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Energy security performance in Japan under different socioeconomic and energy conditions

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ABSTRACT

A secure energy supply is indispensable for Japan's economic activity, but it is becoming more difficult to attain, due to increasing energy demand in emerging countries. The pattern of socioeconomic development and the achievement of a low-carbon society are also strongly related to energy security. This study evaluated energy security performance in Japan under alternative scenarios of future socioeconomic and energy conditions by applying three energy security indicators derived from the Shannon-Wiener diversity index. The 2050 Japan Low Carbon Navigator was used to estimate energy structures under five socioeconomic scenarios and three selected combinations of effort levels toward producing a low-carbon society. It was found that the effort levels were the most influential factors in determining energy security performance, because they greatly affect energy supply and demand. The choice of socioeconomic scenario was also influential, although the impact of this choice was less significant than the choice of effort level. However, the impact of country-risk indicators is less substantial than the above two factors. The energy security performance of Japan will improve in the future, compared with the current level. However, if the country pursues further economic growth, its energy security performance will not greatly improve. Consequently, increasing efforts to achieve a low-carbon society will contribute to the realization of a highly energy-secure society with respect to Japan's current and future socioeconomic situation.

1. Introduction

In Japan in 2015, the self-sufficiency rate of energy (including nuclear energy as semi-domestic energy [1,2]) was 7.0%, the worst level in the history of the country. The country depends strongly on fossil fuels—these accounted for more than 80% of the energy supply before the Fukushima Daiichi nuclear disaster and currently account for more than 90% (Fig. 1)—and most are imported. Although Japan intended to diversify its energy sources after oil shocks in the 1970s, the share of oil in the primary energy supply is still the largest share (41.0% in 2015). More than 80% of Japan's oil supply is also derived from the Middle East, which entails high geopolitical risks, even though Japan has pursued diversification in its oil-supplying countries along with the diversification of its primary energy sources. The supply of oil for export is decreasing in Asian oil-producing countries, due to their own increase in energy demand. Because energy demands in emerging countries, such as China and India, are drastically increasing and therefore these countries will pursue measures to secure their own energy supplies, it will be more difficult for Japan to ensure cheap imported fuels in the near future. Thus, producing domestic energy sources and reducing dependence on imported energy are critical issues for the country.

Nuclear power has been one of the energy sources that could reduce dependence on fossil fuels; however, the Fukushima nuclear disaster completely changed the situation, highlighting safety issues with respect to nuclear power generation. At the time this paper was being written (March 2018), only three of 42 nuclear power plants in the country were in commercial operation. Thus, introducing renewable energy is an important alternative option in securing the national energy supply and in simultaneously 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, renewable energy, except for large-scale hydropower generation, accounts for only a small percentage of the total primary energy supply (Fig. 1). After the introduction of the Feed-In Tariff (FIT) launched in July 2012, the share of renewable energy, particularly photovoltaics (PV), increased more than the historical trend. However, the share of renewable energy in primary energy is still very small (8.5% in

Abbreviations: IAM, Integrated Assessment Model; IGES, Institute for Global Environmental Strategies; FIT, Feed-In Tariff; NIES, National Institute for Environmental Studies; PV, Photovoltaics; LCN, Japan 2050 Low Carbon Navigator; LEAP, Long-range Energy Alternative Planning; ASEAN, Association of Southeast Asian Nations

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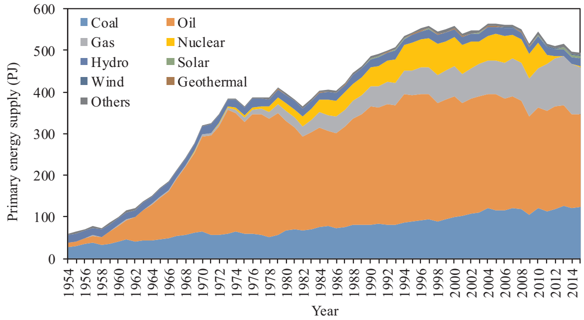

Fig. 1. Structure and transition of primary energy demand in Japan. "Others" refers to other types of renewable energy. 1 Mtoe is equivalent to 41.87 PJ. Source: Energy Data and Modeling Center [3].

2015).

In April 2014, the fourth version of the Strategic Energy Plan [4], developed after the Fukushima nuclear disaster, was endorsed by the government. The plan aims to reexamine and revise the energy strategy of Japan, particularly by reducing dependency on nuclear power, considering the Fukushima disaster. The plan prioritizes energy security, but it also considers economic efficiency and the conservation of the environment, all with a strong focus on safety (3E + S).

In July 2015, the government released the Long-term Energy Supply and Demand Outlook [5]. This outlook was developed based on the Strategic Energy Plan. According to the outlook, Japan will increase its share of renewable energy by 13–14% of primary energy (22–24% of power generation) by 2030. The share of nuclear power will also be increased to 10–11% of primary energy (20–22% of power generation). Drastic energy savings are also expected to reduce energy demand. However, considering the current situation in Japan, there are still difficulties inherent in resuming the use of nuclear power and increasing renewable energy to achieve the levels indicated in the outlook.

In transitioning toward a sustainable society, Japan faces many energy challenges, the main challenges in current energy policies being as follows. In the Strategic Energy Plan, coal-thermal power is still considered an "important baseload power," while the position of the government regarding nuclear power is not clear. The plan indicates that nuclear power is considered an important baseload power source, and the government has set the target for the share of nuclear power to be 10–11% of primary energy. However, at the same time, the plan indicates that dependence on nuclear power should be reduced. Because Japan depends on imports for most of its fossil fuel supply, energy costs and a stable energy supply may remain at risk as long as this continues to be the case.

Achieving a low-carbon society in the future is also closely related to improving energy security, particularly since 2011. In the wake of the Fukushima nuclear disaster, a stable energy supply was considered a key component in developing a low-carbon society [6]. The Ministry of the Environment [6] also indicated that the vulnerability of the domestic energy supply posed a significant challenge to the realization of such a society. To aim for a low-carbon society, it is essential to have a vision not only of the energy but also of the socioeconomic conditions of such a society.

