Energy Strategy Reviews 29 (2020) 100491

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Quantitative evaluation of security of nuclear energy supply: United States as a case study

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ARTICLE INFO

Keywords:
Fukushima nuclear accident
Nuclear power
Energy security
Principal component analysis
Security of supply

ABSTRACT

Nuclear energy utilization became an emerging issue in the global energy security agenda after the Fukushima nuclear accident. Thus, it is crucial to develop a multifaceted measure to assess the performance of security of nuclear energy supply and to aid policy decisions relevant to nuclear energy utilization. For this purpose, quantitative evaluation method for security of nuclear energy supply has been investigated. Indicators which are associated with security of nuclear energy supply are identified by taking the nuclear-specific characteristics including 3S (safeguard, safety and security) and public opinion into account. The methodology for quantitative analysis of security of nuclear energy supply is developed based on the dedicated six indicators by employing the different weighting and aggregation approaches. Finally, composite indices for security of nuclear energy supply are assessed in United States as a case study during the period between 2000 and 2012. It was found that the nuclear energy supply security in U.S. has improved during this target period, and the specific externality which potentially affects nuclear energy supply security could be identified using the proposed method.

1. Introduction

In last several decades, a crucial change of energy landscape has alarming raised a concern on global energy security. Numerous studies on conceptual framework and quantitative analysis of energy security have been hitherto published. As energy security is a multi-dimensional concept, and due to its ambiguity, the use of energy security indicators to evaluate energy security performance has been a growing trend [1]. Most of those energy security studies could be divided into two categories, e.g. the insecurity of specific energy supply [2–8] and the energy security in general [9–15].

For energy security analysis, evaluation of security of specific fuel sources was the general starting point of the analysis. In the studies on insecurity of specific energy supply, discussions on fossil fuels are mostly dominant as fossil fuels may potentially be the cause of supply disruption due to oil price volatility, political instability of supply countries and negative contribution to the reduction strategy of carbon dioxide emission. Such generic approach towards energy security analysis is essentially based on the discussion of insecurity of specific energy supply, where the insecurity of a specific fuel is often expressed using specific indicators in energy security analysis. As the analysis of energy security basically starts from the discussion on fossil fuels, it should be noted that the common approach of energy security analysis is mainly based on the comparison between fossil fuel and its substitution, especially renewable energy, so that the share of renewable power is often used as an important indicator [10,11,13,15].

Notwithstanding the fact that the confrontation structure between fossil fuels and renewable energy has been mostly discussed in the existing researches, the risk or vulnerability of nuclear energy utilization in the stable electricity supply should be considered as an important pillar in the analysis on generic energy security. This importance is well proven after the Great East Japan Earthquake occurred on March 11, 2011, where the earthquake caused a significant impact on economic and social situation of Japan. In terms of energy supply security, Japan's energy infrastructure was severely affected especially in northern and eastern mainland. The Fukushima Daiichi Nuclear power plant accident (hereafter referred to as "Fukushima nuclear accident") triggered by the Tsunami has not only caused a significant impact to environment, but also severely impacted the electricity supply in Japan; all nuclear power plants in Japan, which had previously contributed approximately 30% of the electricity supply, were shut down for re-evaluation of safety aspects and led to a nationwide energy shortage. This situation was even

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https://doi.org/10.1016/j.esr.2020.100491
Received 29 April 2017; Received in revised form 19 December 2019; Accepted 8 May 2020
Available online 15 May 2020

felt globally, pushing the issue of nuclear energy at the top of the global energy security agenda. The impact of Fukushima nuclear accident to the energy supply/demand situation of Japan implies that new issues should be considered for energy security, especially the risk of sudden supply interruption caused by domestic causes and the social impact resulting from a decreased support of a major energy source [16,17].

Based on the present energy landscape after Fukushima nuclear accident, it is now evident that the role of nuclear energy in energy security should be more thoroughly considered in order to develop a comprehensive framework of energy security in general. However, the security of nuclear energy supply has hitherto not been fully analyzed. Several studies on the energy security of Japan post-Fukushima were published, mainly focusing on the overall impact of the Fukushima nuclear accident to Japan's energy supply and demand balance [18,19]. However, these studies do not clearly identify the inherent characteristics of security of nuclear energy supply itself. Several studies have included the share of nuclear energy as an effective measure of CO_2 emission reduction in energy security analysis [11,15], but other natures of nuclear energy have not been explicitly accounted for.

