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Energy security in East Asia under climate mitigation scenarios in the 21st century[☆]

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ABSTRACT

Japan, China, and South Korea depend heavily on imports for most of their energy. This study aims to investigate how energy security in these three East Asian countries will change in the future under climate mitigation policy scenarios. The study will help researchers and policy makers to better understand the relationship between climate and energy issues that will arise in relevant policy discussions. The analysis was conducted using a computable general equilibrium model. A reference scenario and two policy scenarios based on the Representative Concentration Pathways adopted by the Intergovernmental Panel on Climate Change are analyzed and compared between primary energy, fossil fuels imports, and diversification of energy sources.

The findings suggest that to reduce greenhouse gas emissions, the three East Asian countries need to shift their energy structures from currently dominant fossil fuels to renewables and nuclear power. The lower the target of allowable emissions, the larger the required shifts will have to be. Among fossil fuels, coal use in particular must significantly decrease. Such structural shifts improve energy self-sufficiency, thus enhancing energy security. However, the impact of diversification of energy sources (measured by the Herfindahl index) under climate mitigation scenarios differs by country and scenario. Until 2050, diversity improves in all three countries relative to the base year. After that, in some countries the diversity should decline because of high dependence on a specific energy source. Overall, it is revealed that energy security improves along with climate mitigation. This improvement will also contribute to the economy by reducing energy procurement risks.

1. Introduction

Climate change is currently the most significant global environmental issue and policy discussions with mid- to long-term perspectives are ongoing worldwide. A critical negotiated treaty is the United Nations Framework Convention on Climate Change (UNFCCC). The Copenhagen Accord, agreed in December 2009, was an important step along the global path to climate change, and the Annex I parties and some major non-Annex I parties, such as China and India, submitted their pledges on greenhouse gas (GHG) emission reduction by the end of January 2010. The Kyoto Protocol expired at the end of 2012, but at the 2012 UN Climate Change Conference there was agreement to extend it until 2020 and to develop a successor to it by 2015. However, important developed countries such as Canada, Japan, and Russia did not participate in the post-Kyoto Protocol.

In recent years, energy demand has dramatically increased in large emerging countries such as China and India. This demand is driven by economic and population growth, and is expected to increase further [1,2], raising concerns about energy supplies in the future. In addition, because production and reserves of fossil fuels such as crude oil and natural gas are predominately located in a limited number of countries [1], other countries, including those in East Asia, that are poor in energy resources and dependent on imported fossil fuels will face potential price-fluctuations and geopolitical risks.

Climate change measures[1] are aimed at reducing GHG emissions, in particular CO_2. To emit less GHGs, promotion of energy efficiency and shifts to low-carbon energy, namely shifts from coal to natural gas and from fossil fuels to renewables and nuclear

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[1] In this study, only mitigation measures are considered under climate change policies. Adaptation measures are not considered.

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energy, are critical. If energy savings and low-carbon energy use are both adopted as climate change measures, the volume of and the dependence on imported energy will decrease[2]. This in turn will help to improve energy security [5,6].

To achieve energy security—that is, sufficient energy to support economic activity and social welfare—in countries that rely on foreign energy sources, risk diversification is essential. The methods include diversifying supply (importing fuels from many countries and not relying only on a small number of suppliers), diversifying fuel types, and industrial globalization [7]. It is also important to reduce energy imports and to increase energy self-sufficiency. The latter highlights the fact that business analytics research is nowadays essential in identifying and mapping the potential needs and strategies that energy firms and governments need to take in order to tackle the energy security issue that is higher in their agenda than ever before. In that respect, this is where our paper contributes in the existing literature.

In this context, East Asian countries have a significant energy security issue. Japan and South Korea (hereafter Korea) produce little or no fossil fuels [1,2]. China produces fossil fuels, but its demand exceeds its production [1,2]. In addition, it is expected that China will continue to enjoy high economic growth in the future, meaning energy demand and energy imports will both increase significantly [2].

Research on energy security in Asian countries is part of the Asian Energy Security Project [8–22], coordinated by the Nautilus Institute [23]. The research includes Japan, Korea (North and South), China, and Vietnam, and uses both a narrow definition (energy security only in terms of energy supply), and a more broadly defined energy security that is not only based on energy supply, but also includes economic, technological, environmental, social and cultural, and military perspectives, applying the Long-range Energy Alternatives Planning (LEAP) software system [20,21]. The LEAP system is a scenario/energy pathway-based energy-environment modeling tool to create models of different energy systems. Energy pathways or scenarios are internally consistent storylines of how an energy system might evolve over time (often between 20 and 50 years) in a particular socioeconomic setting and under a particular set of policy conditions [20,24]. Multiple energy pathways within a country or a region are compared to indicate which pathway is preferable using various energy security criteria such as cost, energy output, fuel imports and exports, and technological development. Other external methods such as diversification indices, multiple-attribute analysis and matrices, and qualitative analysis can be applied using the results from the LEAP system for further analysis on energy security [20].

There are some studies investigating the subject of energy security. Vivoda [25], for example, develops an energy security assessment instrument, which allows to analyze broadly defined energy security by considering 11 energy security dimensions. However, although the concept is shown, energy security is not analyzed in the paper. Löschel et al. [26] propose ex-post (e.g., energy prices) and ex-ante (e.g., concentration of energy supplies) indicators to evaluate energy security of countries. Using the illustrative indicators, they analyze energy security in Germany, the Netherlands, Spain, and the USA. However, their analysis on future energy security by the ex-ante indicators is only in short term (year 2030) and is based on one of the International Energy Agency (IEA)'s scenario. Kruyt et al. [27] implement more comprehensive analysis on energy security applying a scenario approach using a global energy system model, similar to the abovementioned LEAP system. They use a climate mitigation scenario and apply several energy security indicators, including energy prices and supply/demand, and fuel shares, to Western Europe as a whole in the mid-term perspective (year 2050). Although the approach is similar to our study, they employ an energy system model like the LEAP system and do not analyze Asian countries for which the energy security issue is of enormous concern.

In the operations research (OR) area, research on energy, especially energy system management and decision making on energy-related issues, has been extensively conducted, while that on energy security is fairly limited. The following are two examples on energy security in this area. Lia et al. [28] focus on oil-importing optimal decision using a multi-objective programming approach connecting with emergency (risk) scenarios. Gülpınar et al. [29] tackle with the issue on investment decision in petroleum markets under the supply disruption risk. Although these studies approach important aspects of the energy security issue, they do not consider other energy sources and the wider economic system, important elements that need to be addressed since oil markets are not independent.

Some studies such as Boland et al. [30], Marufuzzaman et al. [31], Matos and Hall [32], and Relvas et al. [33] address the trade (or supply chain) issue of different energy types, which relate to the energy security issue, and are treated in this paper to some extent. Other examples related to energy in OR are as follows. Arora and Taylor [34] generate probability density estimates for electricity consumption using the data of individual smart meters, which can be used for minimizing consumers' excess electricity use and devising time-of-use pricing for suppliers. Similarly, Zhao et al. [35] forecast electricity consumption using the high-order Markov chain based time-varying weighted average method, which will contribute for avoiding wastes of scarce energy resource or electricity shortages. In addition, Li et al. [36] apply the grey theory for forecasting electricity consumption in Asian countries using limited (short-term) data, which is valuable for policy making in developing countries showing high and unstable growth. On the other hand, Papadopoulos and Karagiannidis [37] apply a multi-criteria analysis method for optimizing the penetration of renewables for power generation into an insular system. These studies do not directly approach the energy security issue, but such energy management and decision making are closely related to it by reducing or optimizing energy use. Considering the above aspects, this paper contributes in the area of business analytics with an application on the energy sector, more specifically examining the energy security issue focusing on East Asia.

In this paper, we analyze the energy security issue in three East Asian countries, Japan, China, and Korea. Energy security is an important issue for these countries because their economic activities are highly dependent on fossil fuels and they are among the world's largest fossil fuel importing countries [1,2]; with the majority of imports, particularly oil, coming from the Middle East.

