

Change in Energy Structure and Energy Security under Climate Mitigation Scenarios

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Abstract Purpose The purpose of this study is to investigate how energy structure and energy security of the world and countries will change in the future under various climate change policies, and to better understand the relationship between climate and energy issues that could be used in the related policy discussions.

Design/Methodology/Approach The study is conducted by a simulation model. A reference scenario and three policy scenarios, based on the Representative Concentration Pathways, are analyzed until the end of this century using the AIM/CGE [Global] model. The scenarios are compared from primary and final energy structure and trade of fossil fuels.

Findings Fossil-fuel-centered energy structure shifts to rely more on renewables by introducing climate change policies. Furthermore, the percentage of the trade amount of fossil fuels is smaller in the policy scenarios than in the reference scenario. The findings reveal that energy security also improves by taking climate change measures.

Originality/Value The paper studies an energy security issue in a global framework. In addition, the analysis is based on a long-term perspective. The results of this research could be used for exploring the solutions for both energy and climate change issues simultaneously in a global basis.

Keywords CGE model • Climate mitigation • Energy structure • Energy security • RCPs

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1 Introduction

Climate change is one of the most significant global environmental issues for the present society, and policy discussions from mid- to long-term perspectives are continuing all over the world and the international arena such as in the United Nations Framework Convention on Climate Change (UNFCCC). The Copenhagen Accord was made at the fifteenth session of the Conference of the Parties (COP) to UNFCCC in December 2009, and the Annex I parties and some major non-Annex I parties submitted their pledge on greenhouse gas (GHG) emission reduction by the end of January 2010. Although the second commitment period of the Kyoto Protocol and a mandate to get all countries in 2015 to sign a deal that would force them to cut GHG emissions no later than 2020 are agreed at COP17, some important developed countries such as Canada, Japan, and Russia will not have their emission reduction targets in the second commitment period.

On the other hand, energy has been a significant global issue such as rise in the price and depression of the resources. In recent years, energy demand is dramatically increasing in large emerging countries such as China and India accompanying the economic and population growth, and the demand is expected to increase further (BP 2011; IEA 2010). As a result, there are growing concerns about tight energy supply and demand in the future. In addition, since production and reserves of fossil fuels such as crude oil and natural gas are predominately located (BP 2011), countries poor in energy resources such as Japan will face substantial price fluctuation and geopolitical risks.

Climate change measures¹ are to reduce GHG emissions, especially reducing CO₂ emissions is most effective. In order to reduce CO₂ emissions, promotion of energy savings and shifts to low-carbon energy, namely, shifts from coal to natural gas and from fossil fuels to renewables, are necessary. It is required to further promote energy savings and renewables use to realize tougher emission reduction.

If energy savings and renewables use, which is basically domestic energy, are enhanced as climate change measures in this way, the volume and dependence of import of energy will decrease. It is also effective for an energy security issue. The relationship between climate change and energy security issues is indicated in Stanislaw (2007). In addition, the role of energy in climate change policies is discussed such as in IEA (2008).

Comprehensive research on energy security has been done targeting Asian countries as a part of the Asian Energy Security Project (Falk and Settle 2011; Huang et al. 2011; Kalashnikov et al. 2011; Katsuta and Suzuki 2011; Kim et al. 2011; Takase and Suzuki 2011; Toan et al. 2011; Valentine 2011; Von Hippel and Hayes 2011; Von Hippel et al. 2011a, b, c, d, e; Wang et al. 2011). They analyze the issue for some Asian countries such as Japan, Korea (North and South), and China and the region as a whole from either the narrowly

¹ In this study, only mitigation measures are considered as climate change measures (policies), and adaptation measures are not considered.