Today, nuclear energy policy shows significant difference among the countries, depending on the energy supply and demand status as well as social situation of the country. Even though the Fukushima nuclear accident affected the energy policy of several countries to cease the operation of nuclear power [20], there are countries which have announced to maintain the operation or introduce new nuclear power capacities. As energy security is a driving force of energy policy [1], it is thus crucial to develop a multifaceted measure to assess the performance of security of nuclear energy supply and to aid policy decisions relevant to nuclear energy utilization.

The objective of this paper is to propose a methodology for quantitative analysis of security of nuclear energy supply to meet the needs described above. Based on a set of dedicated indicators, a composite security of nuclear energy supply index is evaluated using different two weighting scenarios. The security of nuclear energy supply of United States is analyzed as a case study.

This study is structured as follows. Review of related literatures on energy security for selecting indicators is given in Section 2. Methodology for the analysis on security of nuclear energy supply is described in Section 3. Using United States as a reference case, a composite index based on the established indicators for the analysis on security of nuclear energy supply is evaluated and discussed in Section 4. Finally, conclusions are summarized in Section 5.

2. Selection of indicators for evaluating security of nuclear energy supply

While several researchers have stated that security of energy supply is not clearly defined [21], it is commonly recognized that the concept of energy security is strongly associated with risk [22], and that the security of energy supply can be achieved by realizing low risk in vital energy utilization system [23]. It can be also said that the risk itself could be considered as a property of energy utilization system [24]. Given the importance of security for the achievement of the uninterrupted system, in this study the security of nuclear energy supply is defined as the interrupted operation of nuclear energy utilization system with low risk.

Fig. 1 shows the several elements of energy which are highly associated with nuclear energy utilization. Economy, population, and energy supply and demand are the basic elements of nuclear-related issues. Rapid economic growth and expansion of population in developing countries drive nuclear energy utilization as an inevitable strategic option [25]. International Energy Agency has reported that the global total energy demand in 2004 will be increased by 53% in 2030 [26], and based on these three aspects in nuclear energy utilization, recent IAEA report forecasts the global nuclear power plant capacity will increase by approximately 100–768 GW in 2050 [27].

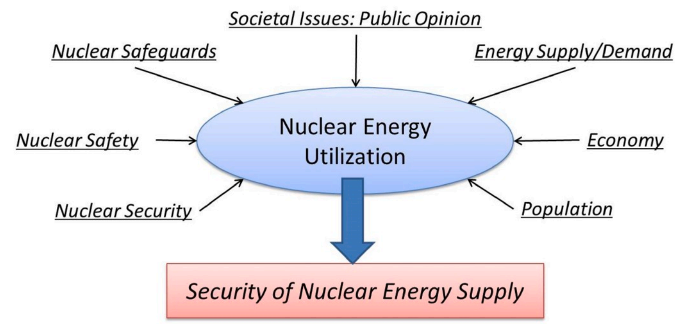

Fig. 1. Security of nuclear energy supply.

Societal issues such as public opinion are also strongly accompanied with nuclear energy utilization. Kim et al. [28] analyzed the change of public acceptance for nuclear energy after Fukushima nuclear accident in 42 countries, and showed that the accident has significantly lowered the public acceptance of nuclear energy. This observation implies that a single event can easily affect the public sense on nuclear energy, causing negative impressions towards nuclear energy utilization.

International governance on the three aspects of nuclear utilization: safety, safeguards and security (hereinafter referred as "3S"), is required in the process of nuclear energy utilization as a specific factor [29,30]. Safeguard is a set of technical measures for verifying countries "are honoring their international legal obligations to use nuclear material and technology only for peaceful purposes", which is a framework crucial to ensure the nuclear non-proliferation [31]. Nuclear safety is defined as "the achievement of proper operating conditions, preventions of accidents or mitigation of accident consequence, resulting in protection of workers, the public and the environment from undue radiation hazards", while nuclear security is defined as "the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities" [32]. The 3S thus deals with potential risks that the nuclear energy contains. Through the international nuclear governance, technical knowledge and commodity distribution in terms of nuclear energy are limited. Various processes in nuclear energy, especially those in uranium conversion, enrichment and fuel fabrication as well as reactor operation and management requires a highly specialized technology, which may be considered as confidential due to the concern on nuclear proliferation and security [33,34]. The resource (e.g. uranium and plutonium), relevant materials and equipment for construction and operation of nuclear energy system are also under strict trade control, which also is a notable characteristic of nuclear energy. Those situations often add restriction on the distribution of relevant technology, information and commodity, which likely causes mutual reliance between countries aiming to use nuclear energy.

