewable energy support [41]. Patt et al. point out that the idea of a European–North African super grid often provokes concerns about European supply security—especially considering Libya's recent unpredictable behavior—and there is currently no commonly accepted method of assessing the security of electricity [42]. According to Toft et al., energy-importing EU nations could benefit from developing strategies to increase stability in energy supply countries that are unstable due to terrorist activity [43]. Otherwise, Lilliestam and Ellenbeck argue that the EU is not vulnerable to extortion by an export cut from only one country. European capacity buffers are sufficient to restore the power supply as a result of the achievement of increased import dependency against Russia's use of the "energy weapon" [44].

In cluster 10, bioenergy, Karp and Shield suggest that bioenergy could substantially contribute toward alleviating the problems of climate change and energy security if high yields could be sustainable as production systems [45]. Demirbas argues that biomass represents a potentially inexhaustible supply of feedstock for methanol production; it is desirable for several reasons that include energy security factors, environmental concerns, foreign exchange savings, and socioeconomic issues [46]. Meanwhile, Wilkinson et al. suggest that reliance on unclean coal and biomass energy are responsible for much ill health in poor countries. Further, unsecure energy supplies and volatile prices can have adverse consequences for the continuity of energy supplies. Internationally, the need to safeguard supplies is a potential source of tension and conflict [47].

Regarding cluster 11, Chen et al. employed the Markal model, which was developed in a cooperative multinational project over a period of almost two decades by the Energy Technology Systems Analysis Programme of the International Energy Agency [48]. An integrated energy, environmental, and economic model, Markal is a dynamic linear programming model based on a reference energy system that minimizes the total discounted energy system costs, including investment costs and both variable and fixed operational and maintenance costs on both the supply and demand sides. It incorporates a full range of energy processes—exploitation, conversion, transmission, distribution, and end use—to study an energy system's carbon mitigation strategies and the corresponding impacts on the economy [49, 50].

The papers in cluster 12 study energy technology strategies designed to introduce alternatives to oil. Such research considers nuclear energy and renewable energy as domestic resources. The average publication year for this cluster (2006.01) makes it the oldest compared to the other paper clusters. At the energy-political level, Bohi and Toman argue that the market-power issue indicates that because of threats of retaliation, direct import controls are not wise strategies for addressing externalities [51]. Valentine concludes that the fragmented structure of the renewable energy technology sector places it at a financial disadvantage in terms of any attempt to break the hold that fossil fuel technologies have on energy provision [52]. Lastly, Chester examines the concept of energy security and makes its polysemic nature explicit by reviewing the European Commission's green paper, *Toward a European Strategy for the Security of Energy Supply* [53].

Cluster 13 suggests that China has viewed energy security in terms of adjusting its dependency on global markets. The impact of growth in China, India, and other countries on the global demand for energy has had enormous influence. Leung argues that because Beijing did not pay much attention to energy security until the turn of the century, China's energy security policy is still evolving, is not well coordinated, and has contradictions [54, 55]. Li shows that Chinese oil prices are cointegrated with major oil prices around the world; this high degree of comovement between oil prices suggests that China is actively engaged in the world oil market [56].

Research on the Middle East (cluster 14) considers the uncertainty in the region as a crucial factor determining world oil prices. Salameh analyzed the impact of the growing dependence on Middle Eastern oil along with price and energy security. He argues that dependence on such a volatile region and the perception of scarce energy resources in the Asia-Pacific region can potentially cause conflict in both regions unless these issues are addressed in geoeconomic, rather than geostrategic, terms [57]. Using the Hirschman–Herfindahl index, Jun and Kim measured the cost of energy security in terms of supply disruption from unstable regions, price volatility, and the degree of concentration in energy supply and demand [58]. Sahir and Qureshi examined concerns specific to Pakistan in the context of energy security along with geopolitical complexities and strategies for leading roles and partnerships [8].

In cluster 15 (batteries), Thomas considers replacing conventional gasoline cars with vehicles such as hybrid electric vehicles, plug-in hybrids fueled by gasoline, cellulosic ethanol and hydrogen vehicles, and all-electric vehicles powered exclusively by batteries or by hydrogen and fuel cells in terms of which ones hold the greatest potential for averting societal threats [59,60]. Zhang shows, in addition, that through available technology integration, there is great potential in biodegradable sugar batteries, sulfur-free jet fuel, hydrogen, sugar hydrogen fuel cell vehicles, high-density electricity storage, and synthetic starch [61].