The purpose of this study is to evaluate energy security performance in Japan up to 2050 under different future socioeconomic and energy conditions, using comprehensive energy security indicators. The socioeconomic conditions are represented by socioeconomic scenarios (i.e., different visions of the future society) and the country risks of energy exporters, while the energy conditions are expressed in terms of the level of effort dedicated to the achievement of a low-carbon society. This study focuses on energy security from the perspective of energy supply.

2. Literature review

Many types of research on energy security have been implemented in the literature, particularly those using some sort of indicator [7–20], studying different countries and regions and different periods with different methods. A significant number of studies have focused on Asian countries and a few on the case of Japan. Here, a literature review is conducted targeting Asian countries, including China, Hong Kong, Taiwan, Korea, Thailand, Indonesia, Malaysia, Singapore, India, Pakistan, Bangladesh, and Japan.

Many studies have analyzed China, for example, Ren and Sovacool [21,22], Wu [23], Yao and Chang [24,25], Su et al. [26] Zhang et al. [27], Zhao and Liu [28], Gao et al. [29], Matsumoto [30], and Cao and Bluth [31]. Ren and Sovacool [21] analyzed energy security from the perspective of availability, affordability, acceptability, and accessibility (often called the 4As) using the DEMATEL method. These authors [22] also evaluated energy security with respect to low-carbon energy, applying an analytic hierarchy process. Wu [23] examined the energy security strategies of China by focusing on overseas oil investment, strategic petroleum reserves, and unconventional gas development in the 11th and 12th Five-Year Programs. Yao and Chang [24] also used the 4As approach and evaluated the transition of energy security performance through the areas of a rhombus made by the 4As in the past (1980–2010). Yao and Chang [25], in another paper, also qualitatively analyzed the reasons why energy security has not improved in China during the period of economic reform. The authors particularly focused on the relationship between energy security and the country's energy policy. Su et al. [26] proposed ecological network analysis as a common tool to systematically evaluate energy supply security, analyzing the crude oil and natural gas supply system from 2000 to 2012. Zhang et al. [27] implemented a province-level analysis in 2013. The authors used a five-dimensional (20 components in total) energy security indicator and also applied multi-criteria decision-making methods to provide weights to the components and the dimensions. Zhao and Liu [28] focused on the relationship between the bioenergy industry and energy security and showed the contribution of the development of the bioenergy industry to China's energy security. Gao et al. [29], using their quantitative energy security model focusing on cost-benefit analysis and the benefits of ensuring energy security, evaluated the optimized scale of a strategic petroleum reserve and alternative fuels for energy security in China. Matsumoto [30] used a computable general equilibrium model and an energy security indicator to evaluate future energy security in China under climate mitigation scenarios. Cao and Bluth [31] qualitatively analyzed energy policy in China from the viewpoint of energy security. The authors investigated the energy mix of the country and the internal and external constraints that the country has faced with respect to its energy policy.

With respect to the other East Asian countries (except for Japan), Holley and Lecavalier [32] explored Hong Kong's challenges in dealing with energy security and environmental sustainability, based on interviews with public and private stakeholders, and made policy recommendations to solve the energy dilemma. Chuang and Ma [33] evaluated energy policy in Taiwan using six energy security indicators of four dimensions in the past (1990–2010) as well as for the future energy policy in terms of energy security, using both a modeling approach and the indicators. Chung and Ma [34] also evaluated the energy security of Taiwan in terms of energy supply diversity from 1996 to 2011. The authors used the Hirschman-Herfindahl index and the Shannon-Wiener index in their evaluation. Shin et al. [35] analyzed energy security in the Korean gas sector from the past to the future (1998–2015), using a model approach (quality function deployment and system dynamics). Chung et al. [36] also evaluated energy security in South Korea in the 2000s, using the indicators of supply reliability, the economy of power generation, environmental sustainability, and technology complementarity. Different from Shin et al. [35], Chung et al. [36] focused on energy security in the power generation sector.

In the studies for the Southeast Asian countries, Martchamadol and Kumar [37] evaluated Thailand's energy security between 1986 and 2030. The authors applied five-dimensional indicators (19 indicators in total), using statistical data for the historical analysis and a scenario approach for the future analysis. Martchamadol and Kumar [38] also evaluated Thailand's energy security using the same methods and periods but at both the national and provincial levels. Thangavelu et al. [39] used an optimization model to explore a long-term energy mix for the future in Indonesia for a society with high energy security and low carbon. Foo [40] summarized the current situation and future vision of Malaysia on the policies and coping strategies for energy security and green energy development. Ang et al. [41] evaluated historical energy security (1990–2010) in Singapore using 22 indicators of three dimensions. The authors also conducted a scenario analysis for the future (until 2035), based on a business-as-usual projection.

In South Asia, Pode [42], Narula et al. [43], and Sharma and Singh [44] targeted India in their studies. Pode [42] analyzed the future energy security of India in terms of the energy mix and diversification of energy sources in the country. For India between 2002 and 2012, Narula et al. [43] assessed sustainable energy security using 16 metrics, including the perspectives of energy demand, conversion and distribution, and supply. Different from the previous two studies, which used some sort of energy security indicators, Sharma and Singh [44] analyzed the contribution of microalgal biodiesel to India's energy security. Anwar [45] evaluated the future energy security of Pakistan under scenarios wherein energy imports were reduced in the future (from 2005 to 2050). This study used three-dimensional indicators (11 indicators in total) combined with a simulation model. Aized [46] evaluated the energy security of Pakistan under four future energy policy scenarios, using the long-range energy alternative planning (LEAP) system, and found that the green Pakistan scenario (the renewable energy scenario) was the most suitable option for the country. Islam et al. [47] summarized the availability, current status, strategies, perspectives, policies, major achievements, and future potential of energy options, particularly focusing on renewable energy, in terms of the energy security of Bangladesh.

In addition to the above single-country analyses, many multinational studies have also been conducted within Asia. Sharifuddin [48] evaluated energy security in five Southeast Asian countries (Malaysia, Indonesia, the Philippines, Thailand, and Vietnam), using 35 indicators representing 13 elements grouped into five aspects of energy security in three periods (2002, 2005, and 2008). Tongsopit et al. [49] quantitatively evaluated the historical energy security of the Association of Southeast Asian Nations (ASEAN) from 2005 to 2010 under the 4As framework. Shadman et al. [50] evaluated energy security in the ASEAN-6 countries in relation to climate change, particularly focusing on the impact of drought on power generation. The authors showed the importance of future planning of the energy mix, considering future climate change. Sovacool [51] conceptualized energy security into the factors of availability, affordability, efficiency, sustainability, and governance and applied these factors to evaluate the energy security in 18 Asia Pacific countries (including non-Asian countries) from 1990 to 2010. Selvakkumaran and Limmeechokchai [52] evaluated 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 [53] used a modeling approach, similar to that of Matsumoto [30], to evaluate future energy security (until 2050) in three East Asian countries (Japan, China, and Korea) under climate mitigation scenarios.