Based on the above considerations, the selection of indicators is required to evaluate how nuclear energy supply is secured in a specific country or region. The critical point to be considered in this step is the fact that there is no rigid consensus on the validity of index configuration; different indicators have been used in studies on both the insecurity of specific energy supply and the energy security in general. The observer's viewpoint somewhat affects the energy security analysis, which needs the appropriate explanation of how indicators are selected. For analyzing the security of nuclear energy supply, it can be mentioned that two different elements should be included as attributes: e.g. common indicators which are widely utilized in the analysis on insecurity of fossil fuel supply, and specific indicators to express the particularities and characteristics of nuclear energy which may potentially lead to supply disruption.

In order to justify the selection of indicators, we have firstly identified five common indicators of energy security based on the literature review as summarized in Table 1. Main common indicators identified and selected are as follows; energy share, energy intensity, energy use per capita, resource diversification and independence. These indicators are selected due to their strong relation to electricity supply, economic level and population level, and thus are considered to be essential for quantifying the impact of the energy supply disruption on the society.

As for the nuclear-specific indicator, public opinion against nuclear energy has been selected, and the five common indicators were modified in terms of nuclear energy utilization as summarized in Table 2. Amongst these indicators, public opinion, nuclear diversification and independence are described in detail as follows.

The concept of diversification and independence are often utilized as the main indicators in many literatures which focus on fuel procurement from supply countries. On the other hand, nuclear fuel supply chain is a complicated combination of various engineering processes so that it is very likely that multiple countries have to mutually rely on each other on the various stages of nuclear fuel cycle; fuel mining and milling, technology of fuel conversion, enrichment, fabrication and also waste management. Amongst these stages of nuclear fuel cycle, the most crucial stage is enrichment, where the relevant technical information is considered as highly confidential and thus the present capability of uranium enrichment is distributed worldwide under strict international control. Therefore, nuclear diversification and independence should cover the technological limitation; the degree of technology distribution amongst relevant countries and the capability of domestic production of enriched uranium and nuclear fuel.

Public opinion could be referred in the discussion of nuclear utilization. Asia Pacific Energy Research Center (APERC) proposed well-known indexes of security of supply called the four A's [35]. They pointed out as an important factor for energy continuous supply "Acceptability" – or elements relating to environment and social issues [36]. Germany's anti-nuclear energy movement would be an example of the most enduring and successful mass movements, which greatly influenced the government's decision on nuclear shut down [37].

3. Methodology

Table 2 shows the definition and equation of each indicator of security of nuclear energy supply. It should be noted that the risks of unexpected interruption of uranium fuel shipping due to, for example, terrorist attacks [38], shall be also considered to evaluate the degree of diversification. Geopolitical factor is assigned to each foreign supply origin in terms of the potential risk of disruption, using two of the dimensions of governance by the Worldwide Governance Indicators which are particularly related to security of supply [6]; 'Political Stability and Absence of Violence' and 'Regulatory Quality'. The formulation of diversification adopts the Herfindahl-Hirshman Index (HHI), where the square of the market shares of the supply origins are weighted according to the assumed geopolitical risk [2–4,6,7]. Here, low value of each indicator corresponds to less vulnerable security of nuclear energy supply.

Table 1
Common indicators of energy security adopted in recent literatures.

Indicator	Literatures referred
Energy share	Gupta, 2008 [3]; Wu, Liu, Han, & Wei, 2012 [13]; Sovacool, 2013 [14]; Sharifuddin, 2014 [8]; Yao & Chang, 2014 [15]
Energy intensity	Gnansounou, 2008 [2]; Gupta, 2008 [3]; Cabalu, 2010 [5]; Sovacool & Brown, 2010 [9]; Institute for 21st Century Energy, 2012 [10]; Martchamadol & Kumar, 2012 [11]; Wu, Liu, Han, & Wei, 2012 [13]; Sovacool, 2013 [14]; Yao & Chang, 2014 [15]
Energy use per capita	Sovacool & Brown, 2010 [9]; Institute for 21st Century Energy, 2012 [10]; Martchamadol & Kumar, 2012 [11]; Wu, Liu, Han, & Wei, 2012 [13]; Sovacool, 2013 [14]
Energy diversification	Gnansounou, 2008 [2]; Gupta, 2008 [3]; Le Coq & Paltseva, 2009 [4]; Cabalu, 2010 [5]; Lefevre, 2010 [6]; Cohen, Joutz & Loungani, 2011 [7]; Martchamadol & Kumar, 2012 [11]; Wu, Liu, Han, & Wei, 2012 [13]
Energy Independence	Cabalu, 2010 [5]; Sovacool & Brown, 2010 [9]; Institute for 21st Century Energy, 2012 [10]; Martchamadol & Kumar, 2012 [11]; Wu, Liu, Han, & Wei, 2012 [13]; Sovacool, 2013 [14]; Yao & Chang, 2014 [15]