We examine climate mitigation policies (or emission pathways) using a computable general equilibrium (CGE) model. By using a CGE model, an inclusive assessment of economic activities (markets), including energy sectors and non-energy sectors, and the whole activities of countries are kept in the analysis; an approach that differs from the abovementioned studies. In addition, multiple climate mitigation scenarios are considered simultaneously for comparison. Since the climate change and broader energy issues are now both related to global business more than ever before, this study contributes to business analytics literature that focus on energy-related research. We analyze energy security in terms of primary energy structure, net imports of fossil fuels, and diversity of energy type. Furthermore, we analyze the entire 21st century, in contrast to previous studies that focus on the short to medium term. The long-term consequences are important, because the world will be highly dependent on fossil fuels for many years to come (e.g., Masui et al. [38]; Riahi et al. [39]; Thomason et al. [40];

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[2] Renewables are basically domestic energy and nuclear energy is considered semi-domestic energy [3,4].

van Vuuren et al. [41]). Analysis on energy security in the global scale has been done by Matsumoto [42].

2. Methods

2.1. Model

We use a CGE model to evaluate how energy security and the energy structure change under climate mitigation scenarios during the 21st century. This model is based on Masui et al. [38], Matsumoto [42], Matsumoto and Masui [43,44], and Okagawa et al. [45]. A CGE model is a top-down model for analyzing the economic implications of energy and climate change issues and policy designs (e.g., Matsumoto and Masui [43,44]; Peace and Weyant [46]; Saveyn et al. [47]; Shukla et al. [48]).

This study applies a global recursive dynamic CGE model, including energy and environmental factors. An overview is provided here and model details are explained in Appendix A. The model, also referred to as an integrated assessment model, is composed of 24 geographical regions and 21 industrial sectors (Tables A1 and A2 in Appendix A), and having a final demand sector. Within the energy sector, electric power is disaggregated into specific production technologies, including thermal, hydro, nuclear, and renewables. Each industrial sector is represented by a nested constant elasticity of substitution (CES) production function (see Figure A1 in Appendix A).

Each industrial sector produces goods/services for international or domestic markets. In each domestic market, the supplied goods/services are consumed as final consumption, investment, or intermediate input for industrial sectors. The total investment demand in each period, which forms capital in the next period, is set exogenously to meet a prescribed future economic growth rate (see Section 2.2.1). To be more precise, economic growth is realized by increasing production factors (capital, labor, land, and resources) and efficiency improvement (including energy efficiency, land productivity, and total factor productivity). In the model, investment demand is assumed to be increased in line with the increase rate of Gross Domestic Product (GDP)[3].

The final demand sector in each region owns all production factors and supplies them to the industrial sectors to earn its income for final consumption and savings. The final demand is determined to maximize the utility.

The model handles the global emissions of 13 gases including CO_2, and is run to follow the emission pathways described in Section 2.2.2 between the base year 2001 and 2100. GHG emissions trading on a global scale is considered in the model.

The model was calibrated to reproduce economic activity and energy levels in the base year using the following data: the Global Trade Analysis Project (GTAP) 6 database [49] for economic activity levels; the Emission Database for Global Atmospheric Research (EDGAR) v4 database [50] for GHG emissions; and the IEA energy balance tables [51,52] for energy.

2.2. Scenarios

Energy security is analyzed by applying the reference scenario and policy scenarios to the CGE model.

2.2.1. Reference scenario

As a first step in the process of developing policy scenarios (see Section 2.2.2), we developed a “no-climate-policy” reference scenario. This means that without policy intervention, GHG emissions and concentrations, and radiative forcing would exceed those of the policy scenarios. The reference scenario assumes that no policies and measures solely aimed at controlling GHG emissions, beyond those already in place, are introduced, and that the existing policies are not renewed when they expire. The reference scenario makes several assumptions. Demographic assumptions are based on a medium variant of the UN World Population Prospects [53]. Future economic growth assumptions are based on the Sustainability First scenario presented in the United Nations Environment Programme (UNEP) (2007) Global environment outlook 4 [54]. Finally, technological improvement is based on the Special Report on Emission Scenarios (SRES) B2 scenario of the Intergovernmental Panel on Climate Change (IPCC) [55]. The SRES B2 scenario is selected because it is a moderate scenario in the series, and the population and GDP are similar to the assumptions in this study [55]. These assumptions are applied to both the reference and the policy scenarios.

The following details summarize the reference scenario. The global population grows from 6.1 billion in the base year to 9.8 billion in 2100, with a peak between 2080 and 2090 (Fig. 1a). Global GDP reaches $230 trillion in 2100 (Fig. 1b), and the global primary energy demand reaches 1178 EJ in 2100 (Fig. 1d–e). Globally, fossil fuel demand, particularly coal, will increase continuously during this century because of its relatively low cost. Consequently, total CO_2 emissions increase to 25.1 GtC/yr in 2100 (Fig. 1c), and the total radiative forcing reaches 7.2 W/m^2 in 2100.

2.2.2. Policy scenarios

The Representative Concentration Pathways (RCPs) are used for the climate change policy (mitigation) scenarios[4]. RCPs are the first step toward the Fifth Assessment Report (AR5) of the IPCC [58] and one of the latest climate policy scenario families. RCPs are defined by radiative forcing levels in 2100 and consist of four scenarios, namely the lowest 2.6 W/m^2 [41], the highest 8.5 W/m^2 [39], and the two middle scenarios of 4.5 W/m^2 [40] and 6 W/m^2 [38].

Two scenarios are analyzed using the CGE model and compared with the reference scenario. They are the medium-low scenario (S4.5 below), with RCP 4.5 W/m^2, and the lowest scenario (S2.6 below), with RCP 2.6 W/m^2 (see Fig. 2). Since this study examines the energy security issue under climate mitigation scenarios, it is preferable to use relatively new scenarios in this area. Thus, we used the RCP scenarios, which are used in the IPCC AR5 [56] and also recent studies in this area [59,60]. Furthermore, since the emissions of the highest RCP 8.5 W/m^2 scenario [39] exceed those of the reference scenario and the climate mitigation level of the RCP 6 W/m^2 is much higher than that required for achieving the ultimate objective of the UNFCCC [38,57], the S4.5 and S2.6 scenarios were selected.

For analyzing the S4.5 and S2.6 scenarios, the emission pathways (Fig. 2b) are set as the constraints in the model. Emissions trading on a global scale is then applied to achieve the emission targets cost-efficiently. Given the constraints, carbon prices corresponding to the emissions are imposed on fossil fuel use (the larger the emission reduction, the higher the carbon price will be), which increase their respective prices. Since the model includes low-carbon technologies such as several types of renewables, nuclear power, and carbon capture and storage (CCS) technology (see Section 2.1 and Appendix), fossil fuels are replaced with such low-carbon technologies according to the CES production functions in the model.

Note that the energy structure is not exogenously controlled to maintain a specific level or percentage (such as *p*% or *e* GWh of

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[3] Since the model used in this study is a recursive dynamic CGE model, the total investment demand cannot be determined endogenously.

[4] See Moss et al. [56] and van Vuuren et al. [57] for the details of RCPs.

