The impact of nuclear policy changes on climate change mitigation policy in Asia

Hiroto Shiraki[1,*)], Shuichi Ashina[2)], Osamu Akashi[2)], Yasuko Kameyama[1,2)], Yuichi Moriguchi[3)]

1) The University of Tokyo, Graduate School of Frontier Sciences, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563 JAPAN

2) National Institute for Environmental Studies, Center for Social and Environmental Systems Research

3) The University of Tokyo, Graduate School of Engineering

*) Corresponding author, E-mail:h.shiraki@kanies.k.u-tokyo.ac.jp, Tel:+81-4-7136-4003

1. Introduction

The long-term targets for climate change mitigation have been discussed under the United Nations Framework Convention on Climate Change. In parallel with these long-term targets, future climate change mitigation potentials have been actively studied. According to the International Energy Agency BLUE-map scenario[1)], nuclear power is expected to be one of the major greenhouse gas (GHG) abatement technologies and could contribute to about 6% of the global GHG emission reduction ny 2050. Akimoto et.al.[2)] estimated that the contribution of nuclear power to carbon reduction in 2100 will be about 10% of the global total carbon emission reductions. Since the large-scale accident of the Fukushima nuclear power plant on March 11, 2011, the future of the nuclear policy both in Japan and the world has reminded in doubt, with a decrease in the public's acceptance of nuclear energy and implementation of stricter safety standards for nuclear power plant construction and operations. In Japan, restarting operations from periodic inspection in many nuclear power plants are postponed because local communities do not approve. In Europe, Germany, Italy and Switzerland have decided to abandon nuclear power for electricity generation. On the other hand, a significant increase in energy demand and GHG emissions is expected in the Asian region by 2050[3)]. Thus, changes to nuclear policies to address GHG mitigation options in the region are likely to affect GHG abatement potential and costs on the global scale.

This study focuses on the effect of nuclear policy changes in the Asian region, and estimates the impact on technology selections and energy consumption by using a global-scale integrated assessment model. We set research questions as described below;

1) As the result of nuclear policy changes, how does energy composition change?
2) Which type of resources will become alternatives to nuclear; renewables, fossil fuel or negawatt? As a result, do CO_2 emissions from the Asian region change?
3) If CO_2 emissions in the Asian region increase, which countries will reduce CO_2 emissions instead in order to stabilize global GHG concentration?

This paper is organized into four sections. We first explain the structure of the model and scenarios for the analysis. Next, we analyze composition changes of energy consumption in the world and some Asian regions based on the results of the model. Finally, we draw conclusions in section 4.

2. Methods

2.1 **Structure of AIM/BCM[Global]**

For the assessment of the effect of nuclear policy changes, we have developed the Asia-Pacific Integrated Model /backcasting [global] (AIM/BCM[Global]), that simulates selections of technologies and energy consumption patterns to minimize the total cost during the analytical period (2005-2050) under several constraints, such as satisfying energy service demands and emission limits. The AIM/BCM[Global] covers entire world, which we divide into 32 regions(Table 1). It can calculate CO_2 emissions from energy supply sectors, energy end-use sectors and nonenergy-use sectors in each region. Inputs of the model, such as assumptions of future energy demand, future prices of fossil fuels and technology costs, are set based on statistics and service demand calculation modules[4)]. For simplifying the model calculation, the variables for nonenergy sector was fixed exogenously. (Fig.1)

Table 1 Regional classification of AIM/BCM[Global]

Code	**Name**	Asia	**Code**	**Name**	Asia	**Code**	**Name**	Asia
JPN	Japan	✓	XCS	Central Asia		XEWI	Other Western Europe in Annex I	
CHN	China	✓	XME	Middle East		XEEI	Other Eastern Europe in Annex I	
IND	India	✓	AUS	Australia		XENI	Other Europe	
IDN	Indonesia	✓	NZL	New Zealand		RUS	Russia	
KOR	Korea	✓	XOC	Other Oceania		MEX	Mexico	
THA	Thailand	✓	CAN	Canada		ARG	Argentine	
MYS	Malaysia	✓	USA	USA		BRA	Brazil	
VNM	Vietnam	✓	XE15	EU-15		XLM	Other Latin America	
XSE	Other South-east Asia	✓	XE10	EU-10		ZAF	South Africa	
XSA	Other South Asia	✓	XE2	EU-2		XAF	Other Africa	
XEA	Other East Asia	✓	TUR	Turkey				

In this study, we define the countries in the Asian region as countries in East Asia, South-East Asia and South Asia.