Quantification of overall security of nuclear energy supply requires the proposed six individual indicators to be synthesized and aggregated into a composite index. For this, we first normalize all the selected indicators. For each of the six indicators in the form of X_{pi}, a normalized indicator I_{pi} is calculated which is used for a composite index. The scaling technique is applied where the minimum value is set to 0 and the maximum to 1 in the following manner:

$$I_{pi} = \frac{X_{pi} - Min(X_{pi})}{MAX(X_{pi}) - Min(X_{pi})} a \tag{1}$$

where p = 1: nuclear share, 2: nuclear intensity, 3: nuclear use per capita, 4: public opinion, 5: nuclear diversification, 6: independence, and i = a given year.

Subsequently, the normalized indicator is weighted and aggregated to obtain a composite index. Among the various indicator weighting methods [1], we adopt 1) principal component analysis (PCA) and 2) equal weights using I_{pi}. The comparison of different weighting methods is useful to evaluate the impact of each selected indicator [39].

PCA is a multivariate statistical approach that replacements a set of correlated variables into a set of uncorrelated variables [40] and has been adopted in several studies on energy security analysis [3,11]. In this study, we calculate the 6×6 correlation matrix A of the six normalized indicators I_{pi}. When the correlations are significant, de-correlated variables can be calculated. Then eigenvalues λcorresponding to X is obtained in the following equation:

$$|A - \lambda I| = 0 \tag{2}$$

The calculated eigenvalues λ are shown in descending order of magnitude, e.g. as $\lambda_1 > \lambda_2 > \lambda_3 > \lambda_4 > \lambda_5 > \lambda_6$. The eigenvectors corresponding to each value of λ is obtained in the following manner:

$$(A - \lambda_j) E_j = 0 \tag{3}$$

where $E_j = [e_{1j}, e_{2j}, e_{3j}, e_{4j}, e_{5j}, e_{6j}]$ is an eigenvector corresponding to λ_j, and is normalized under the following condition;

$$e_1{}^2 + e_2{}^2 + e_3{}^2 + e_4{}^2 + e_5{}^2 + e_6{}^2 = 1 \tag{4}$$

The six principal components by multiplying normalized indicators I_{pi} with six eigenvectors are obtained in the following manner:

$$P_{1i} = I_{pi}E_1, \quad P_{2i} = I_{pi}E_2, \quad \ldots \quad P_{6i} = I_{pi}E_6 \tag{5}$$

It is important to note that the total variance of v_p ($v_p = variance(I_p)$) is equal to the total variance of $v_j^{'}$ ($v_j^{'} = variance(P_j)$), and that $v_j^{'} / \sum v_j^{'}$ is equal to the proportion of total variance accounted for by P_j. Finally, a composite index is computed as a weighted sum of six principal components (PCs), where weights are the proportions of PCs. This composite index is called as the "nuclear energy supply security index 1" ($NSSI_1$) and is expressed as follows;

$$NSSI_1 = \frac{\sum_{j=1}^{6} v_j^{'} P_{ji}}{\sum_{j=1}^{6} v_j^{'}} \tag{6}$$

The second composite index, the "nuclear energy supply security index 2" ($NSSI_2$), is derived as the root mean square of the six relative indicators using equal weight:

$$NSSI_2 = \sqrt{\frac{\sum_{p=1}^{6} (I_{ip})^2}{6}} \tag{7}$$

These two indices, $NSSI_1$ and $NSSI_2$, provide a composite quantitative measure of security of nuclear energy supply by taking into consideration the interactions of the set of indicators. A higher index corresponds to the more vulnerable security of nuclear energy supply.

Table 2
Definition and equation of indicator.

