Transition of energy security performances in Japan: historical and scenario analysis

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Abstract

A secure energy supply is important for Japan, but it is becoming difficult due to increasing energy demand in emerging countries. This study aims to understand how the energy security performances have evolved and will improve in the future in Japan by applying three energy security indicators based on the Shannon–Wiener's diversity. Overall, energy security performances improved until the early 2010s. However, the energy security performances declined after 2011 because of the Fukushima nuclear disaster. In the future, energy security performances will improve under the selected four energy scenarios, compared to the historical levels. Comparing the four scenarios, energy security performances will be higher for the scenarios having balanced primary energy structure including nuclear power. Energy security performances, evaluated by three indictors in this study, are mainly affected by diversity of primary energy sources. In addition, import factors are also important to determine the performances.

Keywords

Energy security performance, energy security indicators, Japan, historical and scenario analysis.

1. Introduction

The self-sufficiency rate of energy (including nuclear and renewable energy) was 6% in 2013 in Japan. The country highly depends on fossil fuels – these accounted for more than 80% of energy supply before the Fukushima Daiichi nuclear disaster and at present account for more than 90%. These fossil fuels are mostly imported and mainly come from the Middle East, which has high geopolitical risks. Because energy demands in emerging countries, such as China and India, are increasing and these countries will secure their energy supply, it will be more difficult for Japan to rely on cheap imported fuels in the near future. Thus, producing its own energy sources and reducing dependence on imported energy are essential.

Nuclear power, which is considered semi-domestic energy, has been one of the energy sources that can reduce dependence on fossil fuels. However, the Fukushima nuclear disaster changed the situation, highlighting the safety issues of using nuclear power. Thus, only three nuclear power plants are in commercial operation (as of November 2016).

As an alternative energy source, renewable energy will be one of the most important elements in securing Japan's national energy supply and solving other environmental issues, such as climate change and air pollution. Although multiple national policies were introduced to diffuse renewable energy after the oil shocks in the 1970s, renewable energy other than hydropower accounted for only a small percentage of total primary energy supply. After the introduction of the Feed-in Tariff (FIT), launched in 2012, the share of renewable energy increased more than the historical trend.

In April 2014, the latest version of the Basic Energy Plan, which was developed after the Fukushima nuclear disaster, was endorsed by the government. The purpose of the plan was to completely revise the energy strategy of Japan, particularly reducing dependency on nuclear power, considering the Fukushima nuclear disaster. The plan prioritizes energy security, but also considers economic efficiency and conservation of the environment, all with a strong focus on safety – so called 3E+S.

In transitioning towards a sustainable society, Japan faces many challenges. The main challenges of energy policies can be summarized as follows. In the Basic Energy Plan, no best energy mix is defined. To establish a sustainable society, the plan indicates that the share of renewable energy should be increased. However, no numerical targets exist for renewable energy. In addition, coal-thermal power is still considered an important baseload power. Furthermore, the position of the government regarding nuclear power is not clear. As mentioned above, the plan indicates that nuclear power is an 'important' baseload power source and, at the same time, that dependency on it should be reduced. The energy structure also closely relates to energy security. Since Japan imports most energy resources, energy costs and a stable energy supply may be at risk if Japan continues to rely on imported fossil fuels.

In July 2015, the Long-term Prospect of Supply and Demand of Energy, which targets year 2030, was released. This prospect was developed based on the aforementioned Basic Energy Plan. According to the prospect, Japan will increase the share of renewable energy to 13-14% of primary energy (22-24% of power generation). In addition, the share of nuclear power will be increased to 10-11% of primary energy (20-22% of power generation). Furthermore, drastic energy saving is expected to reduce energy demand. However, there are still difficulties to resume nuclear power plants and to increase renewable energy to achieve the levels indicated in the prospect.

Many types of research on energy security have been implemented in literature, reviewing different countries and regions, different methods, and different periods. In particular, there is a large number of studies that focus on Asian countries, but few for the case of Japan.