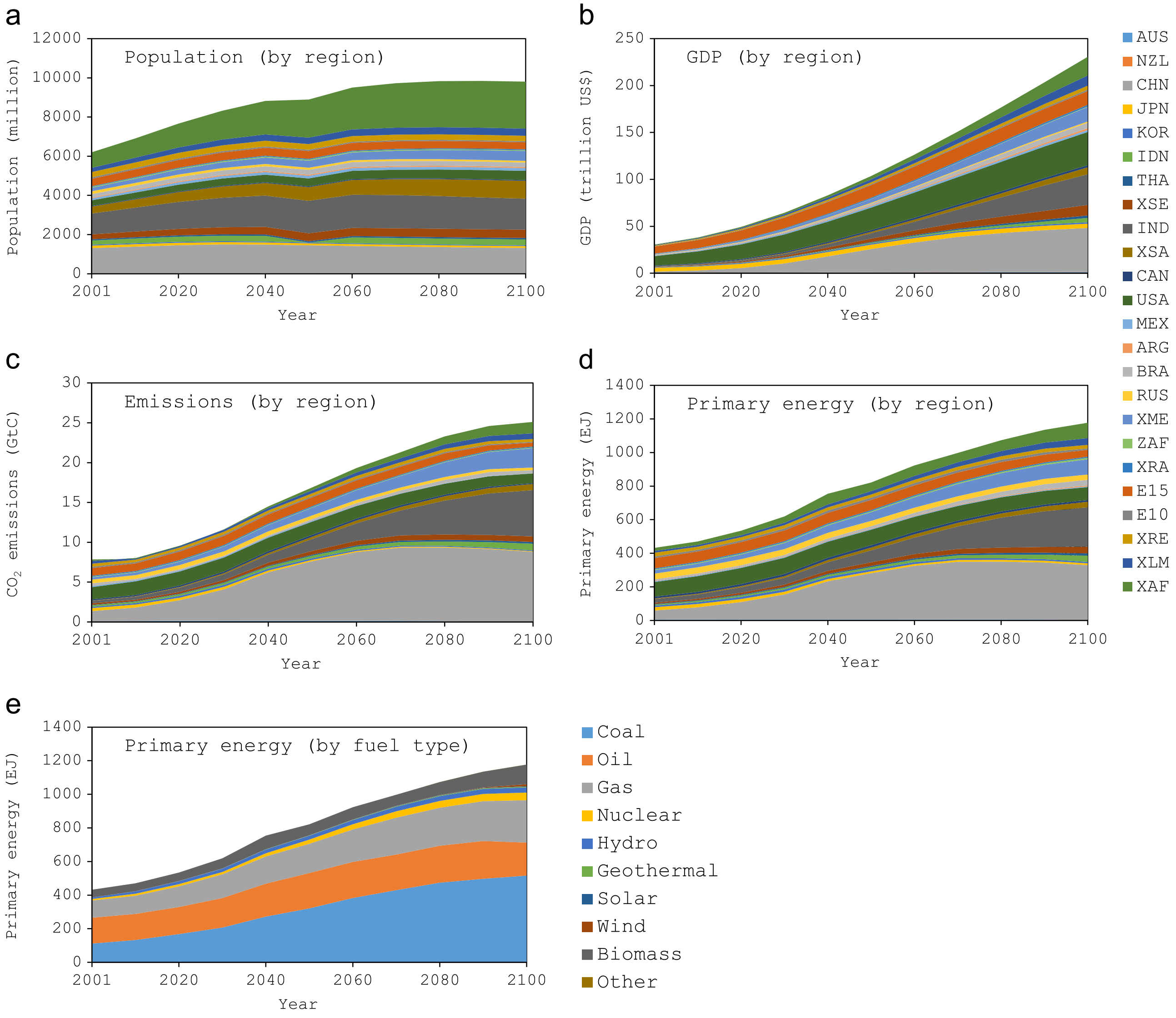

Fig. 1. Reference scenario ((a) population; (b) GDP; (c) total CO_2 emissions; (d and e) primary energy demand (by region and by fuel type)).

nuclear power generation in country *A* in year *Y*) when simulating both the reference and policy scenarios. The model analyzes endogenously changing energy security and energy structure by the scenarios.

3. Results and discussions

To understand energy security under climate change policies, we focused on changes in primary energy demand, fossil fuels imports, and diversity of energy types in the 21st century. In this section, the results in years 2050 and 2100 are discussed.

In the reference scenario, the total primary energy demand in China increases in this century, while in Japan the demand is smaller in 2050 and 2100 than in the base year (Table 1). In Korea, the primary energy demand increases in 2050, and then decreases toward 2100. In China, economic development and a growing population drive the increasing primary energy demand. Conversely, declining populations in Japan during this century and in Korea in the latter half of the century, plus low economic growth rates relative to China, cause a decrease in their primary energy demand. In the two policy scenarios, the total primary energy demand is smaller than the reference scenario in all countries (Table 1), with the demand in the S2.6 scenario the smallest. This means that reducing the total primary energy demand is required to reduce GHG emissions from the reference scenario in this study. It should be noted that in China, even under the S2.6 scenario, the primary energy demand exceeds the 2001 level.

The energy structure drastically changes in the three countries over the study period (Fig. 3). It is important to note that energy structure is not controlled exogenously in the model, but is determined by the relative cost of each energy source in the model. In China under the reference scenario, the percentage of fossil fuels in the total primary energy demand increases and exceeds 90%, with coal the main fuel source. In Korea, the percentage of fossil fuels decreases from the base year level, which was higher than 90%, in both 2050 and 2100, but remains at a high level. In addition, the percentage of coal increases because of its relatively low cost among fossil fuels. In Japan, however, although fossil fuels remain the main energy source in the middle of this century, the percentage of nuclear energy increases significantly by 2100. Following the Fukushima Daiichi nuclear disaster, most nuclear power plants in Japan have not yet been operational. Some countries such as France and China are promoting nuclear energy use, but others including Germany and Switzerland declared a nuclear power phase-out after the Japanese disaster. Introduction and promotion of nuclear energy

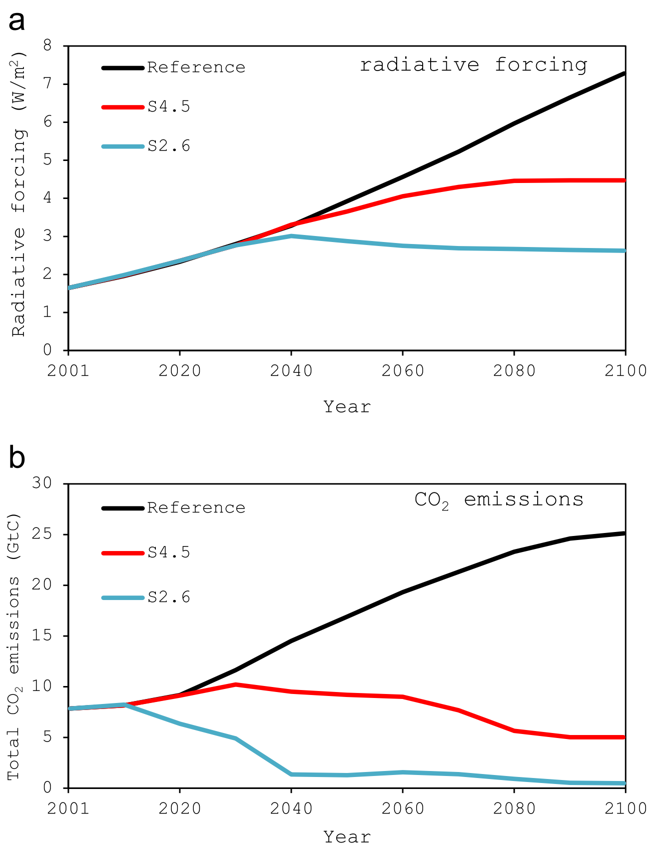

Fig. 2. Radiative forcing levels (panel (a)) and corresponding total CO_2 emissions (panel (b)) in the scenarios (based on Matsumoto [42]).

Table 1
Total primary energy demand (EJ).

	2001	Reference		S4.5		S2.6	
		2050	2100	2050	2100	2050	2100
Japan	19.9	12.1	8.2	11.6	8.0	9.3	7.5
China	53.5	275.6	330.0	149.8	114.8	73.5	98.5
Korea	9.1	13.3	9.2	11.5	7.1	7.2	6.7

is mainly affected by each nation's energy policy. For economic and climate mitigation reasons, nuclear power is still considered an important “base load” power in Japan's new Basic Energy Plan [61]. In addition, electric companies are working toward restarting operations of their nuclear power plants. Although the Japanese government also intends to increase the use of renewables by introducing a feed-in tariff scheme, nuclear power is expected to play an important role in combating climate change and addressing energy issues in the future; at time of writing, however, the government has not yet decided on future targets for its energy infrastructure, including nuclear power. Hence, bearing in mind the aforementioned, even though policies such as a renewable portfolio standard and a feed-in tariff are often introduced to increase the amount/percentage of renewables, it is not possible to develop plausible future assumptions for energy policies of the countries and regions in the model because the future energy policies of every country is more long-term and involves a number of uncertainties. Thus, though GHG emission reduction is considered in the scenarios, specific energy policies are not addressed in this study. Conversely, as it is not possible to introduce energy infinitely, especially renewables, we set the upper limits of potential energy use (see Appendix A and also Matsumoto [42] for the details).