Indicator	Definition	Equation
Nuclear share	The ratio of nuclear energy production to total primary energy supply	$NS_i = C_i / TPES_i$
Nuclear intensity	The ratio of nuclear energy production to GDP	$NI_i = C_i / GDP_i$
Nuclear use per capita	The ratio of nuclear energy production to country's population	$NUPC_i = C_i / Pop_i$
Nuclear diversification	The share of nuclear fuel import with its diversity	$ND_i = \sqrt{\frac{NDUP_i^2 + NDUE_i^2}{2}}$ $NDUP_i = \sum_k h_{ik} p_{ik}^2$ $NDUE_i = \sum_k h_{ik} e_{ik}^2$
Independence	The share of domestic nuclear fuel	$D_i = \sqrt{\frac{(1-UD_i)^2 + (1-TD_i)^2}{2}}$
Public opinion	The percent who somewhat and strongly opposes nuclear energy	PO_i
$\boldsymbol{C_i}$	Nuclear consumption in year i	
$\boldsymbol{NS_i}$	Nuclear share in year i	
$\boldsymbol{TPES_i}$	Total primary energy supply in year i	
$\boldsymbol{NI_i}$	Nuclear intensity in year i	
$\boldsymbol{GDP_i}$	PPP GDP in year i	
$\boldsymbol{NUPC_i}$	Nuclear use per capita in year i	
$\boldsymbol{Pop_i}$	Population in year i	
$\boldsymbol{ND_i}$	Nuclear diversification in year i	
$\boldsymbol{NDUP_i}$	Uranium purchased diversification in year i	
$\boldsymbol{NDUE_i}$	Uranium enriched diversification in year i	
$\boldsymbol{h_{ik}}$	The political risk of country k in year i	
$\boldsymbol{p_{ik}}$	The share of country k in the purchased uranium in year i	
$\boldsymbol{e_{ik}}$	The share of country k in the enriched uranium in year i	
$\boldsymbol{D_i}$	Independence in year i	
$\boldsymbol{UD_i}$	The share of domestic purchased uranium in year i: uranium dependency	
$\boldsymbol{TD_i}$	The share of domestic enriched uranium in year i: technology dependency	
$\boldsymbol{PO_i}$	Percent fraction of negative opinion towards nuclear energy in year i	

The appropriateness of the weighting method such as PCA could be evaluated by the comparison with the simple method such as equal weight.

4. Case study: United States

Security of nuclear energy supply in the United States of America (U. S.) is assessed as a case study. This is not only because U.S. is the world's largest producer on nuclear power which potentially has big impact on global nuclear energy utilization [41], but also the detailed data relevant to nuclear energy utilization is accessible and available. In this study, data on GDP per capita at exchange rate and population has been taken from the World Bank, 'International Comparison Program database' for U.S [42]. TPES, data on purchased and enrichment share, and nuclear production has been taken from U.S. Energy Information Administration, 'International Energy Statics' [43] and '2014 Uranium Marketing Annual Report' [44], and IEA Sankey diagram [45] respectively. The value for public opinion has been taken from Nuclear Energy Institute 'perspective on public opinion' [46].

A brief summary of nuclear-related policy in U.S. is presented below.

Several energy and nuclear policies have been established in U.S. in the beginning of 21st century. In the National Energy Policy in 2001, concrete strategies for the development of nuclear power generation were proposed, including the promotion of update of nuclear power plant operation certificate and the acceleration of licensing procedure for newly established power plants [47]. The Nuclear Power 2010 Program of 2002 aimed to demonstrate licensing process based on the new regulation and to develop the next generation reactor technology in order to initiate the construction of newly established nuclear power plants [48]. The Energy Policy Act of 2005 [49] earmarked the significant increase in government financial support for nuclear industry [50]. Nuclear policy under the Obama Administration basically followed the existing policy under the previous administration. $50 billion in Loan guarantee in FY2011 were earmarked for the construction of nuclear power plants [51]. Meanwhile, the Nuclear Power 2010 Program was terminated, and expenditure of research and development for advanced reactors were reduced. The financial support for the construction of nuclear power plant throughout the decade arose from the anticipated continuous retirement and decommissioning of existing nuclear reactors. In response to the continuous decommissioning, several projects for the installation of nuclear power plants have been launched, including Unit 2 of Watts Bar Nuclear Generating Station (1165 MW: operation initiated in 2016), Blue Castle Project (3000 MW: expected start in 2028 and 2030), Vogtle 3 and Vogtle 4 (1250 MW: under construction).

The actions towards 3S-related issues have been also conducted. U.S. activated the contract with Russian Federation based on the Highly-Enriched Uranium Purchase Agreement in 1999 [52]. National Nuclear Security Administration (NNSA) was established and the new Secretary for Nuclear Security was in charge of managing U.S. defense complex in 1999. Subsequently, U.S. reached an agreement with Russia Federation to dispose of weapons grade plutonium. In 2002, nuclear non-proliferation agreements with Kazakhstan and Uzbekistan were signed to provide the safe and secure storage of nuclear materials [53]. In addition, another nuclear non-proliferation agreement with China was also achieved in 2003 to exchange nuclear technology. In the same year, NNSA disassembled the last nuclear artillery shell to reduce the risk of nuclear weapon creation [54]. In 2010, U.S. implemented the agreement with United Arab Emirates on nuclear energy and non-proliferation. In the same year, a Memorandum of Cooperation with Japan on nuclear safeguards was signed. Finally, in 2012, U.S. and European Atomic Energy Community reinforced the agreement on nuclear material safeguards and security research and development including border monitoring, nuclear forensics, physical protection [55].