In cluster 16 (hydrogen fuel), Dunn argues that it is necessary to question the fundamental sustainability of the current energy system and explore hydrogen as a means to solve the energy-related problems of energy security, air pollution, and climate change [62]. Adhikari and Fernando argue that using hydrogen as an energy source could help address energy security issues such as global climate change and local air pollution. In addition, they discuss different types of membranes used to separate hydrogen from hydrogen-rich mixtures [63]. Lastly, Conte et al. argue that the balanced and incremental introduction of hydrogen would provide an opportunity for a new spectrum of primary energy sources; while it cannot be used directly—as with renewable energy sources—it is necessary as an intermediate conversion step to maintain the improved attributes in terms of availability, cleanliness, and energy security [64].

We should note two important aspects of these results: (1) uncertainty and risks from external factors could affect factors related to energy security, and (2) our results reflect the energy security levels of the current energy systems in each country, which will likely change and could improve. Based on these findings,

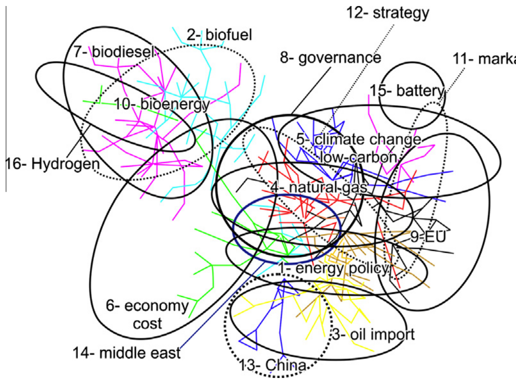

Fig. 2. Visualization of energy security research themes identified by citation network analysis.

we have listed the hazards threatening society under the current conditions for comprehensive consideration (Table 3). Regarding the expectations of risk assessment from science, society, and policy, there is a need to assess how risk assessment is conducted since it usually concerns the degree of impact under uncertain, multidimensional conditions.

Risk exists in the future while hazard is a risk factor that has existed in the past. Therefore, to appropriately assess the types of risk posed by hazards, we should consider essential societal changes—macro or micro, economic, political, social, environmental, scientific, technological, human health, etc.—taking into account future uncertainties. Such work needs to be done to build a mechanism so that when hazards become reality and crisis occurs, damage in the aforementioned areas will be minimized as much as possible.

3.1. Ambiguity in energy security research

Fig. 2 shows the structure of the citation network wherein each line corresponds to each citation. Clusters located in close proximity to each other have close citation relationships among them. As shown in Fig. 2, energy policy (cluster 1) is in the central position. Oil imports (cluster 3), natural gas (cluster 4), economics and cost (cluster 6), and EU issues are closely related. Additionally, biofuel (cluster 2), biodiesel (cluster 7), and bioenergy (cluster 10) are close together and connected with other clusters through the intermediary of economics and cost (cluster 6). Consequently, we show that energy security research crosses lines between disciplines and integrates academic research from geopolitics, policy, economics, and engineering.

As shown in Table 2, there are multiple perspectives on energy supply research. Because there is no simple concept of energy security, we broadly labeled the topics according to the following four perspectives: policy (P), economic (E), geopolitical (G), and technological (T).

We further characterized each cluster quantitatively in Fig. 2 using the Subject Categories of Journal Citation Reports provided by Thomson Reuters for classification. We characterized the clusters by two perspectives—technological and other (policy, economic, geopolitical)—to simplify our discourse since most of the papers were published in technology-oriented journals. Thus, we counted the number of papers published in technology-oriented journals and in policy, economic, and geopolitical journals. The results further demonstrate that energy security, by definition, has more than one possible dimension. Fig. 2 shows the degree of ambiguity for each cluster in energy security. For example, cluster 5 (climate change, low carbon) has high ambiguity because it includes policy, economic, geopolitical, and technological perspectives. The publications in cluster 5 cover a wide variety of journals. On the other hand, cluster 10 (bioenergy) has more technological orientation and less ambiguity since the feasibility of bioenergy for energy security depends on technological progress.