defined energy security (i.e., considering energy security from energy supply) or broadly defined energy security (i.e., considering energy security not only from energy supply but also from economy, technology, environment, society and culture, and military) using the LEAP (Long-range Energy Alternatives Planning) software system developed by the Stockholm Environment Institute (Von Hippel et al. 2011d, e). LEAP is a scenario/energy path-based energy-environment modeling tool to create models of different energy systems, supporting a wide range of different modeling methodologies from bottom-up to top-down. Energy paths/scenarios are self-consistent storylines of how an energy system might evolve over time (often around 20–50 years) in a particular socioeconomic setting and under a particular set of policy conditions (Heaps 2008; Von Hippel et al. 2011d). The results from multiple energy paths within a country or region are compared to indicate which path is preferable with regard to different measures of energy security, such as cost, physical energy output, fuels imports and exports, technological development, or environmental emissions. In addition, other external methods such as diversification indices, multiple-attribute analysis and matrices, and qualitative analysis can be applied using the results from LEAP for further analysis on energy security (Von Hippel et al. 2011d). Since their interest is Asia, they do not mention about other countries and regions and the world. However, it is indispensable to see in a global basis when considering the energy security issue, since energy resources are actively traded and used in a global system, and a lot of important suppliers are in non-Asian regions such as Middle East, Russia, and the USA.

In this study, we analyze the global and national energy structure and energy security when introducing climate change policies using a computable general equilibrium (CGE) model. We focus on the narrowly defined energy security.

2 Methodology

In this study, we use the AIM/CGE [Global] model (Masui et al. 2011; Matsumoto and Masui 2010) for the analysis. The AIM/CGE [Global] model is a multi-sector and multiregional recursive dynamic CGE model. The model is disaggregated into 24 geographical regions each producing 21 goods and services (Tables 1 and 2). Basically, each goods is produced by a single sector, but multiple power sources are considered for power generation. In this study, electric power can be generated using thermal, hydro, and nuclear, as well as renewables including solar, wind, and biomass. Future thermal power plants, including integrated gasification combined cycle (IGCC), are assumed to be available both with and without carbon capture and storage (CCS) technology. Biomass energy is also used for producing bioethanol and biogas, which are alternatives for direct use of fossil fuels. Each sector in the economy is estimated by a nested constant elasticity of substitution (CES) production function. As an example of a CES production function, assuming a goods/service in sector s is

Table 1 Structure of regions

Code	Region
JPN	Japan
CHN	China
KOR	Korea
IDN	Indonesia
THA	Thailand
XSE	Other Southeast Asia
IND	India
XSA	Other South Asia
AUS	Australia
NZL	New Zealand
XRA	Other Asia Pacific
CAN	Canada
USA	United States
MEX	Mexico
BRA	Brazil
ARG	Argentina
XLM	Other Latin America
XE15	EU15 (Western Europe)
XE10	EU10 (Eastern Europe)
RUS	Russia
XRE	Other Europe
XME	Middle East
ZAF	South Africa
XAF	Other Africa

produced using labor (L), capital (K), and intermediate inputs (M) as the inputs, the function is expressed by Eq. (1):

$$Q_s = A_s (sl_s L_s^{\rho_s} + sk_s K_s^{\rho_s} + sm_s M_s^{\rho_s})^{\frac{1}{\rho_s}} \quad (1)$$

where Q is the quantity of production, A is a scale parameter, sl , sk , and sm are shares of each input ($sl + sk + sm = 1$), ρ is a substitution parameter ($= (\sigma - 1)/\sigma$), and σ is elasticity of substitutions.

Resources, including COA, OIL, GAS, and OMN, are produced subject to finite and depletable resource limits. Specifically, the relationship between the magnitude and associated extraction costs of COA, OIL, and GAS is taken from Rogner (1997) (Fig. 1). In the model, it is assumed that the more resources are extracted, the higher the extraction costs and the more costly the resource use (and substitution to other inputs can occur as a result). Likewise, AGR, LVK, FRS, and biomass energy production require land, also a finite resource, in addition to other economic resources.