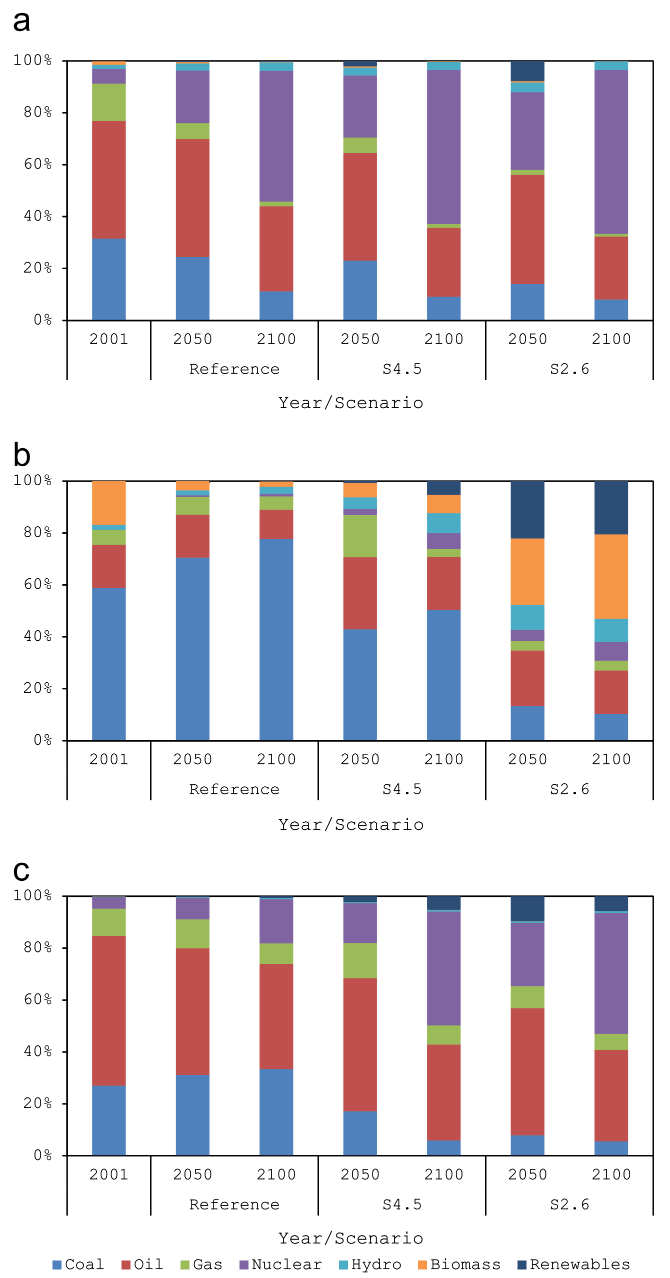

Fig. 3. Structure of primary energy in East Asian countries ((a) Japan; (b) China; (c) Korea). Renewables in the figure include those except hydropower and biomass.

The policy scenarios have fossil fuels, especially coal significantly decreasing in the three countries, and renewables and nuclear energy increasing. In Japan and Korea, nuclear energy occupies the highest percentages among primary energy demand in 2100. In Japan, the percentage is remarkably high because its total primary energy demand is low, but the total amount is not significantly larger. In Japan and Korea, although some renewables are introduced, the percentage is less than 10%, and biomass power increases very little. In China the percentage of renewables, including biomass power, increase significantly relative to the other two countries examined in this paper, especially in the S2.6 scenario and in the later years of the study period. In the model, the available land for agriculture is based on the GTAP database [49], taking into account possible competition in land use among sectors that use land as a production factor, including biomass energy (bio-energy crops) [38,49] (see also Appendix A.2.1). For the future land use, land productivity improvement is also assumed [38]. In addition, for the future renewables, their potential is assumed based on Masui et al. [62]. In these assumptions, land mass of a region is an important factor to determine the potential, since the larger the land area, the larger the areas for cultivating bio-energy crops and installing renewable-energy facilities. The latter reflects China's potential to harness renewable power from its enormous land mass. The absolute amount of nuclear energy in the policy scenarios is larger than in Japan and Korea, but the percentage is smaller because of China's high primary energy demand.

With respect to trade activity of fossil fuels in terms of net imports (imports minus exports) in the three countries (Fig. 4), the total steadily increases in China in the 21st century, increases until 2050 and then decreases in Korea, and continuously declines in Japan. Although China is a net-exporting country of coal in the base year, it soon becomes a net-importing country in both the reference and policy scenarios.

By 2050, under the S4.5 scenario the net imports of fossil fuels relative to the reference scenario are 11.5% lower in Japan, 24.4% lower in China, and 14.2% lower in Korea. Under the S2.6 scenario, the reductions are 37.1%, 74.9%, and 53.9% for Japan, China and Korea respectively.

By 2100, the figures show a similar pattern. According to the S4.5 scenario, net fossil fuel imports have declined from the reference case by 16.6% in Japan, 53.7% in China, and 41.1% in Korea. Greater declines are seen under the S2.6 scenario, with of 29.4% in Japan, 72.5% in China, and 47.9% in Korea.

Considering the net imports by fuel type, the decline in coal is the largest, followed by oil and natural gas. The lower emission scenarios tend to show lower net imports for all types, except for natural gas in 2050, in both China and Korea under the S4.5 scenario. Because the carbon intensity of natural gas is the lowest of the fossil fuels, the use of natural gas is often promoted to reduce GHG emissions. However, to reduce GHG emissions to targets for the latter half of the 21st century, shifting to low carbon-intensive fossil fuels is not sufficient, and reducing the total amount of fossil fuels will be required.

The study indicates that decreasing dependence on fossil fuels and increasing the amount and percentage of renewables and nuclear energy will help to mitigate climate change. The three East Asian countries are net importers of fossil fuels and their dependence is very high. Replacing fossil fuels and reducing their net imports will improve energy self-sufficiency and improve energy security, an important consequence of promoting climate change measures.

As Fig. 3 illustrates, the dependence on fossil fuels, which are largely imported energy sources in the three countries, decreases significantly in the policy scenarios, especially under the S2.6 scenario. Similarly, net imports of fossil fuels decrease under the policy scenarios (Fig. 4), underlining the important roles of reducing imported energy and increasing the rate of self-sufficiency in achieving energy security. Increasing the diversity of energy sources is also important, as this can diversify the risk [7]. The Herfindahl index (HI) is a metric for energy security implications of different patterns of energy supply and demand. It is based on diversity indices in the economic and financial analysis [7,20,63] and is applied to measure the effects of diversification of energy sources. The index has a maximum value of one when there is only one energy source, and decreases with additional energy sources. The lower the value of the index, the more diverse the sources. When calculating the index (Eq. 1), renewables are disaggregated by type, namely solar, wind, geothermal, and other renewables (see Fig. 3).

$$H = \sum_i x_i^2 \tag{1}$$

where H is the Herfindahl index and x_i is the fraction of primary energy demand by energy type i.

Applying the index to the scenarios, the values change both in 2050 and 2100 relative to the base year (Fig. 5). In the reference scenario, diversity worsens in China over time, while it improves in Korea. China depends more heavily on coal in the future, while Korea uses fossil fuels and nuclear energy in a balanced manner in 2100. In Japan, the diversity value decreases until 2050, and then increases in the latter half of the century. This reflects how much the country depends on nuclear energy. A continuous increase in the percentage of nuclear energy in this century is modeled, achieving a balance between fossil fuels and nuclear in 2050, with nuclear energy dominating in 2100.

Comparing the reference with the policy scenarios, there is an increase in the diversity of energy sources in all countries by 2050. Among the policy scenarios, the value is smaller in the S2.6 scenario. However, the situation in 2100 differs by country. In Japan, the values are higher than in 2050, exceeding even the 2001 level. In addition, the lower the emissions, the higher the values, which indicates a less diversified energy structure. In China, although the values are higher in 2100 than in 2050, the lower emission scenarios show lower HI values. Compared with the 2001 level, the value is higher in the reference case, while they are smaller in the policy scenarios. In Korea, the values in 2100 are higher than the 2050 levels in the policy scenarios, while they are lower than the 2001 level. These results indicate that when reducing GHG emissions as part of climate change mitigation, the diversity of energy sources initially improves by reducing dependence on fossil fuels, especially coal. It should be noted that new energy technologies such as fuel cells and algofuels are not considered in the model, since large uncertainties exist on them. Although the Herfindahl indices become higher in 2100 in some cases (Fig. 5), such energy technologies and other future potential technological breakthroughs can improve the diversity of energy sources.