5. Results and discussion

Based on the data and the assessment methodology, each of six indicators is first normalized between 2000 and 2012. The result is shown in Fig. 2. Nuclear share in U.S. gradually increased up to 2009 due to the drop of TPES in 2009, while both of nuclear intensity and nuclear use per capita has gradually deceased. Nuclear diversification has three peaks in 2002, 2005, and 2007. This could be attributed to the following two observations; 1) the uranium imported from Canada covered the substantial share in 2002 and 2005, and 2) Russia was a main contributor to less diversified composite country share in 2007. After 2007, nuclear diversification was gradually improved, since the share of uranium purchased in Kazakhstan has increased since 2007 and thus contributed to increased diversification. Nuclear independence has remained the vulnerable status after 2001, since the share of domestic purchased uranium has decreased. Public opinion has not followed the consistent trend throughout this duration, although it is evident that Fukushima nuclear accident in 2011 contributed to a decline of public support for nuclear to some extent.

Then, the composite index for security of nuclear energy supply is derived from the six normalized indicators as mentioned in Section 3. The security of nuclear energy supply calculated using both PCA ($NSSI_1$) and equal weight ($NSSI_2$) is shown in Fig. 3. Although the absolute value of $NSSI_1$ and $NSSI_2$ cannot be compared due to different weighting methods utilized for the calculation, the higher value of index corresponds to the more vulnerable security of nuclear energy supply. Thus, the quantitative transient behavior of security of nuclear energy supply could be observed.

From the result of both $NSSI_1$ and $NSSI_2$, it can be observed that the current security of nuclear energy supply in U.S. has been improved compared to its status in 2000 despite the fluctuation with year. The main contributors to this improvement are the nuclear intensity, nuclear use per capita, nuclear diversification and independence.

Despite the fact that nuclear energy policy has strongly supported nuclear industry in U.S. after 2000 as highlighted in Section 4, there is no new commissioning of nuclear power plant during 2000–2012. In addition, the reduction of nuclear energy production arising from decommissioning of two nuclear power plants during 2000–2012 may be compensated by the improved conversion efficiency in the reactor [56]. From the perspective of the relatively consistent nuclear production during 2000–2012, the increase in population and economy resulted to reduce the risk of high dependence on nuclear energy. In addition, the Nuclear Energy Institute concluded that public has strongly supported for nuclear energy and consistent favorability has been observed even after the Fukushima nuclear accident [57]. Furthermore, the unremitting consultations for international cooperation to improve 3S in last decades, as mentioned in Section 4, might reflect the improvement of diversification – although indirectly - to some extent. These background facts would also support our observation that the current security of nuclear energy supply in U.S. has been improved compared to its status in 2000.

On the other hand, some notable differences of results from the two different calculation methods can be observed in 2001, 2005 and, especially 2009. These differences will be discussed below.

From the methodological viewpoint, the inclusion of variance of each of the six indicators causes the difference of outcome between $NSSI_1$ and $NSSI_2$. The correlation obtained through the PCA calculation will be focused to discuss the impact of indicator on the determination of composite index. Firstly, a scree plot is obtained by plotting the calculated eigenvalues in the descending order, given in Fig. 4. The scree plot can be used to evaluate components which interpret most of variability. There is a pattern commonly observed in the scree plot where a steep declining curve is followed by a bend and a lower plateau. The obtained scree plot shows both λ_1 and λ_2 are considered as the components consisting of a steep curve, followed by λ_3 which contributes to the first bend and to start the lower plateau. The successive components (λ_3, λ_4, λ_5, and λ_6) contains less proportion over total variance compared with λ_1 and λ_2. Therefore, λ_1 and λ_2 are selected for factor loading, where factor loading L_1 and L_2 are computed in a following manner:

$$L_1 = \sqrt{\lambda_1}E_1, \quad L_2 = \sqrt{\lambda_2}E_2 \tag{8}$$

Subsequently, the calculated factor loading is used to obtain the commonality, which corresponds to the extent of correlation of one of the six components with the others. Commonality is computed in the following equation:

$$commonaility = {L_1}^2 + {L_2}^2 \tag{9}$$

The results of factor loading and commonality for each of the six indicators are shown in Table 3. The commonality of nuclear diversification is the maximum among the six indicators, which means nuclear diversification can be considered to contribute most significantly to the determination of $NSSI_1$. Meanwhile the commonality of nuclear share is the minimum among the six indicators., which means that the nuclear share is the lowest impact factor. It can be observed the impact factor on