Each produced goods are delivered to final consumption, investment, intermediate inputs, and/or exports. The time period of the model is from 2001, the base year, to 2100. Aggregate investment demand in each period is set exogenously to meet prescribed GDP growth rates. Future GDP values are taken from the Sustainability

Table 2 Structure of commodities

Code	Goods and service
AGR	Agriculture
LVK	Livestock
FRS	Forestry
FSH	Fishing
OMN	Mining (except fossil fuels)
EIS	Energy intensive products
M_M	Metal and machinery
FOD	Foods
OMF	Other manufacturing goods
WTR	Water
CNS	Construction
TRT	Transportation
CMN	Communication
OSG	Public services
SER	Other services
COA	Coal
OIL	Crude oil
GAS	Natural gas
P_C	Petroleum products
GDT	Gas distribution
ELY ^a	Electricity

^aIn ELY, following subsectors (power sources) have been considered: coal fired, petroleum products fired, gas fired, nuclear, hydro, biomass, waste, geothermal, solar, wind, and other renewables. As for the advanced technology, IGCC and thermal power plant with CCS are available

First scenario in the Global Environment Outlook (GEO) 3 (UNEP 2002) and GEO4 (UNEP 2007) of the United Nations Environment Programme (UNEP). The rates of energy efficiency improvement are also set exogenously using those derived from the Special Report on Emission Scenarios (SRES) B2 scenario (Nakicenovic and Swart 2000). The model applies a putty-clay approach for capital. Capital is divided into an old capital stock and new capital. Old capital cannot move between sectors, while new capital can be installed in any one sector. However, once new capital is assigned to a sector, it becomes old capital in all subsequent periods. The energy efficiency improvements and other technology changes are applied to new capital only. Productivity of aggregate capital is the weighted sum of technology levels in old and new capital. The increase rates of labor are also set exogenously based on the population growth rates of the UN medium variant until 2050 (UN 2007) and UN long-term estimation beyond 2050 (UN 2004).

The AIM/CGE [Global] model is constrained to follow the global GHG emission pathways² obtained from the AIM/Impact [Policy] model (Hijioka et al. 2008)

²In this study, not only six Kyoto GHGs (i.e., CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆) but also CO, NO_x, NH₃, SO₂, non-methane volatile organic compounds, black carbon, and organic carbon are considered.

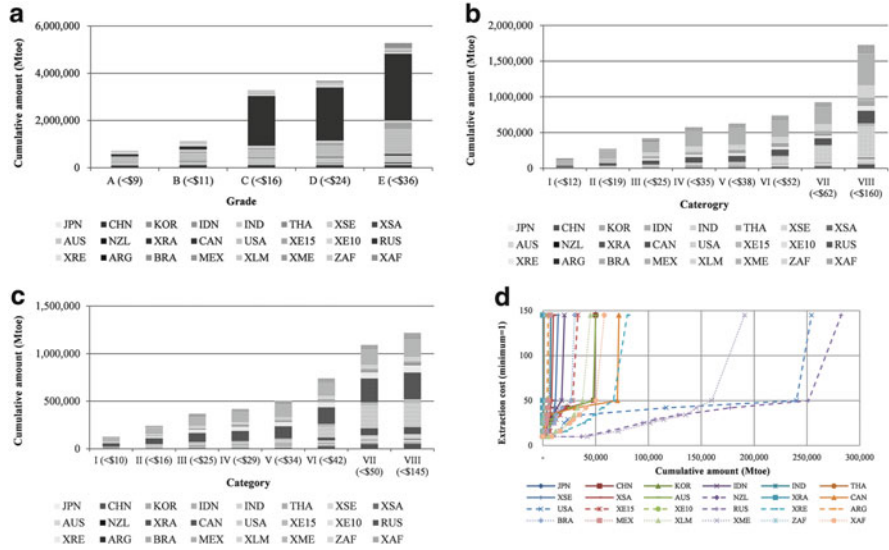


Fig. 1 Cumulative extractable amount of resources in each grade/category [(a) upper left, COA; (b) upper right, OIL; and (c) bottom left, GAS] and relationship between cumulative extractable amount of resources and extraction costs for GAS by region [(d) bottom right]. The grade/category and the corresponding costs are based on Rogner (1997), and the amount of resources in each region is based on Rogner (1997) and our own calculation

for the policy scenarios (see Sect. 3.2 for each scenario). The global GHG emissions are assigned to the regions in proportion to their population in 2050 and beyond. Between 2001 and 2050 regional GHG emission limits are set by linear interpolation of the emissions in 2001 and the assigned limits in 2050. In the model, GHG emission rights are freely traded between regions globally for all gases.