The results suggest that energy security is improved under climate mitigation scenarios by reducing fossil fuels' imports and increasing energy self-sufficiency, a consequence of a reduction in total primary energy demand and a shift in energy structure from fossil fuels. However, the impact on diversity of energy sources differs by country and scenario. It depends on which types of energy sources are selected when shifting from fossil fuels, how fast such a shift takes place, and to what extent such a shift moves the country toward a low-carbon society in 2100. Paradoxically, the diversity measured by the HI declines when the dependency on fossil fuels declines, because the three types of fossil fuels contribute to “diversity” of energy sources, and the use of a specific non-fossil energy source increases. However, such declines in diversity are derived from a decrease in the use of fossil fuels, most of which are imported in all three countries under examination. Thus, overall, it is demonstrated that climate mitigation contributes to improved energy security of the countries, although the diversity of energy sources appears to suggest otherwise.

4. Concluding remarks

In this study, we analyze the impact of climate mitigation policies on energy security by using the CGE model. In the analysis, we use the RCP-based scenarios for the policy scenarios and compare them with a reference scenario.

Overall, to reduce GHG emissions in a sustainable manner, the three studied East Asian countries need to shift their energy structures from fossil fuel dominance to renewables and nuclear power. Among fossil fuels, coal must be significantly reduced, followed by oil and lastly natural gas. The lower the target of allowable emissions, the larger the shifts from fossil fuels must be. The study also reveals that such shifts will improve energy self-sufficiency and are consequently effective from the viewpoint of energy security. However, the impact on diversity of energy

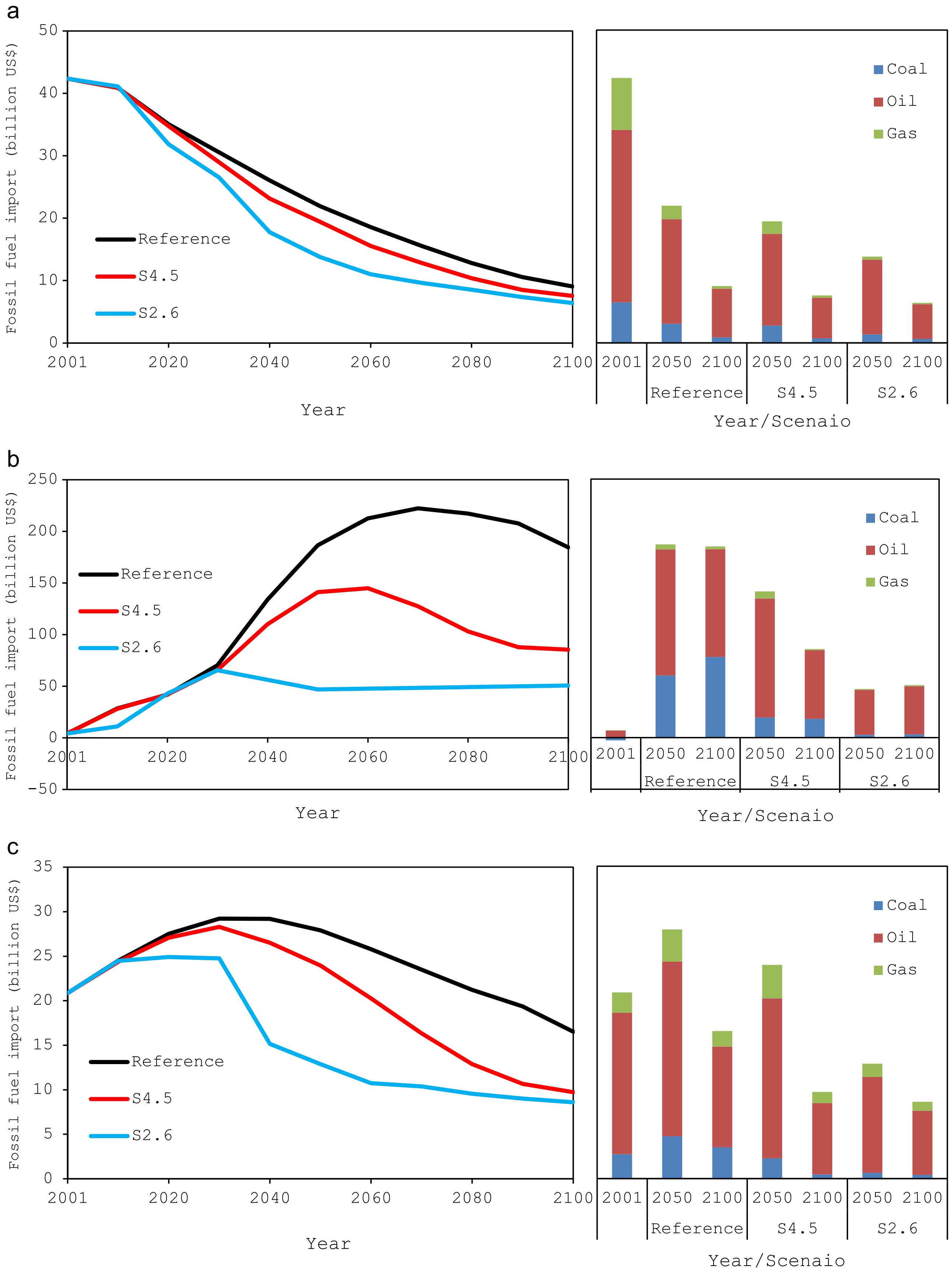

Fig. 4. Net import of fossil fuels ((a) Japan; (b) China; (c) Korea). In each sub-figure, the left hand panel shows the net imports of fossil fuels. The right hand figure shows the structure of fossil fuels in the base year, 2050, and 2100.

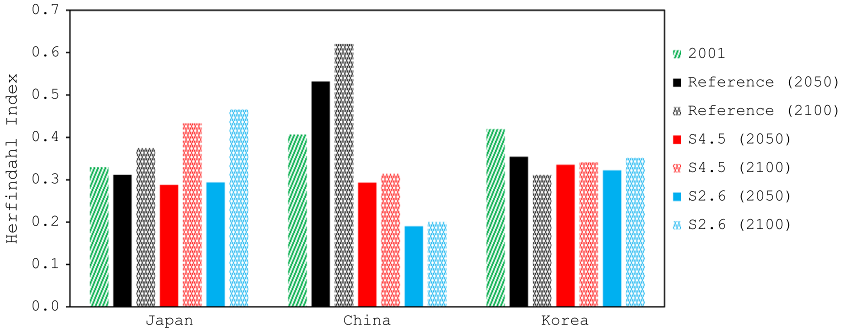

Fig. 5. Herfindahl indices in East Asian countries.

sources under climate mitigation scenarios differs by country and by scenario.

Japan is already one of the most developed countries in the world and its population is in decline. The study indicates that fossil fuel use and imports (along with total primary energy demand) decreases, and energy security improves even in the reference scenario. These results continue through 2050, after which, although the percentages of fossil fuel use and imports continuously decrease, the diversity of energy sources declines due to high dependence on nuclear power.

China is a net exporter of coal in the base year, but it soon becomes a net importer. Unlike Japan, the diversity of energy sources as measured by the HI, worsens in the reference scenario because of a large increase in fossil fuel use, particularly coal. By introducing the policy scenarios to reduce GHG emissions, the diversity index significantly improves in response to an increasing share of renewables and decreasing share of coal. A decrease in fossil fuels imports is also observed.

The situation in Korea lies in between that of Japan and China. In the reference scenario, the total primary energy demand increases until 2050 and then decreases, while the share of nuclear energy constantly increases until 2100. Consequently, its diversity of energy sources improves. Because the use of renewables and nuclear energy increases to reduce GHG emissions, further improvement in energy diversity is realized under the policy scenarios in 2050. Like Japan, however, although the percentages of fossil fuel use and imports continuously decrease, energy diversity declines owing to high dependence on nuclear power.