Fig. 3 shows the degree of ambiguity resulting from energy security being open to more than one interpretation when bibliometrics are applied. According to Leach et al., the degree of ambiguity pertains to disagreements over the relevant outcomes [65]. The vertical axis shows the share of papers in terms of percentage, and the horizontal axis represents the relative distance from the degree of ambiguity line in Fig. 3. This figure shows that while

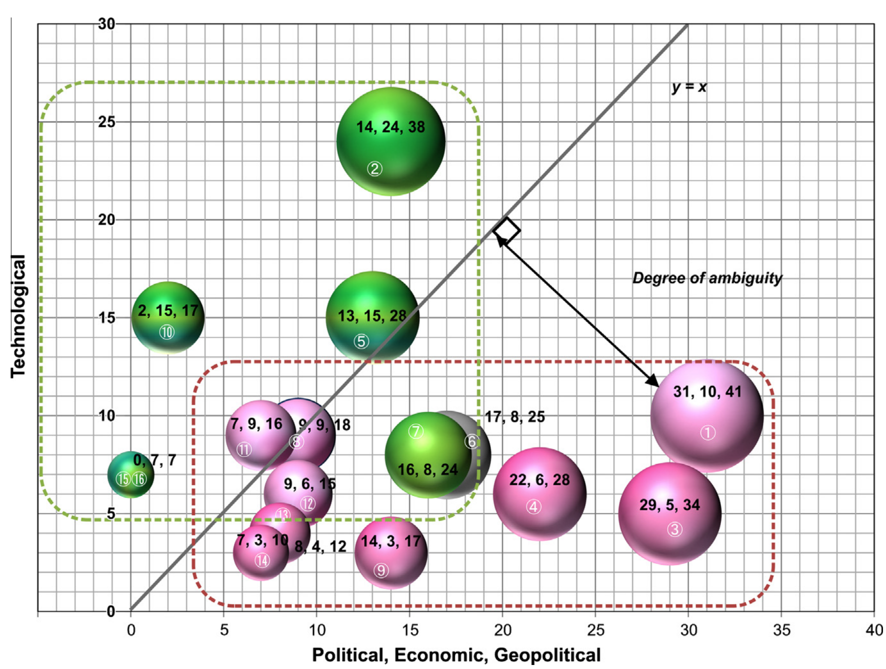

Fig. 3. Clusters ((1) :cluster 1 to (16) :cluster 16) classified according to political and technological perspectives. Numbers in each plot represent the number of political papers, the number of technological papers, and the number of all papers in each cluster.

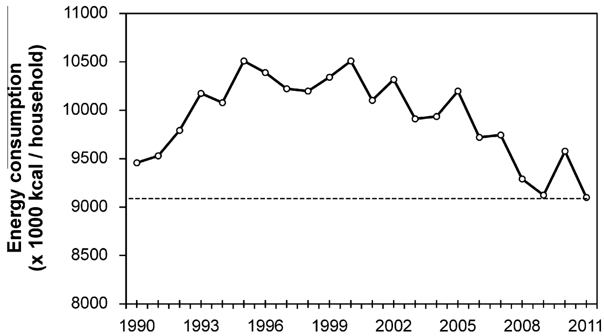

Fig. 4. Energy consumption of the residential sector per household in Japan [71].

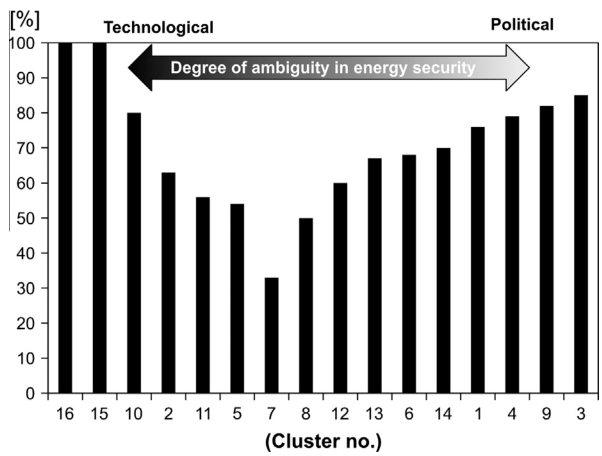

Fig. 5. The degree of ambiguity in energy security.

the policy perspective possesses a certain degree of ambiguity, there is high ambiguity in the technical perspective, which also represents scientific knowledge. Thus, the results of our bibliographic information analysis confirm that scientific knowledge itself with reference to energy security contains ambiguity. In this paper, we only analyzed two dimensions in the clusters—technological and "other" (policy, economic, geopolitical). Further research to investigate the four dimensions of ambiguity—policy, economic, geopolitical, and technological—will open other spaces for energy security discourse. Next, we discuss the limitations of our current understanding along with several points related to enlarging the focus of the discourse.