In 2011, there was also a special issue on Asian energy security from Energy Policy (Volume 39, Issue 11; the overview paper of this issue was provided by von Hippel et al. [54]), and one study is included for Japan [55]. Takase and Suzuki [55] analyzed future energy pathways that would impact energy security, using the LEAP system. The authors mainly focused on energy structures in the future under different nuclear power developments and greenhouse gas emission reductions.

The other studies, targeting Japan with respect to energy security, are summarized as follows. Vivoda [56] analyzed the consequences of the Fukushima nuclear disaster on Japan's energy security and outlined energy policy recommendations for the future. However, this study was a qualitative analysis, although it showed statistical data, and no quantitative results based on the recommendations were provided. Portugal-Pereiraa and Esteban [57] focused on the security of the electricity supply in Japan. The authors evaluated electricity security based on a model analysis of the hourly electricity supply/demand balance under various electricity generation mixes. Thus, their analysis differed from that of this study and other energy security studies. Kitamura and Managi [58] evaluated the energy security of Japan in terms of an energy resource supply disruption in its exporting countries. The study found that public and private oil stockpiling played an important role in ensuring energy security and that nuclear and renewable power generation was able to mitigate the impact of an energy resource supply interruption in the power sector. Matsumoto [59] evaluated Japan's energy security performance from the past to the future. The study's analysis for the future was based on energy scenarios in 2030, and it evaluated how the primary energy structure, determined mainly by the degree of introduction of nuclear power and renewable energy, would affect energy security.

As shown in the abovementioned literature, there are a great many studies on energy security that focus on Asian countries. However, studies targeting Japan are still scarce, although energy security is an important issue for the country, as described in Section 1. Nor have any studies have evaluated how future economic and industrial development can affect energy security performance through changes in the primary energy structure. Understanding such impacts is important, because energy security is an important aspect to evaluate in formulating possible future socioeconomic visions.

In terms of the methodology used to evaluate energy security, most studies applied some sort of indicators to statistical data or to the results of model or scenario analysis. However, different definitions, dimensions, or indexes have been used in each study [7,12,60]. This means that there are no consistent definitions or evaluation methods for energy security performance. When evaluating the energy security performance of countries, the most important factor is the availability of energy, as it is included in the indicators in most related studies [7]. Furthermore, because such indicators are used by policymakers to establish energy policy in a country, a simple and comprehensible methodology is preferable.

There are also many studies on low-carbon scenarios, particularly those analyzing the 2 °C global warming target. For example, Rogelj et al. [61] implemented a systematic analysis of how different levels of short-term emissions (i.e., emission targets for 2020) would impact the technological and economic feasibility of achieving the 2 °C target by 2100. Riahi et al. [62], who compared nine integrated assessment models (IAMs) in their study, used a cumulative emission budget as an indicator to track this 2 °C target. Similarly, Bertram et al. [63] used nine IAMs to examine how weak near-term (up to 2030) climate policies would affect the achievement of the target. Wang et al. [64] proposed a new scheme for carbon permit allocation, considering international cooperation in climate mitigation from the perspective of equity. This scheme considered equality, historical responsibility, capability, and future development opportunities, with different weights on each factor, based on the IAM analysis. There are also studies on the costs of delays in mitigation action [65–72]. However, there have been few studies combining low-carbon and energy security analysis, and none have clarified how different socioeconomic conditions may affect energy security in the future.

3. Methods

In evaluating energy security performance under different socioeconomic and energy conditions, three energy security indicators were applied. Estimates of energy structures in the future were implemented using the Japan 2050 Low Carbon Navigator (LCN).

3.1. Energy security indicators

In order to analyze energy security performance in the future, three energy security indicators were used, based on Jansen et al. [73] and Lehr [74]. The same indicators were also applied in Matsumoto et al. [18]. The proposed indicators enabled an analysis of energy security, focusing on energy supply. The first indicator (S1, Eq. (1)) evaluated the diversity of energy sources based on the Shannon-Wiener diversity index, used to evaluate the diversity of primary energy. Diversity is important in maintaining energy security, because the probability of having to compensate for the loss of a primary energy source with other energy sources will increase, and diversity will thus ensure energy security. However, to discuss energy security on a national scale, it is important to consider where energy sources are located. In general, domestic energy is safe, while a procurement risk exists for energy imported from other countries. Also, as with energy sources, diversity in the origins of imported energy contributes to improving energy security, because energy supply disruption can be compensated for by the supply from other countries. The second indicator (S2, Eq. (2)) considers the country's dependence on imported energy sources as well as the origins of its energy imports. In this S2 indicator, all the energy exporters are treated equally. However, energy security will be worse if energy is imported from politically or economically unstable countries. Thus, the third indicator (S3, Eq. (3)) extends the S2 by incorporating a country-risk factor associated with the country's energy import origins. By definition, the values of the three indicators are S1 ≥ S2 ≥ S3, but these three are not comparable. Energy security performance is higher when the values of the indicators are higher.

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

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

where

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

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

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

$$S3 = -\sum_{i=1}^{N} c3_i p_i \ln(p_i), \tag{3}$$

where

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

$$IM3_i^m = -\sum_{j=1}^{M} r_j m_{ij} \ln(m_{ij}),$$

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

In the above, 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 energy imported from country j; N: the number of primary energy types; and M: the number of origins of primary energy imports.