The main purpose of climate mitigation is obviously to reduce GHG emissions and avoid further climate change. This study indicates that energy security improvement is achieved simultaneously with climate mitigation policies. Although introducing climate mitigation policy has a negative effect on economic growth in general [58], energy security improvements will contribute to the economy by reducing procurement risks.

Reduction in diversity of energy sources is a potential consequence of reducing net imports of fossil fuels and increasing reliance on domestic and semi-domestic energy sources. Dependence on only a few energy sources poses risks. For example, nuclear power plants are susceptible to severe accidents, as demonstrated in Japan in 2011. Renewables such as solar and wind power are also variable and their performance is largely affected by weather. Energy storage solutions and a wider diversity of sources are also important aspects of the countries' efforts to achieve a low-carbon society. In addition, each country has a different endowment of renewable resources. Korea has little potential for geothermal energy, and Japan and Korea, with their limited land masses compared to China, have lower potentials for widely developing biomass fuels. Thus, policies designed to increase the use of renewables must be tailored to each country.

Finally, diversification of the origin of fossil fuels imports is not analyzed in this study, because the model does not disaggregate the regions (Table A1). For example, the countries of the oil-producing Middle East are not disaggregated, which could be a future avenue of research in this area.

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Appendix A

This appendix provides further details of the CGE model used in the analysis.

A.1. CGE models in general

A CGE model is an economic model that uses actual economic data such as input–output tables and national economic accounting to estimate how the economy might react to changes in factors such as policy and technology. This can be on a global or individual country basis, where price is an important signal driving economic agents and balancing supply and demand of each goods/service and each production factor in the economy. A CGE model consists of equations describing model variables and a database consistent with the equations. The equations are generally based on neoclassical economic theory, often assuming industrial sectors (producers) cost minimization, average-cost pricing, and final demands based on optimization behavior. The model is also widely regarded as a top-down model for analyzing the economic implications of climate change [46,48]. Carbon pricing policies such as carbon tax and emissions trading change the relative prices from the baseline condition according to the GHG intensity of the goods. This means that energy-intensive industries such as the steel industry tend to experience a larger negative effect from such policies. Many climate policy designs have been evaluated quantitatively with various CGE models (e.g., Chen et al. [64]; Kumbaroglu [65]; Matsumoto and Masui [43,44]; Saveyn et al. [47]; Timilsina et al. [66]).

A.2. CGE model in this study

A.2.1. Model structure

This study applies a multi-regional and multi-sectoral recursive dynamic CGE model on a global scale, incorporating energy and environmental components that is based on the work of Masui et al. [38], Matsumoto and Masui [43,44], and Okagawa et al. [45]. The model is disaggregated into 24 geographical regions and 21 types of economic goods and service. These structures are shown in Tables A1 and A2. Each region in Table A1 includes the production sectors shown in Table A2. One sector produces one type of goods or service, and we assume perfect competition in all markets and that production is subject to constant returns to scale technology. The electric power sector (the electric power (ELY) sector in Table A2) is disaggregated into specific production technologies, including thermal power (coal-, oil-, and gas-fired), hydropower, nuclear power, solar power, wind power, geothermal power, biomass power, waste power, and other renewable power generation. Advanced thermal power plants such as the integrated gasification combined cycle are assumed to be available in the future. In addition, carbon capture and storage (CCS) technology can be designated an advanced technology for thermal power generation and biomass power generation. These new technologies are also modeled as the production functions of the ELY sector.

Each industrial sector in the economy is represented by a nested constant elasticity of substitution (CES) production function. This function includes the Leontief production function if the value of elasticity of substitution is zero, and the Cobb–Douglas production function if the value is one. Although all of the production structures are based on nested CES functions, we assume several different production structures by sector. The most basic structure is illustrated in Figure A1 where each goods or service is produced as a CES aggregate of value-added, intermediate inputs, and an energy input composite and is applied to several of the defined sectors (energy-intensive industries (EIS), metals and manufacturing (M_M), other manufacturing (OMF), food processing (FOD), construction (CNS), transportation (TRT), communication (CMN), water (WTR), governmental services (OSG), and other services (SER)). The value added is a CES aggregate of labor and capital. The energy composite is a CES aggregate of a fossil fuels composite and ELY. The fossil fuels composite is a CES aggregate of coal (COA), a liquid energy composite, and a gas energy composite. The liquid energy composite and the gas energy composite are CES aggregates of crude oil (OIL) and petroleum products (P_C), and of natural gas (GAS) and gas manufacture and distribution (GDT), respectively. During production, GHG emissions are emitted from fossil fuels and industrial processes. In the production structure, fossil fuel emissions are considered as Leontief aggregates at the bottom-level nests, while industrial emissions are considered as the Leontief aggregate at the top-level nest. GHG emissions are treated the same for the other sectors. In examining the fishery (FSH) and other mineral mining (OMN) sectors, resources are treated as a component of the "value-added." Similarly, in examining the agriculture (AGR), livestock (LVK), and forestry (FRS) sectors, land is treated as a component of the "value-added."

In the production structure for the fossil fuels extraction sectors (i.e., the COA, OIL, and GAS sectors), natural resources are considered to be aggregated at the top-level nest. The magnitude of the resource limits and associated extraction costs are obtained from Rogner [67].

With respect to the P_C sector, crude oil is considered to be aggregated at the top-level nest (and not treated as energy) because most crude oil is used as feedstock in this sector. Similarly, in the GDT sector, natural gas is considered to be aggregated at the top-level nest to treat it as feedstock in this sector.

Finally, there is a slightly different structure in the ELY sector. The thermal power sectors use corresponding fossil fuels as an input (e.g., COA is used for coal power generation), while the renewables sectors do not. However, the biomass power sector uses land as an input, and the other renewables sectors use the input of their corresponding renewable sources. This structure is similar to the Emissions Prediction and Policy Analysis model [68].

In the model, the elasticity parameters are taken from the GTAP6 database, as it was also used for economic data.

Each industrial sector produces goods and services that are delivered for the international market and/or the domestic market, by taking inputs of production factors, raw materials, and energy. The Armington assumption [69] is applied for international trade (i.e., goods and services produced in different regions are imperfect substitutes). In the model, goods and services from different regions are aggregated through a two-stage CES function; first, imports from different regions are aggregated into a composite import and then a composite import and domestic goods and services are aggregated.

In each domestic market, the supplied goods/services are consumed as final consumption, investment, and/or intermediate input for industrial sectors. The total investment demand in each period is set exogenously to meet a prescribed future economic growth rate (see Section A.2.4 below). The model uses a putty-clay approach for forming capital. It includes two types of capital, old (or existing) capital and new capital. Old capital cannot be moved among sectors, while new capital can be installed in any sector. When new capital is installed in a specific sector, it is subsequently handled as old capital. Technological improvements such as energy efficiency improvement are applied only to new capital. Thus, the productivity of aggregated (old and new) capital is the weighted average of the technology levels in old and new capital. This suggests that the more new capital is installed, the more rapid the efficiency change will be. Industrial sectors in which the new investment is not introduced do not realize technological improvement.

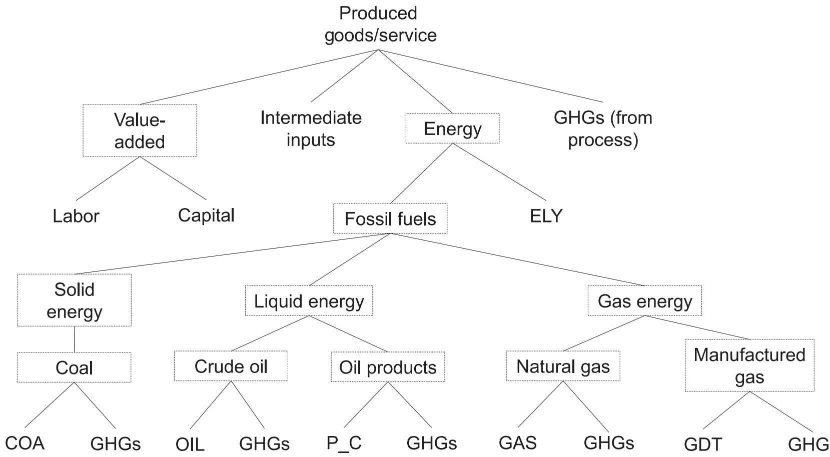

Fig. A1. Production structure for the manufacture and service sectors (EIS, M_M, OMF, FOD, CNS, TRT, CMN, WTR, OSG, and SER). This figure shows the most basic structure in the model. In each nest, corresponding factors are aggregated by a CES function, the elasticity parameters of which are obtained from the GTAP6 database..