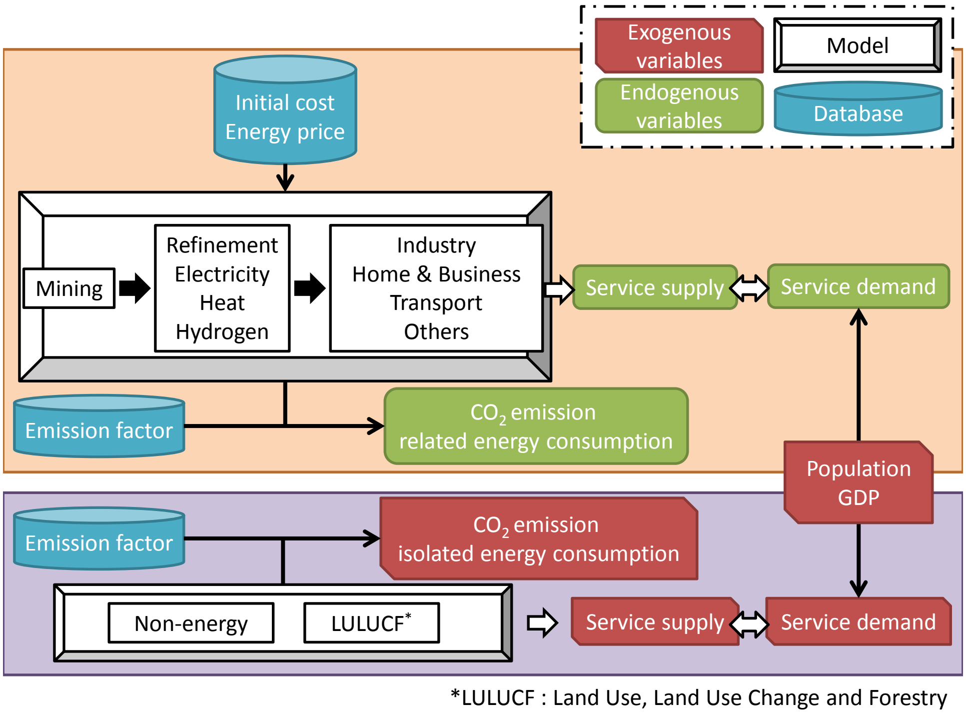


Fig. 1 Structure of AIM/BCM[Global]

2.2 Constraint and objective function

The main equation and constraint are described below. Capital letters represent endogenous variables while lower-case letters represent exogenous variables.

(1) Emission reduction constraint

The first one is constraint for annual global CO_2 emissions. Specifically, we set a 2050 global emission limit of 50% reduction from 2005 levels. The second one is constraint for cumulative CO_2 emissions from 2000 to 2050. In this study, we constrained a cumulative CO_2 emission by 1137 Gt-CO_2. This amount of cumulative CO_2 emissions is based on the average from previous studies[5)] which were calculated to stabilize radioactive forces by 2.5 –3.0 W/m^2.

$$\sum_{i,g} \mathrm{EMS_{i,g,t}} \leqq \mathrm{emsmax}_t$$

$$\sum_{t=1}^{tl} \sum_{i,g} \mathrm{EMS_{i,g,t}} \leqq \mathrm{ccemsmax}$$

where i is sector, g is type of gas, t is time, tl is last year of analysis, EMS is CO_2 emission, emsmax is maximal limit of annual CO_2 emissions, and ccemsmax: maximal limit of cumulative CO_2 emission

(2) Emission equations

CO_2 emissions are calculated by multiplying the energy consumption by the emission factor. We considered CO_2 emissions from each operation along with CO_2 emissions rerated to energy consumption.