The household sector is assumed to own all production factors (i.e., capital, labor, land, and resources) in each region and to supply them to the production factor markets. The income is derived from sale of these factors. The household sector distributes its income between final consumption goods and services and savings. Savings rates are set equal to investment, which is set exogenously to meet prescribed GDP growth rates as described above. The demand for final goods and services is derived as the result of utility maximization subject to an unsaved income constraint in each period.

The model is calibrated to reproduce economic and energy activity levels in 2001 using the GTAP6 database (Dimaranan 2006) for economic activity levels and the energy balance of the International Energy Agency (IEA 2007a, b) for energy and benchmark GHG emission rates.

3 Scenarios

3.1 Reference Scenario

As a first step in the process of developing policy scenarios, we develop a “no-climate-policy” reference scenario. This scenario assumes that policies and measures undertaken to control other environmental problems are adopted but is constructed so that no policies motivated purely to control GHG emissions, except for those already in place, are undertaken and that existing policies are not renewed when they expire.

The reference scenario in this study is an updated version of the SRES B2 [AIM] scenario (Nakicenovic and Swart 2000). Updates include demographic and economic assumptions as described in the previous section. That is to say, the former is based on UN (2004, 2007) and the latter is based on UNEP (2002, 2007) instead of the original B2 scenario.

In the reference scenario, the global population grows from 6.1 billion to 9.8 billion between 2001 and 2100, with a peak between 2080 and 2090. Global GDP grows from \$30 trillion to \$225 trillion between the same periods. Primary energy supply in the world in 2100 reaches 1189EJ/year, and China becomes the largest economy in terms of both GDP and energy demand. Renewable potential and other new technology capacities follow the World Energy Outlook (IEA 2008) and Masui et al. (2010). Annual CO₂ emissions become 27.7 GtC in 2100. As a result, total radiative forcing reaches 7.3 W/m² in 2100.

3.2 Policy Scenario

In this study, the Representative Concentration Pathways (RCPs) are used for the climate change policy scenarios.³ RCPs are the first step toward the next IPCC Assessment Report (fifth version) and one of the latest scenario families in climate change research. RCPs are defined by radiative forcing levels in 2100 and consist of four scenarios, namely, the lowest 2.6 W/m², the highest 8.5 W/m², and the two middle scenarios of 4.5 W/m² and 6 W/m² [Fig. 2. For the original RCPs, see 2.6 W/m²: Van Vuuren et al. (2011b); 4.5 W/m²: Thomson et al. (2011); 6 W/m²: Masui et al. (2011); and 8.5 W/m²: Riahi et al. (2011)]. CO₂ emissions in 2100 are 29.6 GtC (8.5 W/m²), 13.0 GtC (6 W/m²), 5.0 GtC (4.5 W/m²), and 0.47 GtC (2.6 W/m²), respectively (Fig. 3).

In this study, these policy scenarios are analyzed using the AIM/CGE [Global] model and compared with the reference scenario.⁴

³ See Moss et al. (2008, 2010) and Van Vuuren et al. (2011a) for the details of RCPs.