Ren and Sovacool (2015), Wu (2014) and, Yao and Chang (2014) targeted China. Ren and Sovacool (2015) applied an analytic hierarchy process to evaluate energy security with respect to low-carbon energy. Wu (2014) examined China's energy security strategies by focusing on overseas oil investment, strategic petroleum reserves, and unconventional gas development in the 11th and 12th Five-Year Program. Yao and Chang (2014) also used the 4As (availability, affordability, acceptability, and accessibility) approach and evaluated the transition of energy security performance by areas of rhombus made by the 4As in the past (1980-2010). Chuang and Ma (2013) evaluated energy policy in Taiwan using six energy security indicators of four dimensions in the past (1990-2010) and also the future energy policy in terms of energy security using both a modeling approach and the indicators. Shin et al. (2013) analyzed energy security in the Korean gas sector using a model approach (quality function deployment and system dynamics) from the past to the future (1998-2015). Martchamadol and Kumar (2012) evaluated energy security in Thailand from the past to the future (1986-2030). They applied five-dimensional (19 indicators in total) indicators, using statistical data for the historical analysis and a scenario approach for the future analysis. Thangavelu et al. (2015) used an optimization model for exploring a long-term energy mix for society with high energy security and low carbon in the future in Indonesia. Ang et al. (2015a) evaluated historical energy security (1990-2010) in Singapore using 22 indicators of three dimensions. They also conducted scenario analysis for the future (until 2035) based on a business-as-usual projection. Sharifuddin (2014) evaluated energy security in five Southeast Asian countries (Malaysia, Indonesia, Philippines, Thailand, and Vietnam) using 35 indicators representing 13 elements grouped into five aspects of energy security in three periods (2002, 2005, and 2008). Selvakkumaran and Limmeechokchai (2013) evaluated the future energy security (until 2030) with respect to oil security, gas security, and sustainability in three Asian countries (Sri Lanka, Thailand, and Vietnam) using a model approach. Similarly, Matsumoto and Andriosopoulos (2016) used a computable general equilibrium model and an energy security indicator for evaluating the future energy security (until 2050) in three East Asian countries (Japan, China, and Korea) under climate mitigation scenarios. There is also a special issue on Asian energy security from Energy Policy (volume 39 issue 11) in 2011. In the special issue, Takase and Suzuki (2011), using the long-range energy alternatives planning software system, analyzed future energy pathways, which have impact on energy security, in Japan. The authors mainly focus on energy structures in the future under different nuclear power development and greenhouse gas emission abatement.

As shown in the above-mentioned literature, there are many studies on energy security focusing on Asian countries. However, the studies targeting Japan are few, although energy security is an important issue for Japan as mentioned above.

In terms of methodology for evaluating energy security, most studies apply some sort of ‘indicators’ to statistical data or results of model or scenario analysis. However, different definitions, dimensions, or indexes have been used in each study (see for example Ang et al. (2015b) for a comprehensive review of energy security studies), meaning that there are no consistent definitions or evaluation methods for energy security performance. When evaluating energy security performances of countries, the most important factor is the availability of energy as it is included in the indicators in most of the related studies (Ang et al., 2015b). Furthermore, considering that such indicators are used by policymakers to establish energy policy in a country, a simple and comprehensible methodology is preferable. The Shannon–Wiener index is one of the most common and simple indicators in energy security studies and have often been used in the literature (e.g., Jansen et al., 2004; Grubb et al., 2006; Ranjan and Hughes, 2014; Victor et al., 2014).

The purpose of this study is to evaluate energy security performances in Japan from the past to the future, using comprehensive energy security indicators. For the past, statistical data are used, while for the future, energy scenarios are used. Long-term historical analysis is important to understand what contributes for improving energy security. In addition, the scenario analysis for the future can show how energy mix that is considered under energy policy or scenarios in Japan can (or cannot) contribute to improve energy security.