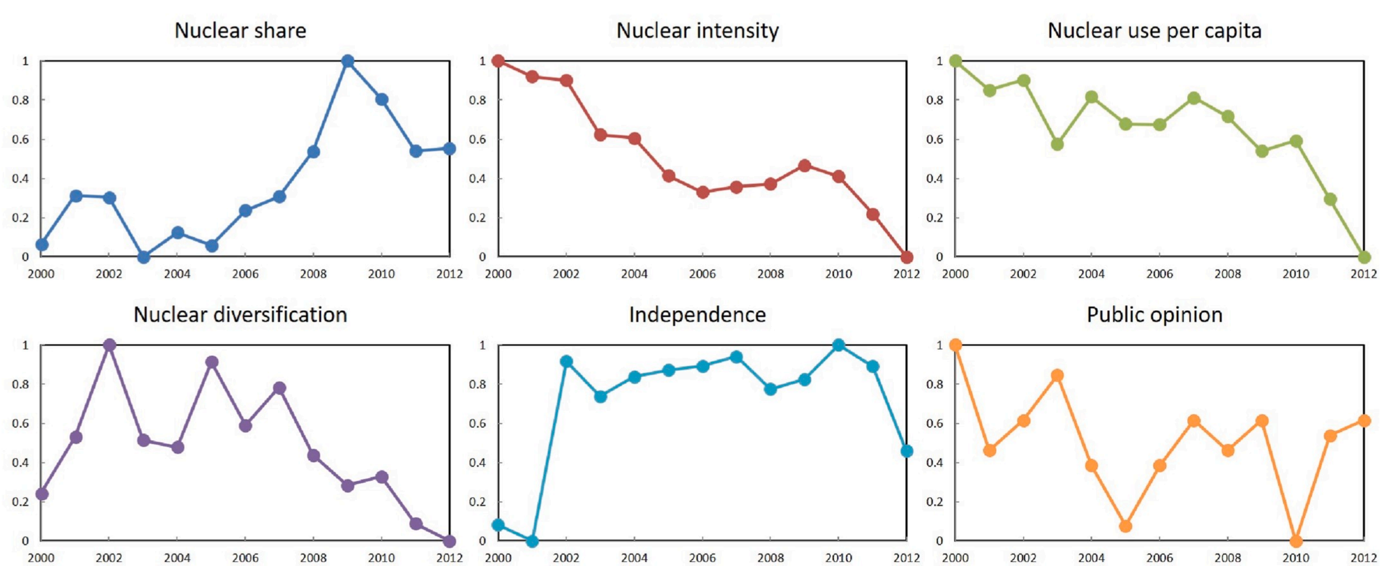

Fig. 2. Results for each normalized indicator.

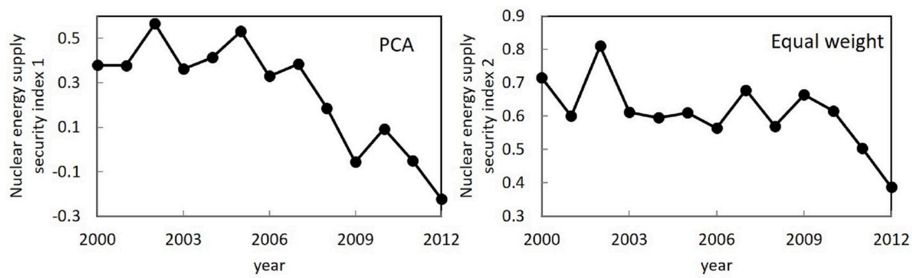

Fig. 3. Results of NSSI1 and NSSI2 between 2000 and 2012.