Emerging research in energy security points to innovation and technological progress that correspond to each layer in the energy supply process. For example, Li et al. argue that the complementary utilization of solar energy and fossil fuels through thermochemistry reactions is energy efficient and could potentially utilize solar energy by using a full-chain assessment of energy performance [66]. Furthermore, Yan et al. suggest that there are five main topics in the discourse on future sustainable energy systems: renewable energy; emission (including greenhouse gas) mitigation, technology, and policy; energy efficiency improvements in buildings, industry, and other sectors; advanced energy technology; and sustainable energy policy and management [67].

Tanaka [68] points out that the Fukushima incident highlighted the need for reforms to Japan's power grid. Because Eastern and Western Japan use different electrical frequencies, for example, utility companies were unable to alleviate electrical shortages and system failures in one region by transmitting power from another. Japan's power grid is not only disconnected from neighboring countries but is not even integrated within the country itself. Yergin [16] points out that there is a "fifth fuel"—*conservation, energy efficiency, energy productivity*—called "energy ingenuity," which involves applying intelligence to consumption. Wangari Maathai [69] notes that *Mottainai* has become a keyword in relation to passing on the earth's beauty to future generations. The Japanese word *Mottainai* denotes the shame of something going to waste without having been used to its fullest potential [70]. This social and cultural perspective, which has been the underpinning for Japan's approach to energy efficiency, was solidified in the Energy Conservation Law of 1979, which was expanded in 1998 with the introduction of the Top Runner program (Fig. 4). Energy consumption per household had been in decline since 2000; however, it increased in 2010 because of the impacts

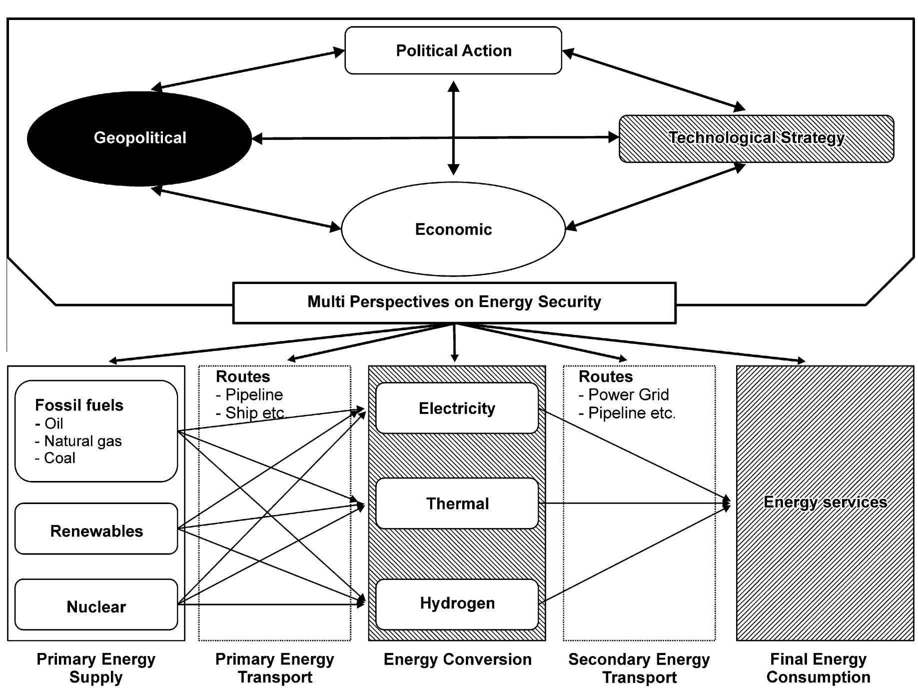

Fig. 6. Multiple perspectives on energy security.

of both a cold spell and a heat wave [71]. The Mottainai spirit was tested during the new energy crisis that resulted from the Fukushima Daiichi nuclear accident in summer 2011. The Japanese people naturally accept the Mottainai spirit as their obligation during such a significant electricity shortfall, so we anticipate that the Mottainai spirit could help achieve lifestyle innovations in future energy societies.