2. Methods

2.1 Energy security indicators

In order to analyze the historical transition of energy security performances and energy security performances in the future, three energy security indicators are used (Jansen et al., 2004; Lehl, 2009). The proposed indicators enable the analysis of energy (supply) security in the past and the future based on historical data or future scenarios. The first indicator (S1, eq. 1) evaluates the diversity of energy sources based on the Shannon-Wiener index, which is an indicator for evaluating primary energy diversity. Diversity is important for maintaining energy security, because the probability of compensating for the loss of a primary energy source by other energy sources will increase, thus preserving energy security. However, concerning the energy security of countries, it is important to consider where the energy sources come from. In general, domestic energy is safe but a procurement risk exists for imported energy. In addition, similar to diversity of energy sources, diversity of the origin of imported energy contributes in improving energy security. The second indicator (S2, eq. 2) considers the import dependence of the country on its energy sources, as well as its energy imports by origin. In this indicator, all of the energy exporters are treated equally. However, energy security will be worse if energy sources are imported from politically and economically unstable countries. Thus, the third indicator (S3, eq. 6) extends the second one by incorporating a country-risk factor associated with the country's energy imports origins. By definition, the values of three indicators will be S1 ≥ S2 ≥ S3, and they are not comparable.

$$S1 = -\sum_{i=1}^{N} p_i \ln(p_i) \tag{1}$$

$$S2 = -\sum_{i=1}^{N} c2_i p_i \ln(p_i) \tag{2}$$

$$c2_i = \left(1 - dm_i \left(1 - \frac{IM2_i^m}{IM2_i^{max}}\right)\right) \tag{3}$$

$$IM2_i^m = -\sum_{j=1}^{M} m_{ij} \ln(m_{ij}) \tag{4}$$

$$IM2_i^{max} = -M \frac{1}{M} \ln\left(\frac{1}{M}\right) \tag{5}$$

$$S3 = -\sum_{i=1}^{N} c3_i p_i \ln(p_i) \tag{6}$$

$$c3_i = \left(1 - dm_i \left(1 - \frac{IM3_i^m}{IM3_i^{max}}\right)\right) \tag{7}$$

$$IM3_i^m = -\sum_{j=1}^{M} A_j m_{ij} \ln(m_{ij}) \tag{8}$$

$$IM3_i^{max} = -M \frac{1}{M} \ln\left(\frac{1}{M}\right) \tag{9}$$

$$A_j = \frac{r_j}{\max_j r_j} \tag{10}$$

where i: the types of primary energy, j: the origin of primary energy imports, p_i: the share of primary energy i, dm_i: the share of imports of primary energy i¸ m_{ij}: the share of imports of primary energy i from country j, r_j: the risk indicator for country j, N: the number of primary energy types, and M: the number of origins of primary energy imports.

2.2 Historical data

To calculate the three indicators for the past (from 1978 to 2014), we obtained the data from the following data sources. First, primary energy production, import, and export in Japan (to calculate the share of primary energy pi and the share of imports of primary energy dmi) are from the Energy Balances of OECD Countries (IEA, 2015b). Since the types of primary energy are broad and in detail in this database, they are aggregated into 10 types of primary energy (i.e., coal, oil, gas, nuclear, hydro, Photovoltaics (PV), wind, geothermal, biomass, and other renewable energy). Primary energy imports by origin (to calculate the share of imports mij) are from the Coal Information (IEA, 2015a), Oil Information (IEA, 2015c), and Natural Gas Information (IEA, 2015d). Finally, the risk indicator is obtained from the World Governance Indicators (World Bank, 2015). Since the original data of the World Governance Indicators range from approximately -2.5 to 2.51, they are normalized to the scale of 0 to 1. The smaller the values, the larger the country risks to secure energy supply.

Among these databases, natural gas imports by origin and risk indicators do not cover the data before 1992 and 1995, respectively. To cover a sufficient time span for the analysis, we complemented the missing data by using the data in the closest existing year (i.e., 1993 and 1996, respectively).