Table A1
Region definitions.

Code	Region
AUS	Australia
NZL	New Zealand
JPN	**Japan**
CAN	Canada
USA	United States of America
E15	15 Western EU countries
RUS	Russia
E10	10 Eastern EU countries
XRE	Other Europe (e.g., Bulgaria)
KOR	**South Korea**
CHN	**China and Hong Kong**
XRA	Other Asia-Pacific (e.g., Mongolia)
IDN	Indonesia
THA	Thailand
XSE	Other Southeast Asia (e.g., Malaysia)
IND	India
XSA	Other South Asia (e.g., Bangladesh)
MEX	Mexico
ARG	Argentina
BRA	Brazil
XLM	Other Latin America (e.g., Chile)
XME	The Middle East (e.g., Saudi Arabia)
ZAF	South Africa
XAF	Other Africa (e.g., Egypt)

[a] The countries with bold font are analyzed in this paper.

Table A2
Commodities/sectors definitions.

Code	Commodities/sectors
Energy commodities/sectors	
COA	Coal
OIL	Crude oil
GAS	Natural gas
P_C	Petroleum products
GDT	Gas manufacture and distribution
ELY	Electric power [a]
Non-energy commodities/sectors	
AGR	Agriculture (e.g., rice)
LVK	Livestock (e.g., bovine cattle)
FRS	Forestry
FSH	Fishery
EIS	Energy-intensive industries (e.g., chemical products)
OMN	Other mineral mining
M_M	Metals and manufacturing (e.g., motor vehicles)
FOD	Food processing (e.g., food products)
OMF	Other manufacturing (e.g., textiles)
CNS	Construction
TRT	Transportation (e.g., air transportation)
CMN	Communication
WTR	Water
OSG	Governmental services (e.g., education)
SER	Other services (e.g., insurance)

[a] The electric power sector consists of thermal power (i.e., coal-, oil-, and gas-fired), hydropower, nuclear power, solar power, wind power, geothermal power, biomass power, waste power, and other renewables. In addition, thermal power and biomass power with CCS technology are available.

Each region has one final demand sector consisting of the household sector and government. The final demand sector in each region is assumed to own all production factors (i.e., capital, labor, land, and resources) and supplies them to the industrial sectors through the economy's factor markets. The household sector income is derived from the sale of the production factors. The final demand sector distributes income between final consumption of goods and services and savings. Savings rates are identical to investment, which is exogenously determined. The final demand for each goods or service is determined to maximize the utility represented by a CES function subject to an unsaved income constraint in each period. GHGs are emitted when the final demand sector consumes fossil fuels.

A.2.2. GHG emissions

The model is run to follow the global GHG emission pathways including: carbon dioxide; methane; nitrous oxide; carbon monoxide; nitrogen oxides; sulfur oxides; non-methane volatile organic compounds; black carbon; organic carbon; ammonia; and fluorinated gases (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride). Because the model cannot handle fluorinated gas emissions endogenously, the emissions of these gases are given exogenously.

A.2.3. Baseline data

The CGE model was calibrated to reproduce economic activity and energy levels in the base year (2001) using the following data sources: the GTAP6 database [49] for economic activity levels; the EDGAR v4 database [50] for GHG emissions; and the IEA energy balance tables [51,52] for energy.

A.2.4. Future scenario

The simulation periods of this study are those between the base year (2001) and 2100 (i.e., 2001, 2005, 2010, and every 10 years thereafter until 2100).

Several assumptions are included to expand the model to a dynamic structure. Demographic assumptions are based on the medium variant of the UN World Population Prospects [53]. Future economic growth assumptions to determine the amount of investment are based on the Sustainability First scenario in the Global Environment Outlook 4 [54]. Finally, technological improvement is based on the SRES B2 scenario [55]. These assumptions are applied to both the reference scenario and the policy scenarios.

The model includes several types of renewables: solar, wind, biomass, hydro, and geothermal energy. It is expected that the role of renewables will increase and thus reduce GHG emissions in the future; however, this increase is not infinite. Therefore, the future potential of each renewables is set in the model. The survey and calculations of Masui et al. [62] are applied in this study.

In the emission reduction cases, the global GHG emissions are assigned to regions in proportion to their population in 2050 and after. Between the base year and 2050, regional GHG emission limits are set by linear interpolation of the emissions in the base year and the limits in 2050. GHG emissions trading on a global scale is also considered in the model.

References

[1] BP. Statistical review of world energy June 2013; 2013. Available at: ⟨http://www.bp.com/statisticalreview⟩ [accessed 03.03.14].

[2] International Energy Agency. World energy outlook 2013. Paris: International Energy Agency; 2013.

[3] Ahn JH, Han KI. Korean experience in self-reliance for nuclear power technology (a case study in the Republic of Korea); 2000. Available at: ⟨http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/31/060/31060504.pdf⟩ [accessed 30.05.14].

[4] Federation of Electric Power Companies of Japan. Harmonizing nuclear energy with deregulation; 2004. Available at: ⟨http://www.fepc.or.jp/english/library/power_line/detail/23/⟩ [accessed 30.05.14].

[5] International Energy Agency. World energy outlook 2008. Paris: International Energy Agency; 2008.

[6] Stanislaw JA. Climate change and energy security: the future is now. Deloitte white paper; 2007.

[7] Neff TL. Improving energy security in Pacific Asia: diversification and risk reduction for fossil and nuclear fuels. Commissioned by the Pacific Asia Regional Energy Security (PARES) Project; 1997. Available at: ⟨http://oldsite.nautilus.org/archives/papers/energy/NeffPARES.pdf⟩ [accessed 05.03.14].

[8] Falk J, Settle D. Australia: approaching an energy crossroads. Energy Policy 2011;39:6804–13.

[9] Huang Y, Bor YJ, Peng C-Y. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy 2011;39:6790–803.

[10] Kalashnikov V, Gulidov R, Ognev A. Energy sector of the Russian Far East: current status and scenarios for the future. Energy Policy 2011;39:6760–80.

[11] Katsuta T, Suzuki T. Japan's spent fuel and plutonium management challenge. Energy Policy 2011;39:6827–41.

[12] Kim H, Shin E, Chung W. Energy demand and supply, energy policies, and energy security in the Republic of Korea. Energy Policy 2011;39:6882–97.

[13] Takase K, Suzuki T. The Japanese energy sector: current situation, and future paths. Energy Policy 2011;39:6731–44.

[14] Toan PK, Bao NM, Dieu NH. Energy supply, demand, and policy in Viet Nam, with future projections. Energy Policy 2011;39:6814–26.

[15] Valentine SV. Japanese wind energy development policy: grand plan or group think? Energy Policy 2011;39:6842–54.

[16] Von Hippel D, Hayes P. DPRK energy sector development priorities: options and preferences. Energy Policy 2011;39:6781–9.

[17] Von Hippel D, Gulidov R, Kalashnikov V, Hayes P. Northeast Asia regional energy infrastructure proposals. Energy Policy 2011;39:6855–66.

[18] Von Hippel D, Hayes P, Kang J, Katsuta T. Future regional nuclear fuel cycle cooperation in East Asia: energy security costs and benefits. Energy Policy 2011;39:6867–81.

[19] Von Hippel D, Savage T, Hayes P. Overview of the Northeast Asia energy situation. Energy Policy 2011;39:6703–11.

[20] Von Hippel D, Savage T, Hayes P. Introduction to the Asian Energy Security Project: project organization and methodologies. Energy Policy 2011;39:6712–8.

[21] Von Hippel D, Suzuki T, Williams JH, Savage T, Hayes P. Energy security and sustainability in Northeast Asia. Energy Policy 2011;39:6719–30.

[22] Wang Y, Gu A, Zhang A. Recent development of energy supply and demand in China, and energy sector prospects through 2030. Energy Policy 2011;39:6745–59.