3.2. Integrating energy security research with existing frameworks and missing parts

To help understand the big picture of energy security, we present the energy supply chain as a five-step process based mainly on the IEA Energy Balance methodology:

1. Primary energy supply: The primary energy supply includes the primary stock and the processes used to supply a primary energy resource to its point of conversion into the final energy product.
2. Primary energy transport: Primary energy transport includes transport processes via pipelines, ports, ships, etc.
3. Energy conversion: Energy conversion involves the production of secondary energy wherein primary energy is transformed into more convenient forms of energy. These are used directly in society and can include electrical energy, refined fuels, or synthetic fuels (like hydrogen).
4. Secondary energy transport: Secondary energy transport includes transport processes via power grids and other means. Transportation encompasses transmission and distribution for final energy consumption.
5. Final energy consumption: Final energy consumption includes the total energy consumed by end users (e.g., industrial, transportation, and residential sectors).

Oil-importing nationals, such as Japan, think in terms of securing the energy supply. Japan itself has a low energy self-sufficiency ratio and is at high risk of supply shortage. However, this leads to downplaying the contributions of energy-saving technologies like efficient air conditioning and double-glazed windows, which contribute to energy security as much as alternative energy supplies. Furthermore, studies of energy security have thus far focused mainly on the national level. We suggest, however, that it is

Table 3
Hazard, risk, and uncertainty over energy security research issues.

Hazard identification	Risk analysis		Evaluate the impact under uncertainty	
	Macro	Micro	Size	Time
War [23,38,53]	Geopolitical Political Economic	Economic	Global	Long (year)
Conflict [7,8,21,38,53]	Geopolitical Political Economic	Economic	Bloc	Long (year)
Terrorism [39]	Geopolitical Social	Economic	National	Medium (month)
Normal accident [62]	Environmental Economic	Human health Technological Economic	Local	Short (week)
Severe accident [62]	Environmental Economic	Human health Technological Economic	Global	Long (year)
Natural hazard [62]	Scientific Economic	Technological Economic	National	Medium (month)
Earthquake [62]	Scientific Economic	Technological Economic	National	Long (year)
Tsunami [62]	Scientific Economic	Technological Economic	National	Long (year)
Flood [25]	Scientific Economic	Technological Economic	National	Medium (month)
Typhoon [25]	Scientific Economic	Technological Economic	National	Medium (month)
Climate change [4,25,45]	Scientific Environmental Economic Political	Technological Economic	Global	Long (year)
Depletion of resources [53]	Scientific Political Economic	Technological Economic	Global	Long (year)
Population growth [21,53]	Political Social Economic	Economic	Global	Long (year)
Deregulation [7,62]	Political Economic	Economic	National	Medium (month)
Market turmoil [7,20,21,54]	Political Economic	Economic	Global	Medium (month)

necessary to view energy security at multiple levels—global, bloc, and national—because if there is a problem with any actor within each energy supply process, affordable and stable energy might not reach the end user. Regarding energy management for business enterprises, Rudberg et al. show that it is possible to generate alternative revenues from the energy system and interact with the surrounding community in a cost-efficient way [72]. They suggest that geographical location influences the possibilities for generating alternative revenues from energy products.

Thus, energy security—a system composed of national policies and international institutions—must be designed to respond in a coordinated way to disruptions, dislocations, and emergencies to maintain stable energy supplies [16].

The IEA suggests that achieving energy security in such a way presents multiple challenges on scales that range from global supply to household access. Moreover, the IEA suggests that national governments should cooperate regionally with the private sector, with financial support from the international community to help boost investment [73]. Many researchers have sought to address and evaluate the risks and uncertainties involved in energy technology options and ascertain the role of future energy systems, including national, bloc, and global.

We presented a five-step process for the energy supply chain with dimensions of ambiguity (Fig. 5 and Fig. 6). This further breakdown of information will complement and help to further comprehend the overview of energy security that emerges from using bibliometrics and reviewing research articles. Energy security should be considered in terms of the entire energy supply process, from the primary energy supply to the final consumption. Perspectives on energy security differ depending on the stage of the energy supply process that is considered. Risks and uncertainties, therefore, must include the natural, political, technological, economic, and geopolitical risks and uncertainties that correspond to each layer in the energy supply process. Thus, actions taken for energy security must indicate how to protect energy security to lessen risks based on existing research collected for each layer in the energy supply process.