3.2. Japan 2050 Low Carbon Navigator

The LCN, developed by the Institute for Global Environmental Strategies (IGES) and the National Institute for Environmental Studies (NIES), is a tool utilized to simulate the existence of a low-carbon society in Japan by 2050.[1] This tool can simulate the structure of energy supply and demand (primary and final energy as well as electricity), energy flows, and costs under different socioeconomic scenarios and effort levels. The concept of the tool was based on the 2050 Energy Calculator developed in the United Kingdom [75]. The main feature of the LCN (Japanese version of the 2050 Energy Calculator) is the variety in the socioeconomic scenarios. In the LCN, five socioeconomic scenarios extending to 2050 are considered, based on the societies or visions developed by the Government of Japan [6]. These scenarios are called Made-in-Japan (MIJ), Research and Development (R&D), Service and Brand (SB), Resource-Independent (RI), and Share (Table 1). The characteristic differences among the scenarios included the assumption of economic growth. The average annual GDP growth rates (in real terms) were 1.2% (MIJ), 1.1% (R&D), 0.9% (SB), 0.4% (RI), and − 0.6% (Share). The Share society offered the only scenario assuming negative economic growth in the future. In 2050, the GDP of the five socioeconomic scenarios was predicted to be JPY 859 trillion (MIJ), JPY 826 trillion (R&D), JPY 761 trillion (SB), JPY 632 trillion (RI), and JPY 421 trillion (Share). In addition, the level of economic growth and economic activity determines a baseline of energy demand in each scenario. Basically, the scenario with a higher level of economic activity raises a higher baseline of energy demand. However, these socioeconomic scenarios existed independently of the low-carbon policy in the LCN. Thus, policies aiming for a low-carbon society were not taken into account within the socioeconomic scenarios.

The low-carbon policies were modeled in terms of effort levels in the LCN that were dedicated to the creation of a low-carbon society. For each society, the effort levels directed toward this aim could be selected according to both demand and supply in the energy systems. These effort levels were common for the five scenarios. Table 2 shows the sectoral coverage of the LCN. For each sector, the LCN provided four or five levels of effort expended for the degree of change that might occur (Table 3). These levels reflect the range of potential future changes in each sector. In the energy supply sectors, these effort levels include a potential rollout of energy generation infrastructure. In the energy demand sectors, the effort levels represent behavioral and technological changes. The measures applied to each level within each sector are described in IGES and NIES [76].

3.3. Cases of analysis

In this study, three types of analysis were conducted using the results from the LCN: a comparison of socioeconomic scenarios; a comparison of the different effort levels exerted toward the achievement of a low-carbon society; and a sensitivity analysis of the risk indicators. The first and third analyses were carried out to investigate how socioeconomic conditions affect energy security. The first analysis in particular was designed to identify the impact of a domestic factor, while the third was intended to identify the impact of an external factor. The second analysis was conducted to investigate how energy conditions affect energy security, based on the degree of effort dedicated to the achievement of a low-carbon society. Because these efforts are related to low-carbon policy, this analysis shows the impact of a domestic factor.

[1] The web version of the tool is available here: http://www.en-2050-low-carbon-navi.jp/. Also, the full Excel version can be downloaded from here: http://www.2050-low-carbon-navi.jp/web/files/PDF/2050_Low_Carbon_Navigator_v2_web.xlsx.

Table 1
Overview of the socioeconomic scenarios in the LCN.
Source: Created based on IGES and NIES [76].

Socioeconomic scenarios	Economic development	Characteristics
Made-in-Japan (MIJ) society	A society in which domestic industrial manufacturing drives high economic growth.	The Japanese economy is boosted by the domestic production of competitive low-carbon technologies and high-value-added products for mid- to high-income customers overseas. There may be a lack of innovation, and salary levels may be kept low to compete internationally. The economy will also be more vulnerable to changes in currency exchange rates.
Research and Development (R&D) society	A society in which the overseas expansion of Japanese manufacturing industries drives high economic growth.	Japan will become the global hub of research and development (R&D) for the manufacturing industry, including low-carbon technologies. Revenues are generated by sales overseas. To maintain a technological edge on competitors, the country needs to be successful in a harsh global competitive environment by developing state-of-the-art infrastructure and supporting entrepreneurs and game-changers.
Service and Brand (SB) society	A society in which the expansion of a high-quality service industry toward foreign customers drives high economic growth.	Japan will achieve high economic growth through the expansion of its high-quality service industry to attract wealthy foreign customers, including tourists. A large fraction of services provided by the Japanese economy, which targets wealthy foreign customers, may not be affordable by average Japanese consumers.
Resource-Independent (RI) society	A society in which resource independence is considered most important for prosperity.	The society will become more resilient with respect to global resource protectionism by supplying as much food and energy and as many resources domestically as possible. Japan needs to bear additional costs for energy and resources to maintain resource independence.
Share society	A society in which wellbeing and a humble lifestyle is sought.	Necessary goods and services will be provided domestically, and a more laid-back lifestyle will be achieved. The economy will become more vulnerable to external factors. A sense of community will also prevail over individualism, so that collective actions and the sharing of goods become the basis of daily life.

In analyzing the above three scenarios, a benchmark was first developed, because the LCN can create a large number of future energy scenarios by combining socioeconomic scenarios and effort levels in each sector. This benchmark was designed to emulate the energy structure presented in the Long-term Energy Supply and Demand Outlook [5], the official energy plan of the government developed in 2014. Thus, it is considered the most likely scenario. First, a socioeconomic scenario with economic assumptions similar to the outlook was selected. In comparing the assumptions of the economic activities (GDP and the production of crude steel, cement, ethylene, and papers, which are the variables available both in the LCN and in the outlook) from both the socioeconomic scenarios and the outlook, it was concluded that the MIJ society was the closest to the outlook [5,76]. The effort levels under the MIJ society were then adjusted to fit the

Table 2
Sectoral coverage of the LCN and selected levels for LV_A.
Source: Created based on IGES and NIES [76].