$$\mathrm{EMS_{i,g,t}} = \mathrm{emf}_{g,k} \times \mathrm{ENE}_{i,k,t} + \mathrm{emf0}_{i,g,m,t} \times \mathrm{OPE}_{i,m,t}$$

where k is type of energy, m is type of technology, ENE is emission consumption, OPE is amount of operation, emf is emission factor of each energy and, emf0 is emission factor of each operation

(3) Balance equations of service demand

The quantities of service output supplied by all devices satisfy service demand which is given exogenously.

$$\mathrm{SRV}_{i,j,t} = \mathrm{sdm}_{i,j,t}$$

where j is type of service, SRV is service supply, and sdm is service demand

(4) Balance equations of device input and output

Energy input into the device and service output from the device are constrained by the energy efficiency of the device and operating quantity.

$$\mathrm{SRV}_{i,j,t} = \mathrm{uout}_{i,j,m,t} \times \mathrm{OPE}_{i,m,t}$$

$$\mathrm{ENE}_{i,k,t} = \mathrm{uin}_{i,k,m,t} \times \mathrm{OPE}_{i,m,t}$$

where uout is service supply per operation, and uin is energy consumption per operation

(5) Operating capacity constraints

Operation amount of the device must not exceed its stock net of the operating rate.

$$\mathrm{OPE}_{i,m,t} \leqq \mathrm{cf}_{i,m,t} \times \mathrm{CAP}_{i,m,t}$$

where CAP is Stock capacity of technology, and cf is capacity factor

(6) Balance equations of device stock

In order to consider the device lifetime, the AIM/BCM[Global] distinguish installed capacity of devices as a cohort in terms of installed year. Surviving capacity of cohort h in t is calculated by multiplying the installed capacity of cohort h by the survival function. Then, the stock capacity of devices in t is calculated by summation of surviving capacity of the cohort in t.

$$\mathrm{CAP\_h}_{i,m,\hbar,t} = \mathrm{sp}_{m,\hbar,t} \times \mathrm{CAP\_f}_{i,m,\hbar}$$

$$\mathrm{CAP}_{i,m,t} = \sum_{h} CAP\_h_{i,m,h,t}$$

where h is cohort, CAP_h is capacity of cohort h in t, CAP_f is introduction amount of cohort h, and sp is survival rate

(7) Variable renewable energy constraint

We considered that renewable energies, which can have fluctuating output as a result of weather conditions, i.e. photovoltaic and wind power, are constrained to large scale installation. The AIM/BCM[Global] deals with these installation limits of variable renewable energies (VRE) as limits of the installation share of VRE. Specifically, we set the constraint that upper share limit of VRE without secondary battery to 20% of the total electricity generation and the upper share limit of VRE with and without secondary battery to 50% of the total electricity generation.

$$\sum_{j \in VRE} \mathrm{SRV}_{i,j,t} \leqq \mathrm{limVRE} \times \sum_{j \in ELE} SRV_{i,j,t}$$

where limVRE is maximal limit of installation share of VRE, VRE is subset of j (service outputs from VRE devices), and ELE is subset of j (service outputs from devices in electricity sector)

(8) Objective function

The objective function is the discounted present value of the system cost during the analytical period. This comprises total initial cost, total energy cost and total running cost.

$$\mathrm{TC} = \sum_{t} \frac{1}{(1+r)^{t-1}} \times \left\{ \sum_{i,m} cfix_{m,t} \times CAP_{f\,i,m,t} + \sum_{i,k} cvar_{i,m,t} \times ENE_{i,k,t} + \sum_{i,m} co\&m_{i,m,t} \times OPE_{i,m,t} \right\}$$

where TC is total system cost during the analytical period, r is discount rate (5%), cfix is initial cost per device capacity, cvar is variable cost per energy consumption, and co&m is operation and management cost per quantity of operation