The energy supply process refers to the entire process by which energy actors acquire primary energy from external suppliers to meet import demands through trade and transportation. In oil-importing countries, policy discourse on energy security concentrates on security in the primary energy supply. However, as our analysis clearly shows, energy security perspectives represent different layers within different energy supply chains. The dependence on energy systems, and their growing complexity and reach, underlines the need to understand risk and uncertainty in assessing energy security. Energy trade traverses national borders, and energy security is not merely about countering a wide range of hazards; it also includes interactions between nations and how energy affects national security. Yergin, for instance, argues that energy security will increasingly be of paramount importance and that concerns over energy security are not limited to oil; thus, the current model of energy security must be expanded to include protecting the entire energy supply chain and infrastructure [16].

4. Conclusion

Energy security has been an important issue in the creation of energy policies for each nation. In an increasingly global world, however, a diverse energy market is needed to strengthen regional cooperation, such as in the EU. This study was a first attempt, by means of citation network analysis, to show that global trends in energy research have shifted from a basic understanding of self-sufficiency to internationally coordinated energy network infrastructures. The results revealed the degree of ambiguity in energy security (Fig. 5) and multiple perspectives on energy security (Table 2). Energy security is defined as a state of having multiple perspectives on geopolitical, economic, political, and technological factors (Fig. 6). In addition, our analysis showed that bibliometric tools are useful for revealing the ambiguities in research outcomes. A sustainable energy system for energy security must ensure adequate supplies and infrastructure and should be stable and durable in the long term under uncertain conditions. Thus, a sustainable energy system requires two important properties—robustness and resilience—so that, as discussed above, when hazards became real events, the impact of shock and/or stress on energy security can be minimized. A robust energy supply system has multifaceted protective mechanisms, including operable assets, reliable infrastructures, available energy sources in stock, flexible trade routes, and transportation. A resilient energy supply system provides replacements and substations that offer a buffer and a margin against shock and stress by facilitating flexibility, interchangeable assets and infrastructure, exchangeable energy sources in stock, flexible trade routes, and transportation.

Our multilayered analysis of the energy supply process revealed that a diversification strategy is very important for ensuring energy security over the entire supply process. This process needs to be addressed, from initial production down to the consumer where a fifth "fuel" may be found: the potential for lifestyle innovation for the future well-being of our energy society. We hope the information provided here will help with the development of countermeasures, open up public discussion, and promote a shared awareness of energy risk management and uncertainty.

Acknowledgments

This work was supported by KAKENHI through a Grant-in-Aid for Scientific Research B, No. 24310109 and Grant-in-Aid for Research Activity Start-up No. 24860026. The lead author would like to express cordial gratitude to her dear grandmother; Michie Kiriyama aged 91, who passed away on 21 November 2013. This research would not have been possible without her selfless love and moral support.

References

[1] National Policy Unit. Options for energy and the environment: the energy and environment council decision on June 29, 2012; 2012. Available from <http://www.npu.go.jp/policy/policy09/pdf/20120720/20120720_en.pdf> (accessed 28.04.13).
[2] Kiriyama E, Kajikawa Y, Fujita K, Iwata S. A lead for transvaluation of global nuclear energy research and funded projects in Japan. Appl Energy 2013;109:145–53.
[3] Cherp A, Jewell J. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. Curr Opin Environ Sustainability 2011;3:202–12.
[4] Sovacool BK, Brown MA. Competing dimensions of energy security: an international perspective. Annu Rev Environ Resour 2010;35:77–108.
[5] Jansen JC, Seebregts AJ. Long-term energy services security: what is it and how can it be measured and valued? Energy Policy 2010;38:1654–64.
[6] Eunju J, Wonjoon K, Soon HC. The analysis of security cost for different energy sources. Appl Energy 2009;86:1894–901.
[7] Zhang HY, Ji O, Fan Y. An evaluation framework for oil import security based on the supply chain with a case study focused on China. Energy Econ 2012;38:87–95.
[8] Sahira MH, Qureshi AH. Specific concerns of Pakistan in the context of energy security issues and geopolitics of the region. Energy Policy 2007;35:2031–7.
[9] Kostoff RN, Tshiteya R, Pfeil KM, Humenik JA. Electrochemical power text mining using bibliometrics and database tomography. J Power Sources 2002;110:163–76.
[10] Kostoff RN, Tshiteya R, Pfeil KM, Humenik JA, Karypis G. Power source roadmaps using bibliometrics and database tomography. Energy 2005;30:709–30.
[11] Konur O. The scientometric evaluation of the research on the algae and bio-energy. Appl Energy 2011;88:3532–40.
[12] Liping D. Analysis of the relationship between international cooperation and scientific publications in energy R&D in China. Appl Energy 2011;88:4229–38.