⁴ Since the model used in this study is different from those used in the original RCP analyses, the features are different from them except for the 6 W/m² scenario. Radiative forcing of the 8.5 W/m²

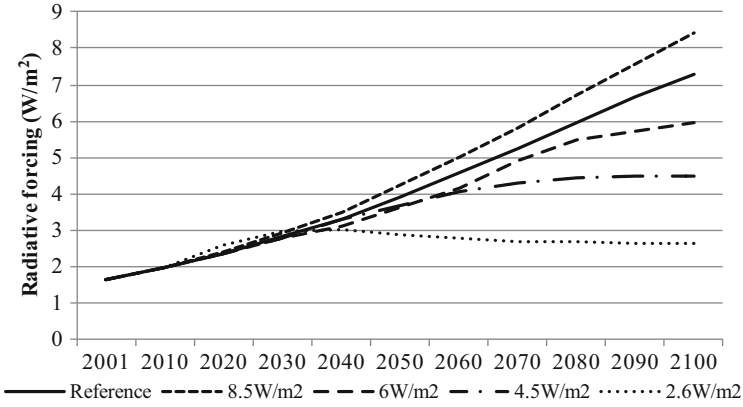


Fig. 2 Radiative forcing levels (Since these radiative forcing pathways are our calculation, they are different from original RCPs)

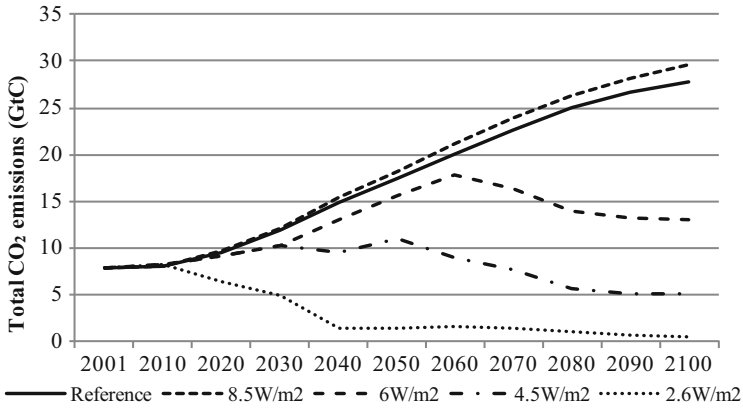


Fig. 3 Total CO₂ emissions (Since these emission pathways are our calculation, they are different from original RCPs)

4 Results and Discussions

Concerning primary energy in the world, although the demand increases in all the scenarios until 2100, it lowers in the stricter scenarios (the demand is 429EJ in 2001, and 1189EJ in the reference scenario and 651EJ in the 2.6 W/m² scenario in 2100). In addition, energy structure changes drastically (Fig. 4). In the reference scenario, fossil fuels occupy 90 % of the global primary energy demand in 2100.

scenario is higher than that of the reference scenario of this study, meaning that it is required to increase GHG emissions from it. Since such operation has little meaning, we do not show the result of the 8.5 W/m² scenario below.