In Japan, total primary energy demand has largely increased from 1960 to the present (Fig. 1). After its peak in early 2000s, the total demand tended to decline. The large increase in the total primary energy demand in 1960s is mainly due to increases in oil demand. However, after the oil shocks in the 1970s, oil demand did not increase, but rather tended to decrease. Until the early 1980s, coal and oil occupied the largest part of primary energy demand, but after that the shares of nuclear and natural gas increased. Hydropower, which is for power generation, was used constantly during the observed periods. The share of other renewable energy sources has increased recently, although these percentages are still small compared to traditional energy sources. After the Fukushima nuclear disaster, the trend has tremendously changed. Because all nuclear power plants were shut down and most of them have not been resumed, the share of nuclear power has been reduced to almost zero. Although total primary energy demand is getting smaller in recent years, such a decline in demand could not compensate for the shut-down of nuclear power plants. This decrease in primary energy supply is compensated for by increases in coal and natural gas. As a result, the share of fossil fuels rose to more than 90%. Although the introduction of renewable energy, particularly PV, has increased after the FIT was implemented in 2012, the share is still very small.

Figure 2 shows how much Japan depends on foreign energy sources. During the observed period, almost 100% of oil was imported. Dependence on imported coal and natural gas was not great from the 1960s to the early-1970s. However, the dependence on imports is rising over time, increasing to almost 100% for these two fossil fuels, similar to oil. These trends show that most of fossil fuels are imported in Japan.

2.3 Scenario analysis

For the scenario analysis for the future, energy scenarios developed by the Institute of Energy Economics, Japan (IEEJ; IEEJ, 2015a, b) are used. These scenarios target the year 2030. As described in Section 1, the Government of Japan released the Long-term Prospect of Supply and Demand of Energy. However, to investigate the broad future possibility, it is suitable to use multiple future scenarios. Therefore, IEEJ’s energy scenarios are used in this study.

[1] http://info.worldbank.org/governance/wgi/index.aspx#doc-methodology

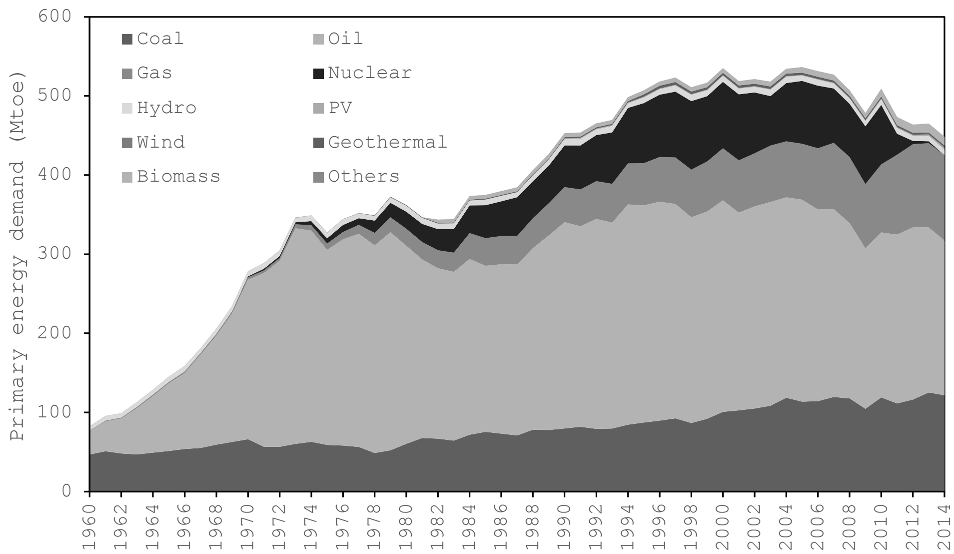

Fig. 1. Structure and transition of primary energy demand. "Others" means other renewable energy. Source: IEA, 2015b.