Energy supply sector			Energy demand sector		
Categories	Subcategories	Levels	Categories	Subcategories	Levels
Nuclear and conventional power plants	Nuclear power stations	4	Transport	Domestic passenger transport behavior	4
	Conventional power plants	2		Shift to zero emission passenger transport	4
Conventional power plants	Fuel mix for conventional power plants	1		Choice of zero emission vehicle technology	4
	Availability of carbon capture and storage (CCS) technology	1		Biofuel mixture (passenger transport)	4
Renewables	Solar PV	3		Domestic freight behavior	4
	Wind (onshore)	2		Shift to zero emission freight	4
	Wind (offshore)	2		Biofuel mixture (freight)	4
	Wind (floating)	1	Residential	Installation of home energy management system	4
	Hydropower (small and medium)	1		Home insulation	4
	Geothermal electricity	1		Home heating/cooling electrification	4
	Ocean power	1		Energy efficiency of heating/cooling	2[a]
				Choice of hot water supply technology	4
				Energy efficiency of hot water supply	2[a]
				Solar thermal boilers	2
				Energy service demand per household	4
				Energy efficiency of cooking, lighting, and appliances	2[a]
			Commercial	Energy service demand per floor space (heating, cooling, and hot water supply)	4
				Building insulation	4
				Choice of appliances (heating, cooling, and hot water supply)	4
				Energy service demand per floor space (cooking, lighting, and appliances)	4
				Energy efficiency of cooking, lighting, and appliances	2[a]
			Industry	Energy intensity per industrial output	2[a]
				Energy mix in the industry	4
				CCS technology in industrial sectors	2

[a] Only two levels (levels 1 and 2) are prepared in the tool.

Table 3
Effort levels in the LCN.
Source: Created based on IGES and NIES [76].

Level[a]	Degree of effort
1	No effort (existing capacity, same technology, and no change in consumption)
2	Greater effort than level 1
3	Greater effort than level 2
4	Great effort (increased renewable energy, advanced technology, and reduced unit energy service demand)
5	Physical limit and technical potential (for renewable energy)

[a] Not all levels are set for each sector.

energy demand and structure to the outlook. This combination of effort levels is called "LV_A" ("A" stands for "adjusted"; Table 2). In this LV_A, the effort levels for most energy demand sectors needed to be set to the highest level, level 4. In the power sectors, the existing nuclear power plants needed to be restarted, and some new nuclear plants needed to be constructed. PV and wind power were increased significantly, but the other types remained at the levels from 2010. As a result of this adjustment, the final energy demand and electricity consumption of LV_A and of the outlook were 304 Mtoe and 302 Mtoe, and 965 GWh and 981 GWh, respectively.

The three types of analysis were conducted as follows. First, to investigate the impact of socioeconomic scenarios (i.e., domestic socioeconomic conditions) on energy security performance, the performance was evaluated for the five socioeconomic scenarios with a combination of effort levels. The selected combination of effort levels in this case was represented by LV_A, described above.

Second, to investigate the impact of the effort levels (i.e., energy conditions) on energy security performance, the performance for three selected combinations of effort levels under a selected socioeconomic scenario was evaluated. In addition to the benchmark level (LV_A), two combinations of effort levels were selected: level 1 for all sectors (hereafter, "LV_1") and level 4 for all sectors (hereafter, "LV_4"). Note that in LV_4, the levels of some sectors with only two levels were set to level 2 (the higher one). These two (LV_1 and LV_4) represented the minimum and maximum effort-level combinations in the LCN. Although level 5 could be selected for some sectors, it was not chosen for the analysis, because level 5 was set as the physical limit of the energy supply; thus, it was an option with very low potential (Table 3).

Finally, to investigate how the country risks (i.e., external socioeconomic conditions) affected energy security performance, a sensitivity analysis was conducted for the country risk r_j. In the above analyses, historical data were used for future r_j, because the future country risks are not known and are not possible to estimate with the LCN. However, the country risks can be higher or lower in the future compared with the current levels. Therefore, the sensitivity of the risk indicator applied in the S3 indicator was checked. Since a large percentage of imported energy comes from the Middle East, and this situation will not change in the future as long as Japan depends on imported energy, a sensitivity analysis was conducted against the risk indicators of the Middle East countries. Two possible conditions were set: r_j for the Middle East countries became either the maximum or minimum in the region's historical values.

3.4. Data for the evaluation

The data used for the abovementioned evaluations (Eqs. (1)–(3)) were obtained mainly from the LCN. However, some data were not available in this tool, so in this case, historical data were applied. The share of primary energy p_i was calculated based on the primary energy supply obtained from the LCN. The types of primary energy are coal, oil, natural gas, nuclear power, hydropower, solar, wind, geothermal, biomass, and other renewable energy. The share of imports of primary energy dm_i was also calculated based on the primary energy imports of the LCN. However, the tool does not provide data on imports of primary energy by origin (needed to calculate m_{ij}). Therefore, the shares of imports by origin for the latest available year, taken from statistical data, were applied [3]. These shares of imports were only applied for fossil fuels, and the other types of primary energy, including nuclear, were regarded as domestic energy sources.

Finally, the risk indicator r_j was also unavailable in the LCN and was thus also obtained from statistical data. In this study, the World Governance Indicators [77] were applied for the risk indicators, as with