[23] Nautilus Institute. Asian energy security; 2013. ⟨http://nautilus.org/projects/by-name/asian-energy-security/⟩ [accessed 10.08.14].

[24] Heaps C. An introduction to Long Rang Energy Alternatives Planning System (LEAP); 2008. Available at: ⟨http://www.energycommunity.org/documents/LEAPIntro.pdf⟩ [accessed 05.05.14].

[25] Vivoda V. Evaluating energy security in the Asia-Pacific region: a novel methodological approach. Energy Policy 2010;38:5258–63.

[26] Löschel A, Moslener U, Rübbelke DTG. Indicators of energy security in industrialised countries. Energy Policy 2010;38:1665–71.

[27] Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H, et al. Indicators for energy security. Energy Policy 2009;37:2166–81.

[28] Lia J, Tanga L, Suna X, Wu D, et al. Oil-importing optimal decision considering country risk with extreme events: a multi-objective programming approach. Computers & Operations Research 2014;42:108–15.

[29] Gülpınar N, Canakoglu E, Pachamanova D. Robust investment decisions under supply disruption in petroleum markets. Computers & Operations Research 2014;44:75–91.

[30] Boland N, Savelsbergh M, Waterer H. A decision support tool for generating shipping data for the hunter valley coal chain. Computers & Operations Research 2015;53:54–67.

[31] Marufuzzaman M, Eksioglu SD, Huang Y. Two-stage stochastic programming supply chain model for biodiesel production via wastewater treatment. Computers & Operations Research 2014;49:1–17.

[32] Matos S, Hall J. Integrating sustainable development in the supply chain: the case of life cycle assessment in oil and gas and agricultural biotechnology. Journal of Operations Management 2007;25:1083–102.

[33] Relvas S, Magatão SNB, Barbosa-Póvoa APFD, Neves F, et al. Integrated scheduling and inventory management of an oil products distribution system. Omega 2013;41:955–68.

[34] Arora S, Taylor JW. Forecasting electricity smart meter data using conditional kernel density estimation. Omega 2015;59:47–59. http://dx.doi.org/10.1016/j.omega.2014.08.008.

[35] Zhao W, Wang J, Lu H. Combining forecasts of electricity consumption in China with time-varying weights updated by a high-order Markov chain model. Omega 2014;45:80–91.

[36] Li D, Chang C, Chen C, Chen W, et al. Forecasting short-term electricity consumption using the adaptive grey-based approach—an Asian case. Omega 2012;40:767–73.

[37] Papadopoulos A, Karagiannidis A. Application of the multi-criteria analysis method Electre III for the optimisation of decentralised energy systems. Omega 2008;36:766–76.

[38] Masui T, Matsumoto K, Hijioka Y, Kinoshita T, Nozawa T, Ishiwatari S, et al. An emission pathway for stabilization at 6 W m^{-2} radiative forcing. Climatic Change 2011;109:59–76.

[39] Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, et al. RCP8.5: a scenario of comparatively high greenhouse gas emissions. Climatic Change 2011;109:33–57.

[40] Thomson AM, Calvin KV, Smith SJ, Kyle P, Volke A, Patel P, et al. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 2011;109:77–94.

[41] Van Vuuren DP, Stehfest E, den Elzen MGJ, Kram T, van Vliet J, Deetman S, et al. RCP2.6: exploring the possibility to keep global mean temperature change below 2 °C. Climatic Change 2011;109:95–116.

[42] Matsumoto K. Change in energy structure and energy security under climate mitigation scenarios. In: Leal W, Voudouris V, editors. Global energy policy and security. London: Springer; 2013. p. 45–57.

[43] Matsumoto K, Masui T. Mid-term dynamic effects of carbon tax based on the imputed price of carbon. Environmental Science 2009;22:391–400.

[44] Matsumoto K, Masui T. Analyzing long-term impacts of carbon tax based on the imputed price applying the AIM/CGE model. Management of Environmental Quality 2011;22:33–47.

[45] Okagawa A, Masui T, Akashi O, Hijioka Y, Matsumoto K, Kainuma M. Assessment of GHG emission reduction pathways in a society without carbon capture and nuclear technologies. Energy Economics 2012;34:S391–8.

[46] Peace J, Weyant J. Insights not numbers: the appropriate use of economic models. White paper. Washington, DC: Pew Center on Global Climate Change; 2008.

[47] Saveyn B, van Regemorter D, Ciscar JC. Economic analysis of the climate pledges of the Copenhagen Accord for the EU and other major countries. Energy Economics 2011;33:S33–40.

[48] Shukla PR, Dhar S, Mahapatra D. Low-carbon society scenarios for India. Climate Policy 2008;8:S156–76.

[49] Global trade, assistance, and production: the GTAP 6 database. In: Dimaranan BV, editor. West Lafayette: Center for Global Trade Analysis, Purdue University; 2006.

[50] European Commission. Joint Research Centre Emission Database for Global Atmospheric Research (EDGAR) release version 4.0. 2010. Available at: ⟨http://edgar.jrc.ec.europa.eu/index.php⟩ [accessed 11.11.13].

[51] International Energy Agency. Energy balances of OECD countries: 2009 edition. Paris: IEA Publications; 2009.

[52] International Energy Agency. Energy balances of non-OECD countries: 2009 edition. Paris: IEA Publications; 2009.

[53] United Nations, Department of Economic and Social Affairs, Population Division. World population prospects: the 2010 revision. New York: United Nations Publication; 2011.

[54] United Nations Environment Programme. Global environment outlook 4. Valletta: Progress Press; 2007.

[55] Special report on emissions scenarios. In: Nakicenovic N, Swart R, editors. Cambridge: Cambridge University Press; 2000.

[56] Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, et al. The next generation of scenarios for climate change research and assessment. Nature 2010;463:747–56.

[57] Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. Representative concentration pathways: an overview. Climatic Change 2011; 109:5–31.

[58] Intergovernmental Panel on Climate Change. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge and New York: Cambridge University Press; 2014.

[59] van Vuuren DP, Kriegler E, O'Neill BC. A new scenario framework for climate change research: scenario matrix architecture. Climatic Change 2014;122: 373–86.

[60] National Center for Atmospheric Research. International Committee on new integrated climate change assessment scenarios; 2014. Available at: ⟨https://www2.cgd.ucar.edu/research/iconics⟩ [accessed 11.08.14].

[61] Government of Japan. Basic Energy Plan; 2014. Available at: ⟨http://www.meti.go.jp/press/2014/04/20140411001/20140411001-1.pdf⟩ [accessed 11.06.14].

[62] Masui T, Ashina S, Fujino J. Analysis of 4.5 W/m^2 stabilization scenarios with renewable energies and advanced technologies using AIM/CGE [Global] model; 2010. Available at: ⟨http://www-iam.nies.go.jp/aim/reports_html/rpt/2010/cge_4.5W.pdf⟩ [accessed 02.12.11].

[63] US Department of Justice and the Federal Trade Commission. Horizontal merger guidelines; 2010. Available at: ⟨http://www.justice.gov/atr/public/guidelines/hmg-2010.html⟩ [accessed 29.05.14].

[64] Chen Y-HH, Reilly JM, Paltsev S. The prospects for coal-to-liquid conversion: a general equilibrium analysis. Energy Policy 2011;39:4713–25.

[65] Kumbaroglu GS. Environmental taxation and economic effects: a computable general equilibrium analysis for turkey. Journal of Policy Modeling 2003;25: 795–810.

[66] Timilsina G, Csordas S, Mevel S. When does a carbon tax on fossil fuels stimulate biofuels? Ecological Economics 2011;70:2400–15.

[67] Rogner H-H. An assessment of world hydrocarbon resources. Annual Review of Energy and the Environment 1997;22:217–62.

[68] Paltsev SV, Reilly JM, Jacoby HD, Eckaus RS, McFarland J, Sarofim M, et al. The MIT emissions prediction and policy analysis (EPPA) model: version 4. MIT Joint Program on the Science and Policy of Global Change Report 125. Cambridge, MA: Massachusetts Institute of Technology; 2005.

[69] Armington PS. A theory of demand for products distinguished by place of production. International Monetary Fund Staff Papers 1969;16:159–78.