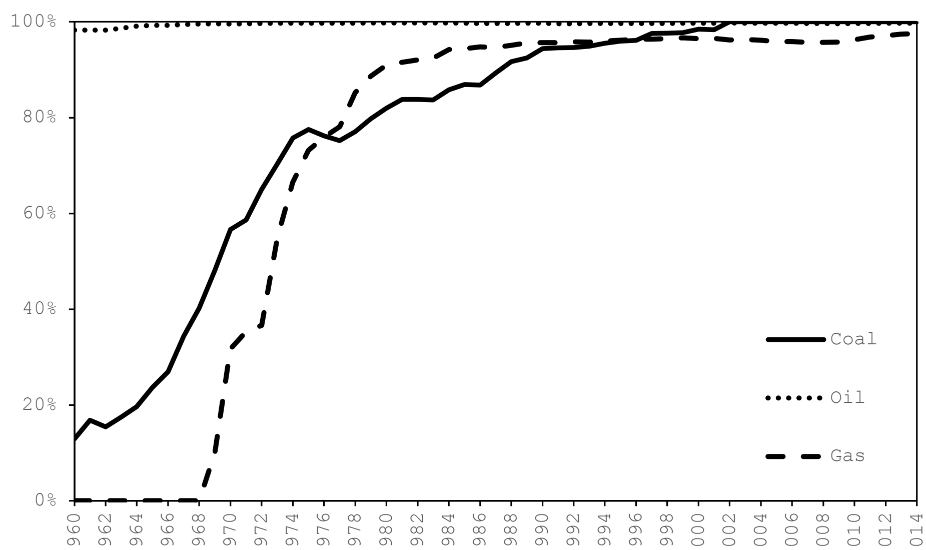

Fig. 2. Dependence on imported fossil fuels. Source: IEA, 2015b.

IEEJ's energy scenarios were developed using their econometric model considering future uncertainties. Four scenarios, hereafter called ES1-4, were developed particularly focusing on the power generation mix (renewable energy and nuclear power). Table 1 shows the overview of the scenarios. The ES1 scenario assumes to use more renewable energy and no nuclear power, while the ES4 scenario uses less renewable energy and more nuclear power. The ES 2 and 3 scenarios are in between the other two. Nuclear power plants meeting the regulatory standards will operate for 40 years in the ES2 scenario, while power plants passing the special inspection extend their operating periods in the ES3 and 4 scenarios. Power generation by renewable energy will be 2.1 to 4.1 times higher than the current level. Since it is not possible to fully replace nuclear power plants, which comprise baseload power, with renewable energy, the share of thermal power is higher in the low-nuclear scenario. Consequently, ES4 shows lower CO_2 emissions and higher GDP than the other scenarios. Figure 3 and Table 2 shows the primary energy structure under the four scenarios.

3. Results and discussion

3.1 Historical trend of energy security performances

Figure 4 shows historical trends of energy security performances evaluated by three indicators. In the early stage of the analysis (from 1978 to early 1980s), all of the three indicators have increased. This is due to a decrease in the share of oil, and an increase in the share of natural gas and nuclear power in the primary energy structure (see also Fig. 1). This trend is brought about by the oil shocks. After the first oil shock in 1973, the government released administrative guidelines to reduce use of oil and electricity. Furthermore, Japan established several policies to secure stable energy supply, such as reduction of dependence on oil and diversification of energy sources by introducing non-fossil fuels, stable supply of oil, energy savings, and research and development of new types of energy. However, the trends are different by indicator after that. The S1 indicator has continuously increased until the early 2010s, while the S2 and S3 indicators (in which energy imports and country risks were taken into account) generally continued to be flat, or become even slightly worse, in the same period.

Table 1. Overview of the IEEJ's energy scenarios.

		ES1	ES2	ES3	ES4
Power generation mix	Renewable energy (%)	35	30	25	20
	Thermal (%)	65	55	50	50
	Nuclear (%)	0	15	25	30
Economy	Power generation (PWh)	1.1	1.2	1.2	1.2
	Power generation costs (JPY/kWh)	21.0	19.0	16.4	14.8
	Real GDP (trillion JPY)	684	690	693	694
Energy	Self-sufficiency ratio (%)	19	25	28	28
Environment	CO_2 emissions (percent change from 2005 level)	-20	-24	-26	-26