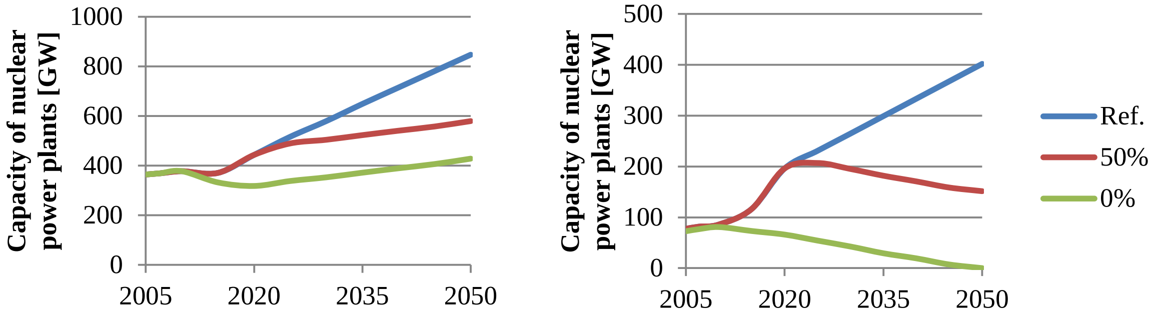
2.3 Socio-economic parameter

The future population of each country was taken from the United Nations medium variant. In this scenario, the world population reaches 9.2 billion in2050. GDP growth is based on the IPCC SRES B2 scenario.

2.4 Scenario

We assumed three nuclear policy scenarios, which are described in Fig.2. The future capacities of nuclear power plants were set based on the World Nuclear Association[6)].

(1) Reference (Ref.): No impact on global nuclear policy by an accident. All nuclear plants that are under construction, planned, and proposed can be used in the future. The capacity factor of every nuclear power plant increases by 95% in 2050, which was the capacity factor of nuclear power plants in the USA in 2005.
(2) 50% construction (50%): Proposed nuclear power plants in the Asian region are not allowed to start commercial operation in the future. The capacity factor of nuclear power plants in the Asian region is held at the level in 2005 for each country.
(3) No construction (0%): There will be no new plants after the accident in the Asian region, but existing nuclear plants can be used until the end of their lifetime (40 years). The capacity factor is the same as the 50% construction scenario.



(a) World (b) Asia

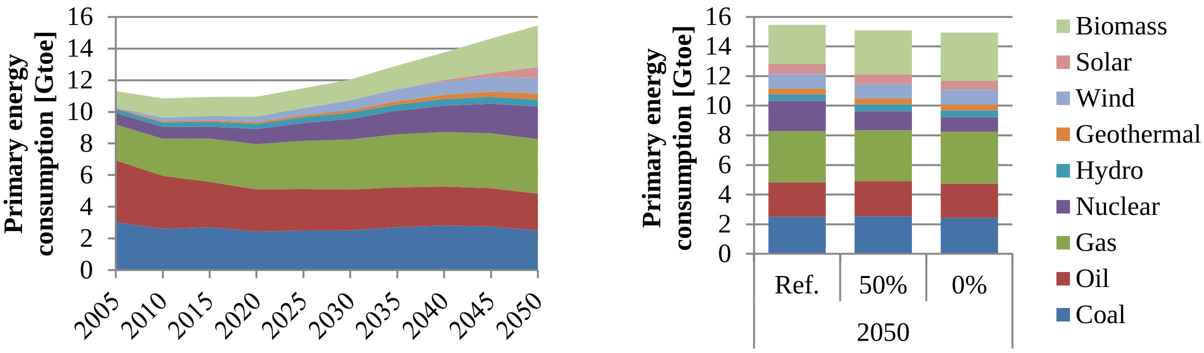
Fig.2 Assumptions of capacity of nuclear power plants