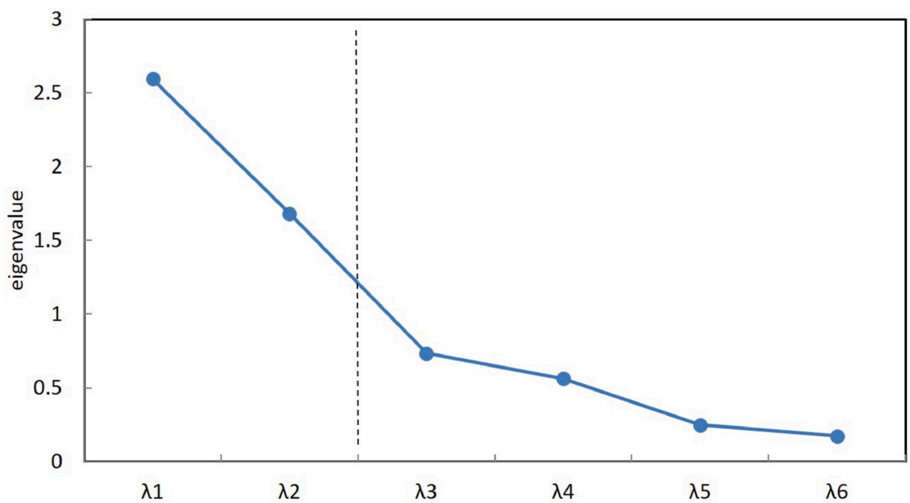

Fig. 4. Scree plot.

Table 3
Factor loading and commonality for each of the six indicators.

Indicator	L_1	L_2	Commonality
Nuclear share	0.69	0.062	0.48
Nuclear intensity	−0.88	0.13	0.79
Nuclear use per capita	−0.86	−0.26	0.80
Nuclear diversification	−0.56	−0.73	0.85
Independence	0.42	−0.75	0.74
Public opinion	−0.36	0.70	0.62

the determination of PCA results increases in the order of nuclear share, public opinion, independence, nuclear intensity, nuclear use per capita, and nuclear diversification.

The time trend of $NSSI_1$ and $NSSI_2$ in 2008–2010 shows a significant difference: e.g. $NSSI_1$ showing downward convex and $NSSI_2$ showing upward convex. Closer look shows that $NSSI_1$ is convex downward around 2009 due to the high-ranked impact factor of both nuclear use per capita and nuclear diversification. On the other hand, the other four indicators contribute to the upward convex trend of $NSSI_2$. It must be noted that TPES and GDP from 2008 to 2009 were significantly declined due to bankruptcy of Lehman Brothers. This causes the increase of both nuclear share and nuclear intensity, which contributed to the upward convex of $NSSI_2$. However, bankruptcy of Lehman Brothers is considered as an externality, which is not directly associated with the security of nuclear energy supply itself. Therefore, $NSSI_2$ could be considered to be significantly influenced by the externality, while $NSSI_1$ can be computed adequately by excluding externalities. It could be said that the comparison of PCA and the equal weighting can highlight the external specific element which affects security of nuclear energy supply.

It should be noted that most of earlier studies on both security of specific energy supply and generic energy security are limited to using a single weighting and aggregation approach. This study could confirm that the use of different weighting and aggregation approach can intrinsically grasp the similarity in the general trend of nuclear energy supply security. This study also illustrated that the specific nature of PCA could aid to identify the hidden factors that may have been overlooked in the conventional single-method approach.

6. Conclusion

A quantitative evaluation method for security of nuclear energy supply has been investigated. We firstly identified six indicators which are associated with security of nuclear energy supply (nuclear share; nuclear intensity; nuclear use per capita; nuclear diversification; independence; public opinion). A methodology for quantitative analysis of security of nuclear energy supply has been developed on the basis of the set of dedicated six indicators. Finally, a composite index for security of nuclear energy supply has been assessed by using PCA and equal weight in United States as a case study.

The proposed approach shall contribute as a starting point to comprehensively understand nuclear energy utilization from energy security perspective. In addition, the present analysis could be expanded to include additional indicators and factors, which were not available at present. These data may include the detailed data on uranium import from certain countries, which is not disclosed at present. In addition, the potential disruption risk of domestic production (such as court dispute on nuclear power plant restart, which is becoming a significant risk to operators in Japan) should also be addressed. The depletion risk of reserve fuel or the fuel mining capacity in a supply country would also lead to the vulnerability of continuous supply. As such, it is highly recommended to develop more comprehensive indicators for nuclear-related issues and to ensure their transparency and availability for further understanding of nuclear energy utilization from energy security perspective.

The analysis about security of nuclear energy supply in this paper uses diachronic approach which aims to monitor the change of the nuclear landscape of a given country. The proposed model will be refined assigning to the different countries. In-depth study on security of nuclear energy supply will be undertaken in order to take into consideration the possibility of expansion of nuclear power utilization in future energy landscape.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Shoki Kosai: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Supervision, Writing - original draft, Writing - review & editing. **Hironobu Unesaki:** Conceptualization, Investigation, Supervision, Validation, Writing - original draft, Writing - review & editing.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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