Source: IEEJ, 2015a,b

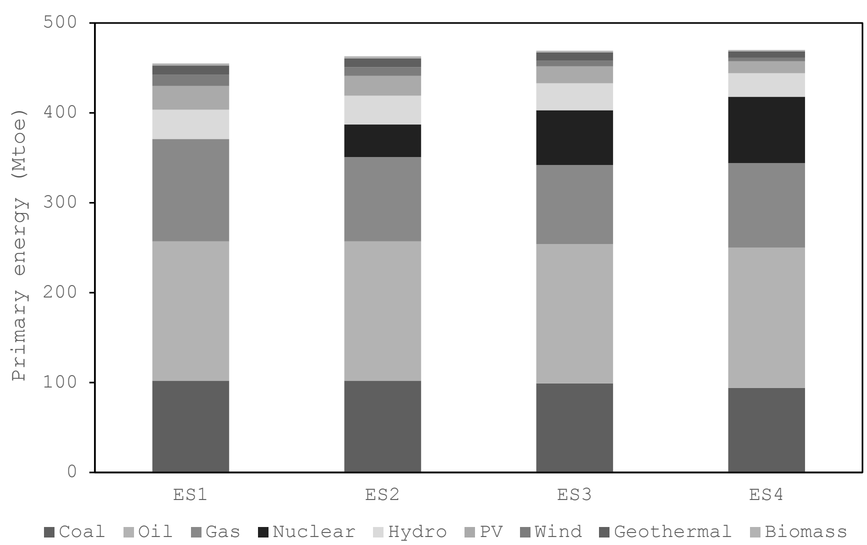

Fig. 3. Primary energy structure under the IEEJ's energy scenarios. Source: IEEJ, 2015a, b.

Table 2 Share of each energy source in primary energy under the IEEJ's energy scenarios.

	ES1	ES2	ES3	ES4
Coal	22.4%	22.0%	21.2%	20.0%
Oil	34.1%	33.5%	33.1%	33.2%
Gas	25.1%	20.3%	18.8%	20.0%
Nuclear	0.0%	7.8%	13.0%	15.7%
Hydro	7.2%	6.9%	6.4%	5.5%
PV	5.8%	4.8%	4.0%	2.8%
Wind	2.8%	2.1%	1.4%	0.8%
Geothermal	2.2%	2.1%	1.9%	1.6%
Biomass	0.5%	0.5%	0.4%	0.3%

Source: IEEJ, 2015a,b

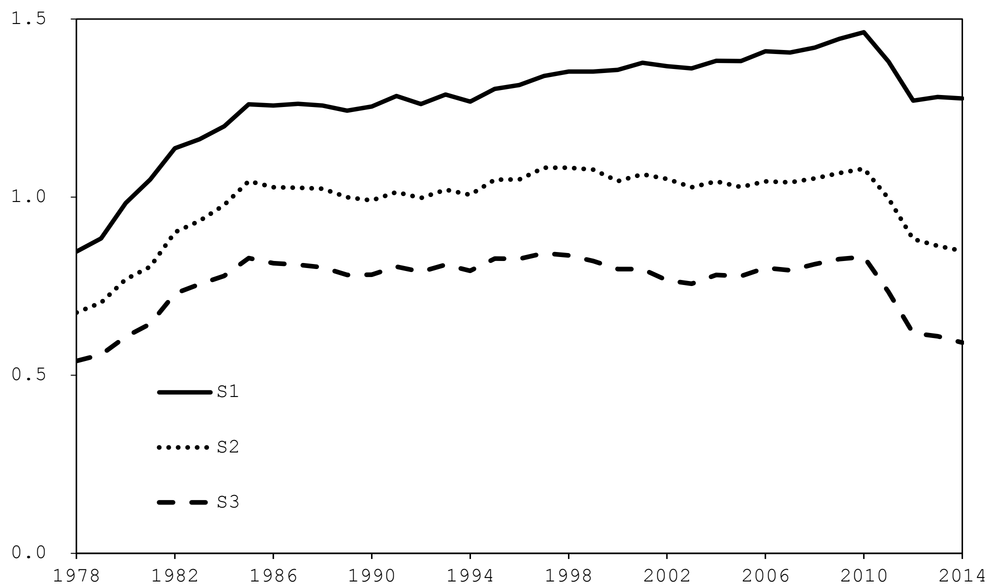

Fig. 4. Historical energy security performances in Japan.