[13] Shibata N, Kajikawa Y, Takeda Y, Matsushima K. Comparative study on methods of detecting research fronts using different types of citation. J Am Soc Inf Sci Technol 2009;60:571–80.
[14] Newman MEJ. Fast algorithm for detecting community structure in networks. Phys Rev E 2004;69:66–133.
[15] Adai AT, Date SV, Wieland S, Marcotte EM. LGL: creating a map of protein function with an algorithm for visualizing very large biological networks. J Mol Biol 2004;340:179–90.
[16] Yergin D. The quest: energy, security, and the remaking of the modern world. New York: Penguin; 2011.
[17] Yergin D. Ensuring energy security. Foreign Aff 2006;85:69–82.
[18] Jansen JC, Seebregts A. Long-term energy services security: what is it and how can it be measured and valued? Energy Policy 2010;38:1654–64.
[19] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: a synthesized approach. Energy 2011;36:5343–55.
[20] Demirbas A. Importance of biodiesel as transportation fuel. Energy Policy 2007;35:4661–70.
[21] Hammond GP, Kallu S, McManus MC. Development of biofuels for the UK automotive market. Appl Energy 2008;85:506–15.
[22] Zhou A, Thomson E. The development of biofuels in Asia. Appl Energy 2009;86:S11–20.
[23] Vivoda V. Diversification of oil import sources and energy security: a key strategy or an elusive objective? Energy Policy 2009;37:4615–23.
[24] Hippel D, Savage T, Hayes P. Introduction to the Asian energy security project: project organization and methodologies. Energy Policy 2011;39:6712–8.
[25] Wu G, Wei YM, Fan Y, Liu LC. An empirical analysis of the risk of crude oil imports in China using improved portfolio approach. Energy Policy 2007;35:4190–9.
[26] Bambawale MJ, Sovacool BK. China's energy security: the perspective of energy users. Appl Energy 2011;88:1949–56.
[27] Bilgin M. Geopolitics of European natural gas demand: supplies from Russia, Caspian and the Middle East. Energy Policy 2009;37:4482–92.
[28] Correlje A, Linde C. Energy supply security and geopolitics: a European perspective. Energy Policy 2006;34:532–43.
[29] Turton H, Barreto L. Long-term security of energy supply and climate change. Energy Policy 2006;34:2232–50.
[30] Brown SPA, Huntington HG. Energy security and climate change protection: complementarity or tradeoff? Energy Policy 2008;36:3510–3.
[31] Cai YP, Huang GH, Yang ZF, Tan Q. Identification of optimal strategies for energy management systems planning under multiple uncertainties. Appl Energy 2009;86:480–95.
[32] Brathwaite J, Horst S, Iacobucci J. Maximizing efficiency in the transition to a coal-based economy. Energy Policy 2010;38:6084–91.
[33] Stern RJ. United States cost of military force projection in the Persian Gulf, 1976–2007. Energy Policy 2010;38:2816–25.
[34] Frondel M, Ritter N, Schmidt CM, Vance C. Economic impacts from the promotion of renewable energy technologies: the German experience. Energy Policy 2010;38:4048–56.
[35] Koh LP, Ghazoul J. Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities. Biol Conserv 2008;141:2450–60.
[36] Phalan B. The social and environmental impacts of biofuels in Asia: an overview. Appl Energy 2009;86:S21–29.
[37] Singh A, Olsen SI. A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. Appl Energy 2011;88:3548–55.
[38] Goldthau A, Witte J. Back to the future or forward to the past? Strengthening markets and rules for effective global energy governance. Int Aff 2009;85:373–90.
[39] Nagy K. The additional benefits of setting up an energy security centre. Energy 2009;34:1715–20.
[40] Florini A, Sovacool BK. Bridging the gaps in global energy governance. Glob Gov 2011;17:57–74.
[41] European Commission. 2012. Connecting Europe: the energy infrastructure for tomorrow. Available from <http://ec.europa.eu/energy/mff/facility/doc/2012/connecting-europe.pdf> (accessed 28.04.13).
[42] Patt A, Komendantova N, Battaglini A, Lilliestam J. Regional integration to support full renewable power deployment for Europe by 2050. Environ Polit 2011;20:727–42.
[43] Toft P, Duero A, Bieliauskas B. Terrorist targeting and energy security. Energy Policy 2010;38:4411–21.
[44] Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade—will Desertec make Europe vulnerable to the "energy weapon"? Energy Policy 2011;39:3380–91.