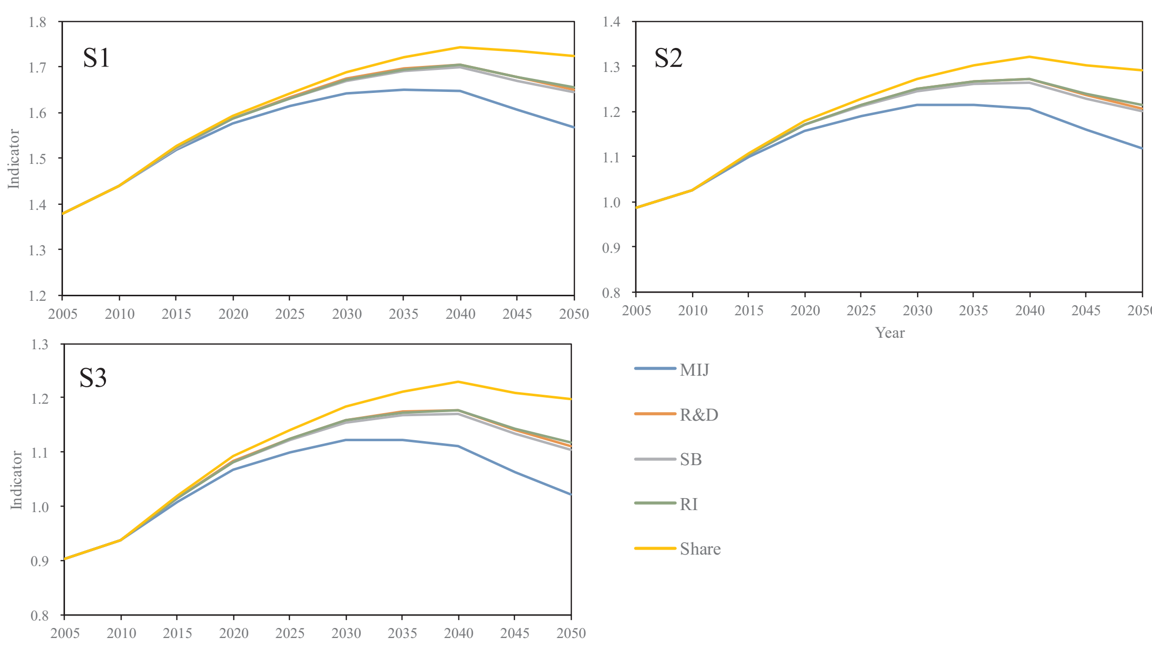

Fig. 2. Future energy security performance of five socioeconomic scenarios.

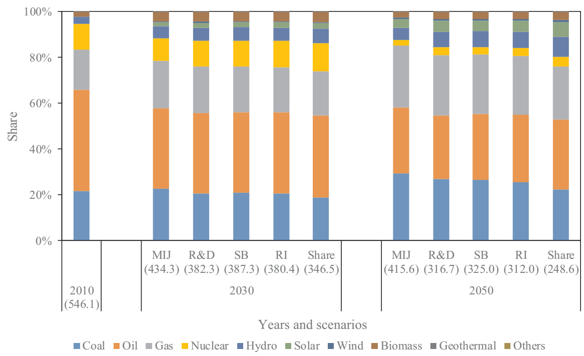

Fig. 3. Primary energy structure in 2010 (actual) and of five socioeconomic scenarios in 2030 and 2050 (the total primary energy demand in parentheses; unit: Mtoe).

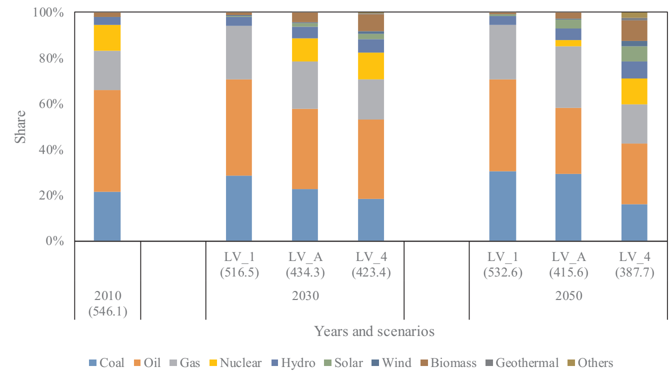

Fig. 5. Primary energy structure of three selected effort levels under the MIJ society (the total primary energy demand in the parentheses; unit: Mtoe).

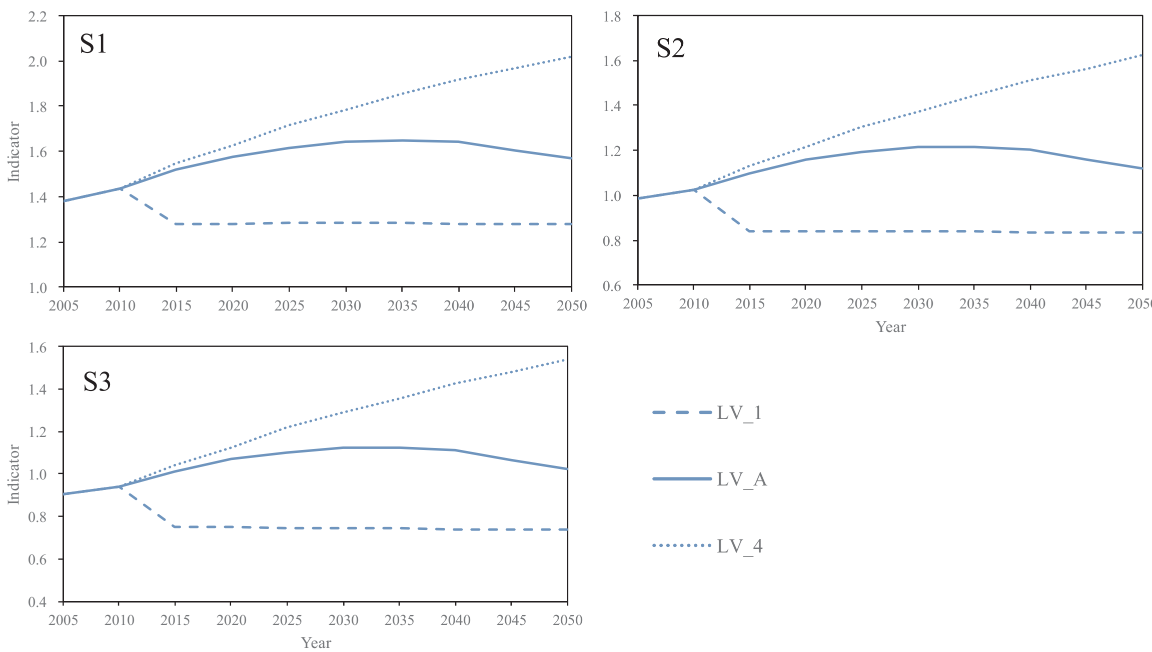

Fig. 4. Energy security performance of three effort levels under the MIJ society. (The performance of LV_A is the same as that shown in Fig. 3.).

our previous study [59]. Because the original data regarding the World Governance Indicators ranged from approximately −2.5–2.5,[2] the values were normalized to a scale of 0–1. The smaller the values, the higher the risks the country faces in securing its energy supply.