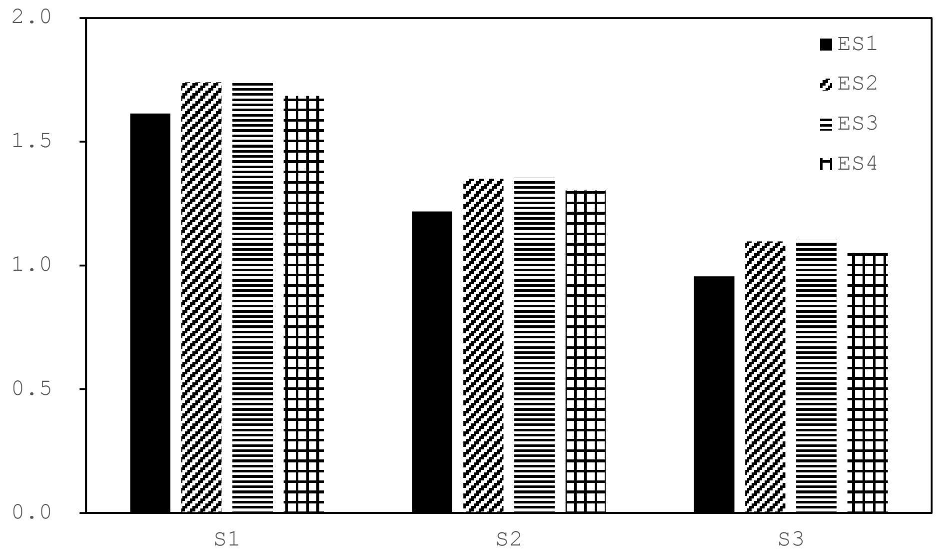

Fig. 5. Future energy security performances under the IEEJ's scenarios.

The S1 indicator purely measures diversity of primary energy. During the corresponding period, the share of oil continuously decreased, while the share of natural gas and nuclear power continuously increased. In addition, the share of renewable energy slightly increased. These effects, in total, increased the diversity of the primary energy sources. In the case of the S2 and S3 indicators, the dependence on imports cause the indicators to be flat from the 1980s to the 2000s. As shown in Fig. 2, the import of natural gas sharply increased until 1980 and slowly but continuously increased after that. The import of coal also increased from 1978 to the present. Such increases in imports offset the increases in value by diversifying energy sources. For the country risk indicator, because same values are used until 1996, country risk affects the energy security indicator only when the share of import by origin changes. If more fossil fuels are imported from higher-risk countries, the energy security performance declines. From 1996, the situation is also similar to that of before 1996 since the country risk indicator does not change greatly. In the case of coal, imports from Australia and Indonesia increased from the mid-1990s to 2000s, while those from Canada and the US decreased. Australia, Canada, and the US are countries with lower risk, while Indonesia is a country with high risk. With regard to oil, imports from Saudi Arabia, which is a higher-risk country, increased, while small decreases were observed in some countries in the same period. For natural gas, imports from Australia, Qatar, and Russia increased, while those from Brunei and Indonesia decreased. Australia is a country with lower risk as indicated above, while Brunei and Qatar are in the middle, and Indonesia and Russia are countries with higher risk. Comparison between the S2 and S3 indicators suggests that import is a more influential factor in determining the performances than the country risk factor.

Finally, after 2010, all three indicators declined tremendously due to the shutdown of nuclear power plants after the Fukushima nuclear disaster. During this period, the decrease in the use of nuclear power was compensated for by fossil fuels, particularly natural gas. This change caused a reduction in the diversity of the primary energy structure.

The above results suggest that the diversity of energy structure is the primary factor in determining the performances of energy security. In addition, imports (total imports and diversity of the origin of imports) are also an important factor. Since the country risk indicator does not seem to affect the performance in this study, it might be due to the fact that the risk indicator changes only slightly over time. Therefore, if an incident, such as a war or a civil war, largely changes the situation of a country, it can affect the energy security performance.