[45] Karp A, Shield I. Bioenergy from plants and the sustainable yield challenge. New Phytol 2008;179:15–32.
[46] Demirbas A. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energy Convers Manage 2008;49:2106–16.
[47] Wilkinson P, Smith KR, Joffe M, Haines A. A global perspective on energy: health effects and injustices. Lancet 2007;370:965–78.
[48] Chen W, Wu Z, He J, Gao P, XuChen S. Carbon emission control strategies for China: a comparative study with partial and general equilibrium versions of the China MARKAL model. Energy 2007;32:59–72.
[49] Anandarajah G, Strachan N. Interactions and implications of renewable and climate change policy on UK energy scenarios. Energy Policy 2010;38:6724–35.
[50] Mallah S, Bansal NK. Nuclear and clean coal technology options for sustainable development in India. Energy 2010;35:3031–9.
[51] Bohi DR, Toman MA. Energy security: externalities and policies. Energy Policy 1993;21:1093–109.
[52] Valentine SV. Emerging symbiosis: renewable energy and energy security. Renew Sustain Energy Rev 2011;15:4572–8.
[53] Chester L. Conceptualising energy security and making explicit its polysemic nature. Energy Policy 2010;38:887–95.
[54] Leung GCK. China's energy security: perception and reality. Energy Policy 2011;39:1330–7.
[55] Leung GCK. China's oil use, 1990–2008. Energy Policy 2010;38:932–44.
[56] Li R, Leung GCK. The integration of China into the world crude oil market since 1998. Energy Policy 2011;39:5159–66.
[57] Salameh MG. Quest for Middle East oil: the US versus the Asia-Pacific region. Energy Policy 2003;31:1085–91.
[58] Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. Appl Energy 2009;86:1894–901.
[59] Thomas CE. Fuel cell and battery electric vehicles compared. Int J Hydrogen Energy 2009;34:6005–20.
[60] Thomas CE. Transportation options in a carbon-constrained world: hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles. Int J Hydrogen Energy 2009;34:9279–96.
[61] Zhang YHP. Simpler is better: high-yield and potential low-cost biofuels production through cell-free synthetic pathway biotransformation (SyPaB). ACS Catal 2011;1:998–1009.
[62] Dunn S. Hydrogen futures: toward a sustainable energy system. Int J Hydrogen Energy 2002;27:235–64.
[63] Adhikari S, Fernando S. Hydrogen membrane separation techniques. Ind Eng Chem Res 2006;45:875–81.
[64] Conte M, Prosini PP, Passerini S. Overview of energy/hydrogen storage: state-of-the-art of the technologies and prospects for nanomaterials. Mater Sci Eng 2004;B108:2–8.
[65] Leach M, Scoones I, Stirling A. Dynamic sustainability: technology, environment, social justice. London: Earthscan; 2010.
[66] Sheng L, Jun S, Hongguang J, Jianjiao Z. Full chain energy performance for a combined cooling, heating and power system running with methanol and solar energy. Appl Energy 2013;112:673–81.
[67] Yan J, Chou SK, Desideri U, Tu ST, Jin HG. Research, development and innovations for sustainable future energy systems. Appl Energy 2013;112:393–5.
[68] Tanaka N. Asia's tangled power lines: ensure energy security by building a smarter grid; 2012. Available from <http://www.foreignaffairs.com/article/137806/nobuo-tanaka/asias-tangled-power-lines> (accessed 28.04.13).
[69] Mottainai. MOTTAINAI campaign was set into motion by Prof. Wangari Maathai. 2012. Available from <http://mottainai.info/english/> (accessed 28.04.13).
[70] Ministry of the Environment (MOE). Minister Koike created the "Mottainai Furoshiki" as a symbol of Japanese culture to reduce waste. 2006. Available from <http://www.env.go.jp/en/focus/060403.html> (accessed 28.04.13).
[71] METI. Energy demand and supply 2010; 2013. Available from <http://www.enecho.meti.go.jp/info/statistics/jukyu/resource/pdf/130412_honbun.pdf> (accessed 28.04.13; in Japanese only).
[72] Rudberg M, Waldemarsson M, Lidestam H. Strategic perspectives on energy management: a case study in the process industry. Appl Energy 2013;104:487–96.
[73] IEA. Better policies for development: recommendations for policy coherence. OECD Publishing, online; 2011. Available from <http://www.oecd.org/pcd/48110465.pdf> (accessed 28.04.13).