4. Results and discussion

4.1. Comparison among five socioeconomic scenarios

Fig. 2 shows the energy security performance, for all three indicators, of each of the five socioeconomic scenarios in the future. Energy security performance will improve in the future compared to historical performance [59], tending to increase gradually over time. In all cases, the performance will decrease after 2040, but it was shown to be higher in 2050 than the current levels. Among the five scenarios, the Share society emerged as the best scenario during the analyzed periods, while the MIJ society represented the worst. As shown in Fig. 3, the share of fossil fuels (total of coal, oil, and natural gas), which occupies the highest share of primary energy in all scenarios, was lowest in the Share society (76.2% in 2050), while this share was highest in the MIJ society (85.3% in 2050). This means that because the share of nuclear and renewable energy is low in the MIJ society, primary energy sources are least diversified in this society. Also, because Japan imports most of its fossil fuels [59], a higher fossil fuel supply means higher fuel imports, which lowers energy security performance (S2 and S3). Decreases in energy security after 2040 were mainly attributed to gradual decreases in the share (and the amount) of nuclear power. Instead of nuclear power, the share of fossil fuels, particularly coal and natural gas, increased.

Economic and industrial development in the scenarios with a lower energy security performance tended to be greater (also see Section 3.2 for the development levels). Because of the strong relationship between economic development and energy consumption, the energy demands of such scenarios became higher and were covered by increasing the fossil fuel supply. As a result, the share of renewable energy and nuclear power declined, and thus, the energy security performance was reduced. Matsumoto and Andriosopoulos [53] found that a diversity of energy sources was the most influential factor in determining energy security performance. These three indicators showed similar trajectories. For the R&D society, which showed the second-highest economic growth, the energy security performance was at the medium level. This

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

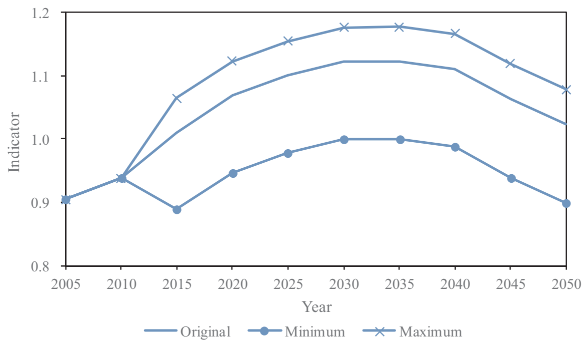

Fig. 6. Sensitivity analysis for the S3 indicator against the country risk in the Middle East under the MIJ society with LV_A.

is because this society transfers manufacturing sectors abroad; thus, domestic energy demand differs greatly from that of the MIJ society, although a similar GDP growth rate is observed.

4.2. Comparison by effort levels

Fig. 4 shows the energy security performance for the three selected effort levels dedicated to the achievement of a low-carbon society. In the case of LV_1, three indicators tended to decline and become lower than the historical levels; the value 0.74 of S3 in 2050 was the lowest among the S3 values in this study. This LV_1 did not use nuclear and biomass-based thermal power generation, while renewable electricity remained at the status quo. This level's primary energy demand was also large compared to that of the higher effort levels, because the efforts dedicated to energy saving were minimal. Thus, this level depended primarily on fossil fuels for its energy supply (Fig. 5). On the other hand, in the case of LV_4, three indicators continuously increased until 2050; the value 1.54 of S3 in 2050 was the highest among the S3 values in this study. This is because in LV_4, energy demand decreased, and the renewable energy supply increased. As a result, the structure of energy sources was more diversified (Fig. 5). Reductions in fossil fuel use also caused imports to be reduced, which also contributed to the improvement of energy security performance (S2 and S3). The energy security performance of LV_A was in between LV_1 and LV_4, because of the combination of the effort levels in LV_A (i.e., all effort levels were set between levels 1 and 4).

These results suggest that although the MIJ society is the worst among the five socioeconomic scenarios (Fig. 2), the energy security performance can be greatly improved by exerting significant effort toward producing a low-carbon society in the energy supply and demand sectors. The maximum differences in energy security performance among the scenarios in 2050 (LV_A) were 0.16–0.18 (Share society minus MIJ society), depending on the indicators (see also Fig. 2); these differences were smaller than those recorded between LV_A and LV_4 of the MIJ society (0.45–0.51). LV_4 assumed high levels of effort regarding the reduction of energy demands, together with resuming the use of existing nuclear power plants and operating new plants (those under the plan) from 2035 forward. It was also assumed that biomass occupied 30% of thermal power generation and that renewable electricity became 4–10 times greater than the current levels (i.e., increasing 14–17.5 GW of capacity). Thus, the energy security performance could be improved by significantly decreasing dependence on fossil-fuel use (Fig. 5).

From the results of this section and Section 4.1, it is concluded that energy security performance will be greatly affected by the effort exerted toward creating a low-carbon society, in terms of energy supply and demand, rather than by the direction of economic and industrial development.

4.3. Sensitivity analysis on the risk indicators

Finally, the sensitivity of the risk indicator r_j applied in the S3 indicator was analyzed to understand the possible impact of changes in the risk indicator. The results (Fig. 6) suggest that the energy security performance of the minimum case was 0.12 (or 10.8–12.1%) smaller than the original values during the study period (0.90 for the minimum case and 1.02 for the original case in 2050). The values were also at almost the same level as recent historical levels.

If r_j for the Middle East countries is set to the maximum, meaning that the country risks are lower than the current levels, the energy security performance will be 0.06 (or 4.9–5.5%) higher than the original values during the study period (1.08 for the maximum case and 1.02 for the original case in 2050). Compared with the Share society (Fig. 2), these levels are higher before 2030, but they are lower after that. In the Middle East, the range of country risks is broad. For example, the countries with high risk (i.e., the value of the indicator was low) were Syria and Iraq; in fact, these countries are two of the highest-risk countries in the world [77]. On the other hand, the risk of countries like Qatar and United Arab Emirates was determined to be much lower than that of Syria and Iraq. Thus, energy security performance was more affected in the case where minimum values were applied.

The above three analyses (socioeconomic scenarios in Section 4.1, effort levels toward a low-carbon society in Section 4.2, and country risks in this section) indicate that in Japan, the level of effort exerted toward producing a low-carbon society is the most influential factor with respect to energy security performance. However, economic and industrial development also affects performance, and compared with these two factors, the impact of country risks is less significant. The effort levels affect both energy supply and demand. Through the increase in effort levels, primary energy demand decreases, and the supply of nuclear power and renewable energy increases. Such changes in energy demand and supply also reduce fossil-fuel imports. Energy security performance improves by increasing the effort levels due to these effects, because the share of fossil fuels decreases. Therefore, the sustainable energy supply and demand realized under a low-carbon society will also improve energy security performance.