3.2 Comparison of scenarios

In analyzing the scenarios, primary energy sources in the original references were aggregated into the sources treated in the historical analysis, although the scenarios do not include the “others” (other renewable energy). Because the share of “others” is very small, this difference does not affect the comparison between the historical and scenario analysis. Note that since only primary energy structure is available from the references, historical data are applied for energy imports and country risk indicators.

When calculating the S2 indicator for the scenarios, we assume that fossil fuel production in the latest year is kept in the future (to calculate the coefficient c2i). This means that fossil fuel production does not change in 2030 from the current level (production of the 10-year average is used) and the fossil fuel demand that cannot be fulfilled by the production is imported. Similar to the S2 indicator, this assumption on the coefficient (c3i) is also considered for calculating the S3 indicator.

Figure 5 shows the results under the IEEJ’s energy scenarios. Since the same assumption is applied for imports and country risk indicators for all the scenarios, the differences by scenario are similar for each indicator. The results suggest that ES2 and ES3 scenarios show the highest energy security performances (the second scenario is slightly higher than the third one for the S1 indicator, while the third one is slightly higher than the second one for the other two indicators), while the ES1 is the lowest. As Table 1 and Fig. 3 showed, the ES1 is the extreme scenario, which uses no nuclear power at all. It means that the primary energy structure is biased towards fossil fuels, although the share of renewable energy is larger than in the other scenarios. The ES2 and ES3 have more balanced primary energy structures, particularly for important energy sources (energy sources with larger shares), compared to the other two. The ES4 also looks to have balanced energy structure, but the large share of nuclear power reduces the share of renewable energy that consists of several energy types. Consequently, the ES2 and ES3 scenarios have more diversified primary energy structures than the ES4. Observing the S2 and S3 indicators, because import and country risk factors affect evaluation against fossil fuels, the scenarios with higher shares of fossil fuels tend to be more greatly affected.

Comparing the above results with the historical analysis shows that the values in the four scenarios are higher than those in the historical analysis for all the indicators, meaning that the energy security performances are expected to improve in the future under the given energy scenarios. For the three scenarios using nuclear power (ES2-4), use of nuclear power as well as increase in renewable energy contributes to improving energy security performances. Comparing the primary energy structure in this scenario (Fig. 3) with the historical one (Fig. 1) shows that the decrease in nuclear power is compensated for by greater use of renewable energies. In addition, although the total share of fossil fuels remains almost the same, the structure is more balanced by using more natural gas and less oil.

4. Conclusion

Because Japan is poor in energy sources and because its energy situation will be severer in the future, securing its energy supply will be a more significant issue. In this paper, we first evaluated transition in the historical energy security performances and then analyzed energy security in the future under four energy scenarios.

From the historical analysis, it was shown that energy security performances evaluated by three energy security indicators improved over time, although the indicators S2 and S3 were almost flat from the late 1980s to the early 2010s. However, energy security performances declined from 2011 due to the Fukushima nuclear disaster. This means that diversity of primary energy sources, including nuclear power, is important for keeping high energy security performances. From the scenario analysis, energy security will improve under the future scenarios considered in this study. It is suggested that energy balances mentioned above and also energy saving can improve the energy security performances of Japan compared to the historical situation.

To further improve energy security, additional measures can be considered. First, an increase in the share of renewable energy is necessary to balance primary energy structure. This will also decrease dependence on imported fossil fuels. However, if the share of unstable renewable energy increases too much, power system stability will be affected. Therefore, increases of stable renewable sources (e.g., medium- and small-hydro, biomass, and geothermal power) are expected. In addition, introducing energy storage systems will reduce the influence of increasing unstable renewable energy, although such storage systems will generate an additional cost. Next, with regard to energy imports, balancing the origin of imported energy and reducing imports from high-risk countries will also contribute to improvements in energy security, although these affect only the indicators S2 (only the former) and S3. Last but not least, reducing energy demand, i.e., energy saving, is also an important factor for improving energy security performances. By reducing energy demand, energy supply from fossil fuels can be reduced. This will contribute to balancing primary energy sources (increasing the share of renewable energy sources), balancing the origin of energy import, and reducing energy imports from high-risk countries.

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