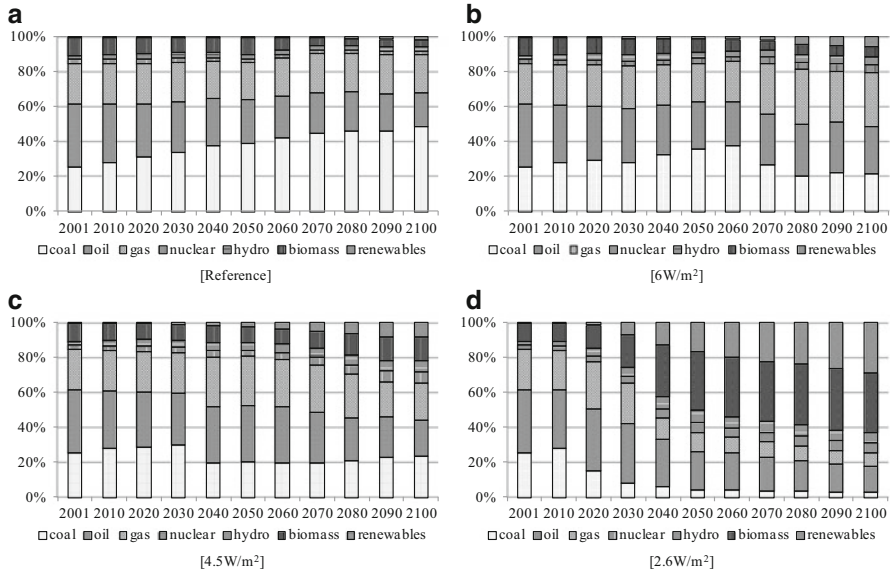


Fig. 4 Structure of primary energy in the world (“renewables” in the graphs include renewables except hydropower and biomass)

It is due to dependence on coal, the price of which is relatively low in its no-GHG-constraint situation. In the policy scenarios, on the other hand, the percentage of fossil fuels, especially that of coal, becomes lower and that of renewables becomes higher instead. The percentage of renewables is remarkably high in the 2.6 W/m² scenario, higher than 60 %. In the renewables, except for hydropower and biomass, the percentage of wind power is the highest, about 75 % in the reference scenario. The larger the amount of emission reduction, the higher the percentage of solar power (the percentage of wind power is 58 % and that of solar power is 40 % in the 2.6 W/m² scenario).

As a metric for energy security implications of different patterns of energy supply, the Herfindahl index [Eq. (2)], which is based on diversity indices in the economic and financial analysis, is available (Neff 1997; Von Hippel et al. 2011d). The index has a maximum value of one when there is only one energy type and goes down with increasing diversity of energy types, so that a lower value of the index indicates more diverse supply conditions:

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

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 value in 2001 is 0.26; those in 2050 are 0.27 (reference), 0.26 (6 W/m²), 0.24 (4.5 W/m²), and 0.21 (2.6 W/m²); and those in

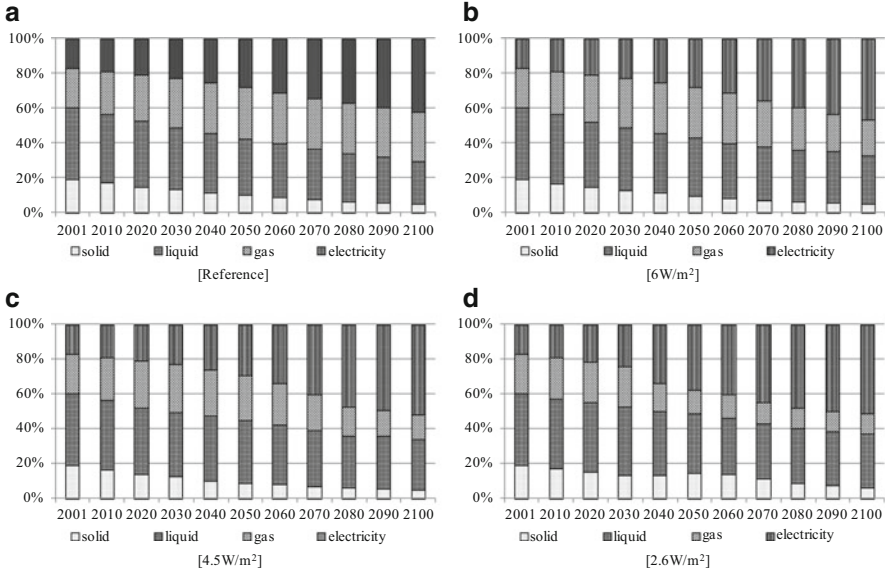


Fig. 5 Structure of final energy in the world

2100 are 0.33 (reference), 0.23 (6 W/m^2), 0.18 (4.5 W/m^2), and 0.24 (2.6 W/m^2). The diversity worsens with time in the reference scenario because of its dependence on coal, while it improves in the three policy scenarios. Although the value in the 2.6 W/m^2 scenario is lowest in 2050, it worsens and becomes higher than the others in 2100. However, since it is due to increase in the percentage of renewables, it does not necessarily mean worsening of the energy security.