3. Results

3.1 World and Asia

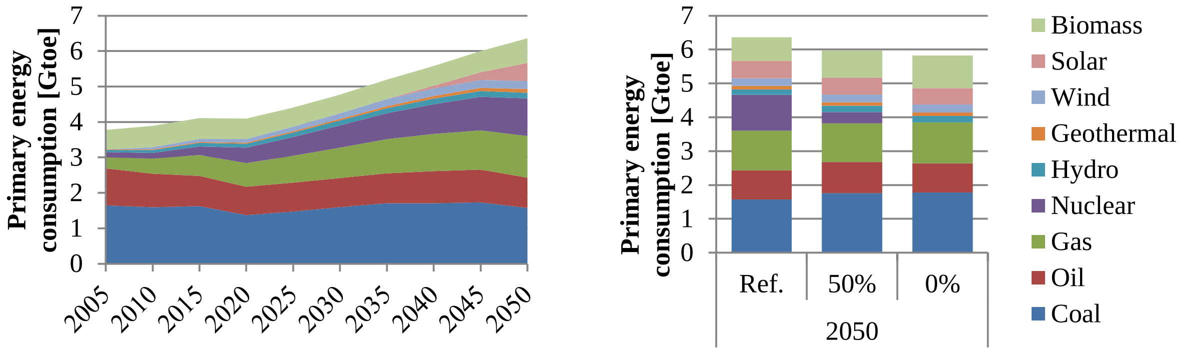
(1) Primary energy consumption

Fig.3 and Fig.4 describes primary energy consumption in the world and in the Asian region, respectively. In the ref. scenario, global total primary energy consumption increases from 11.3 Gtoe in 2005 to 15.5 Gtoe in 2050. The energy consumption from natural gas and renewables, i.e., wind, solar, and biomass, increases by about 0.7 and 1.5Gtoe respectively. In Asia, total primary energy consumption increases more rapidly than global primary energy consumption, which in 2050 is 1.68 times as much as that in 2005. Especially, the increases in energy consumption from nuclear, natural gas and solar are about 0.9, 0.8 and 0.5 Gtoe, respectively. In the each of nuclear constraint scenario, global primary energy consumption in 2050 decreases by about 370 Mtoe and 516 Mtoe from that in the ref. scenario, respectively. Both in the world and in Asia, the energy consumption from biomass and coal increase instead of nuclear energy consumption in the ref. scenario.