Economic and industrial development determines energy demand. Because the supply of renewable energies is limited, the fossil fuel supply increases with higher economic development, if the same effort level (e.g., for solar PV in Table 2) is selected. This decreases energy security performance, as shown in the case of the MIJ society.

Finally, in the case of the S3 indicator, the country risks of energy suppliers represent a factor that affects performance to some extent. However, the impact is not larger than that of the other two factors. Nor is it realistic that country risks largely improve in all countries in the Middle East, as observed in this paper. However, this result indicates that because there is uncertainty regarding country risk in the future, importing energy from countries with lower risk offers an important way to improve energy security; however, the potential for the shift is limited, because the reserves and production of fossil fuels, particularly oil, are dominated by the Middle East and a few other countries [78].

5. Conclusion

Because Japan lacks fossil fuels and because its energy situation is expected to be more severe in the future, securing its energy supply will also be a more significant issue. This paper evaluated energy security performance in Japan under alternative scenarios of future socioeconomic and energy conditions, using comprehensive energy security indicators.

The study found the following: (1) The energy security performance of a society with high GDP levels tends to be worse, due to the relationship between economic levels and energy use (the Share society was the best and MIJ was the worst); (2) The effort levels directed toward the establishment of a low-carbon society have a larger impact on improving energy security performance than do the socioeconomic scenarios, because of substantial increases in the shares of nuclear and renewable energy; and (3) Country risks also affect the energy security of a country, although the impact is smaller than that of the above two factors.

In this study, the MIJ society combined with high effort levels achieved the highest energy security performance, although the Share society combined with high effort levels was able to achieve slightly higher performance (S1: 1.95, S2: 1.65, and S3: 1.54 in 2050). However, the Japanese government is aiming for continuous economic growth and forecasting a moderate decline in material production in the Long-term Energy Supply and Demand Outlook [5], which is similar to the economic conditions of the MIJ society. In addition, a drastic transition in socioeconomic conditions would be required to achieve the Share society, assuming negative economic growth; this would seem quite difficult. Thus, the MIJ society is the most probable vision of the society.

Even though Japan aims to be a low-carbon society, it will still be a large importer of fossil fuels, at least in the short- to mid-term future. To further improve its energy security, additional policy measures should therefore be introduced. First, an increase in the share of renewable energy will be indispensable to diversify the primary energy structure. Japan still heavily relies on fossil fuels, but it has significant potential to introduce renewable energy. This would also decrease its dependence on imported fossil fuels. Therefore, a policy to increase renewable energy, such as the enhancement of the FIT and R&D subsidies and the promotion of technology improvement, will be essential. However, if the share of variable renewable energy, such as PV and wind, increases too much, the stability of the power system will be affected. In Japan, after the FIT was introduced, renewable energy increased, but most of the increases were achieved by PV. Therefore, increases of stable and dispatchable renewable sources (e.g., medium- and small-hydro, biomass, and geothermal power) are expected. Simultaneously introducing energy storage and demand management systems will also reduce the influence of increasing variable renewable energy, although such systems will generate an additional cost. Second, with regard to energy imports, balancing the origins of imported energy and reducing imports from high-risk countries will also contribute to improvements in energy security, although these will affect only the S2 and S3. Finally, reducing energy demand, or energy saving, is also an important factor in improving energy security performance. Energy saving is also related to decoupling economic growth and energy consumption, as current economic activities are highly driven by energy consumption. By reducing energy demand, energy supply from fossil fuels can be reduced. This will contribute to balancing the primary energy sources (increasing the share of renewable energy sources), balancing the origin of energy imports, and reducing energy imports from high-risk countries. These measures suggest that achieving a low-carbon society and improving energy security are compatible aims.

This study focused on the case of Japan, but the same indicators can be applied to other countries to evaluate energy security in the same manner. Many countries with large energy consumption depend heavily on fossil fuels for their energy supply [79]. For example, China, the largest energy consumer in the world, turned to a net coal importer in 2009 because of its rapid economic growth, becoming the second largest coal importer. About 28% of the oil consumption in the United States still comes from imported oil, although the country has experienced the shale revolution in its domestic oil industry. The European Union imports about 70% of its gas consumption. India, one of the emerging energy consumers, depends on imported fossil fuels for 30% (coal), 80% (oil), and 40% (natural gas) of its consumption. Therefore, the same lessons mentioned above can be adapted to other countries, particularly to countries who import energy like Japan. Most of these energy importers are also large greenhouse gas emitters. Hence, it is recommended that they make a great effort to move toward a low-carbon society, not only to fulfill their responsibility of climate change mitigation but also to improve their energy security.

As mentioned earlier, increasing renewable energy will be the highest priority for the improvement of energy security, because this type of energy can substitute for imported fuels and can diversify energy sources. Because of differences by country of meteorological conditions and other sociotechnical conditions, such as seasonal and daily variation in energy demand, grid flexibility, and social acceptance of power generators, no renewable energy can be a single dominant energy source all over the world. Policymakers should promote the renewable energy suitable to their countries. A reliable international and intranational energy grid should also be developed.

Although each country may pursue high economic growth considering the values of its current society, there are diverse ways to realize economic growth, as indicated in the difference between the MIJ and R&D societies. Several studies have revealed that renewable energy consumption has a positive impact on economic growth [80,81]. Some countries have decoupled their GDP growth and energy consumption by shifting from heavily energy-intensive industries to less energy-intensive and service industries. Dealing with the interaction between economic growth strategy and energy policy is not a minor task. However, no matter what growth strategy a society selects, considering the direction of economic growth with renewable-energy use and energy savings will simultaneously improve the energy security of the country.

In this study, we took from the LCN socioeconomic scenarios and effort levels directed toward a low-carbon society, to cover a plausible range of future energy scenarios. Although the parameters until 2050 in the LCN are determined by an interpolation between parameters in 2010 and 2050, future trajectories and technology options may be diverse [82].

We also did not consider mitigation costs or the impact of future climate change in this study, and other energy security issues might occur that result from climate change mitigation. For example, the large-scale importation of biomass energy or hydrogen generated by variable renewable energy could be one mitigation option. A high penetration of variable renewable energies may accelerate the international and intranational transmission of electricity, with fluctuating outputs. An analysis of these new security issues would be tasks for the future.

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Declaration of interest

None.

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