Since most of renewables are used for power generation, the percentage of electricity in final energy demand also increases in the stricter scenarios (Fig. 5). Although it increases from 17 % in 2001 to 42 % in 2100 even in the reference scenario, it exceeds 50 % in 2100 in the 2.6 W/m^2 scenario.

Observing the trade amount of fossil fuels in the world, it doubles in 2100 compared to the 2001 level in the reference scenario. On the other hand, although the trade amount also increases compared to the 2001 level, about 154 %, in the 6 W/m^2 scenario, it is 25 % smaller than the reference scenario. In the 4.5 W/m^2 and 2.6 W/m^2 scenarios, the trade amount in 2100 is 92 % and 52 % in 2100, which is lower than the 2001 level. Observing it by fossil fuel, although the trade amount of natural gas and crude oil relatively increases accompanying decrease in coal demand in the policy scenarios, the trade amount of both becomes smaller in absolute terms compared to that of the reference scenario and even smaller than the 2001 level in the strict scenarios.

These results are also true in a regional basis. For example, in China and the USA, which are the two most energy-consuming countries, the percentage of renewables tends to increase in the stricter scenarios (Fig. 6). The Herfindahl

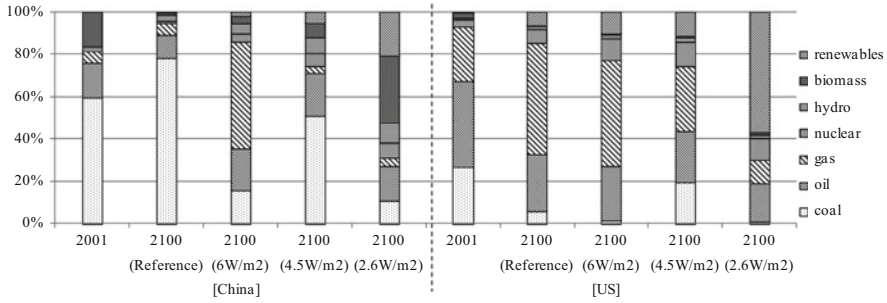


Fig. 6 Structure of primary energy in China and the USA

index values in China are 0.41 in 2001 and 0.62 (reference), 0.32 (6 W/m²), 0.31 (4.5 W/m²), and 0.20 (2.6 W/m²) in 2100 and those in the USA are 0.30 in 2001 and 0.36 (reference), 0.33 (6 W/m²), 0.21 (4.5 W/m²), and 0.27 (2.6 W/m²) in 2100. As a result, the percentage of electricity in final energy in 2100 increases from 44 % in the reference scenario to 64 % in the 2.6 W/m² scenario in China and from 38 % to 48 % in the USA. In addition, the import amount of fossil fuels becomes 141 % of the 2001 level in 2100 in the 2.6 W/m² scenario, which is lower than the reference scenario (530 %), in China. Likewise, the amount is 31 % of the 2001 level in 2100 in the 2.6 W/m² scenario, which is lower than the reference scenario (65 %), in the USA.

From the above analysis, it is necessary to decrease the dependence on fossil fuels and to increase the amount of renewables compared to the reference scenario in order to reduce GHG emissions. It also links to reducing the trade amount of fossil fuels. That is to say, the self-sufficiency of energy supply will increase by promoting climate change measures; especially energy-importing countries can also improve their energy security. Conversely, such situations can negatively affect the economy of energy-exporting countries.

5 Concluding Remarks

In this study, we analyzed the change in energy structure and impacts on energy security when introducing climate change policies by using the AIM/CGE [Global] model. In the analysis, we used RCPs for the policy scenarios and compared them with the reference scenario.

As a result, in order to reduce GHG emissions, we need to shift energy structure from the fossil fuel centered to the more renewables used. The stricter the emission reduction, the larger shifts will be required. It is also indicated that such shifts also improve the self-sufficiency of energy supply and are consequently effective from the viewpoint of energy security.

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