(a) Ref. scenario (b) in 2050

Fig.3 Primary energy consumption in the world

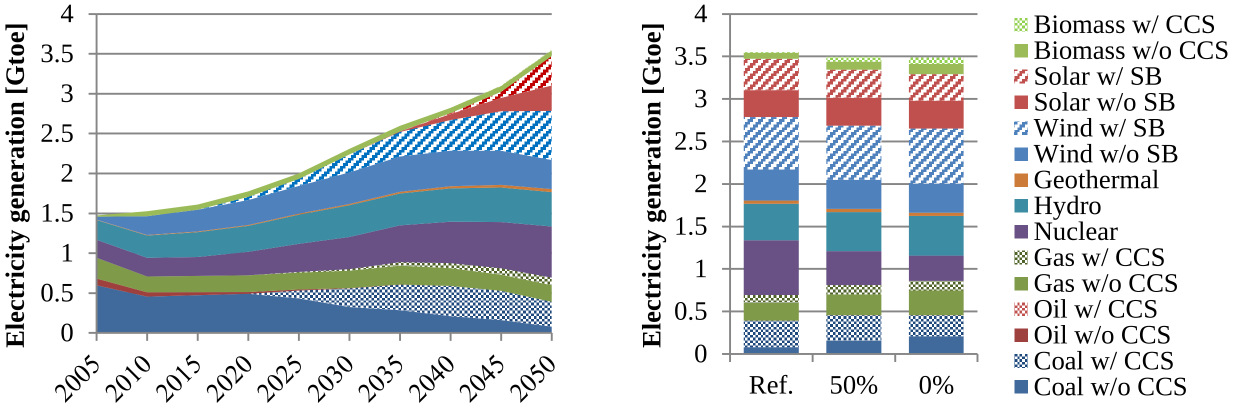


(a) Ref. scenario (b) in 2050

Fig.4 Primary energy consumption in Asian region

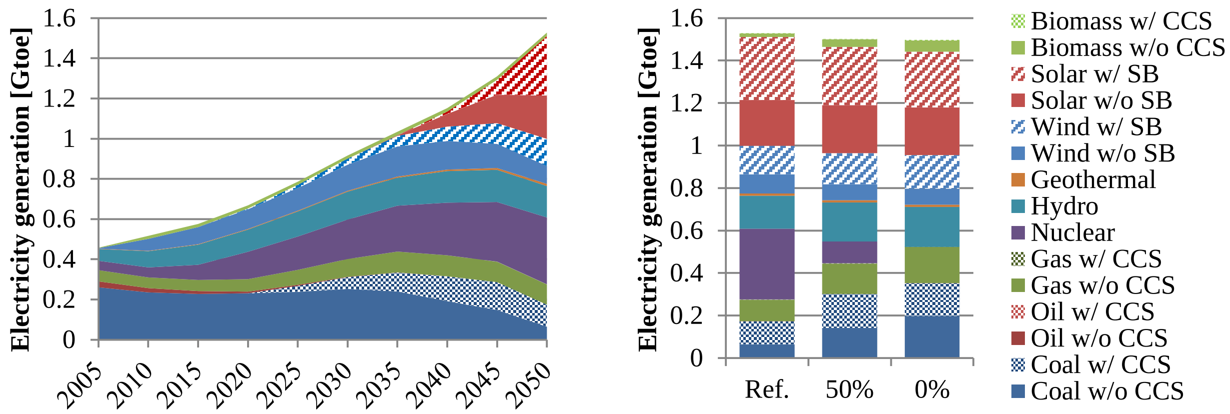
(2) Electricity

Fig.5 and Fig.6 describes electricity generation in the world and in the Asian region, respectively. In the ref. scenario, global total electricity generation increases from 1.5 Gtoe in 2005 to 3.5 Gtoe in 2050. In Asia, total electricity generation increases more rapidly than global total electricity generation to 1.5 Gtoe in 2050, which is 3.3 times as much as that in 2005. Both in the world and in Asia, generated electricity from wind power and solar power increase; electricity generated by these renewables account for 47% of total electricity generation in 2050. The share of generated electricity by fossil fuels decreases to about 20% of total electricity generation in 2050. In the nuclear constraint scenario, the share of nuclear power generation decreases, and the share of coal power generation without CCS and renewable energies increases. In addition, electricity demand decreases by installing high-energy-efficiency appliances. In the 0% scenario, 0.5 Gtoe of electricity consumption in the Asian region is saved between 2005 and 2050.



(a) Ref. scenario (b) in 2050

Fig.5 Electricity generation by fuel in the world[1]



(a) Ref. scenario (b) in 2050

Fig.6 Electricity generation by fuel in the Asian region

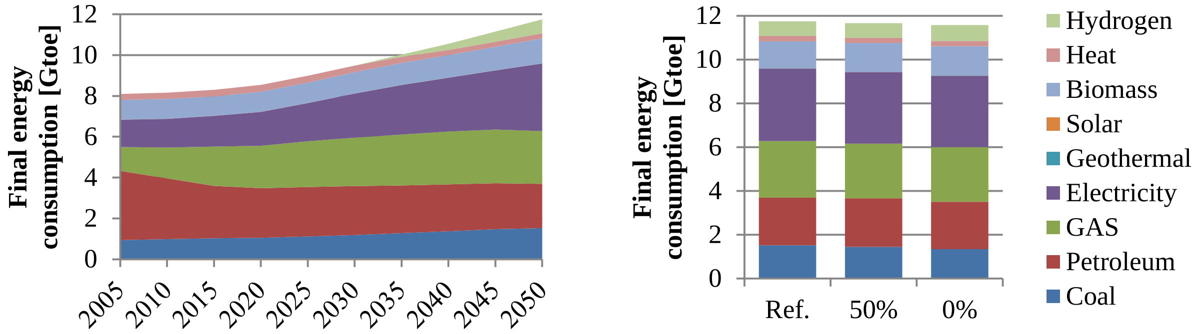
(3) Final energy consumption

Fig.7 and Fig.8 describes final energy consumption in the world and in the Asian region, respectively. In the ref. scenario, global total final energy consumption increases from 8.1 Gtoe in 2005 to 11.8 Gtoe in 2050. Specifically, consumption of natural gas and electricity increases while consumption of oil decreases. In Asia, consumption increases more rapidly than the global total final energy consumption by 4.9 Gtoe, which is 1.9 times as much as that in 2005. Consumption of natural gas increases more than 7 times as much as that of amount in 2005. In contrast with oil consumption in the world, that in the Asian region maintains its 2005 level. In the nuclear constraint

---

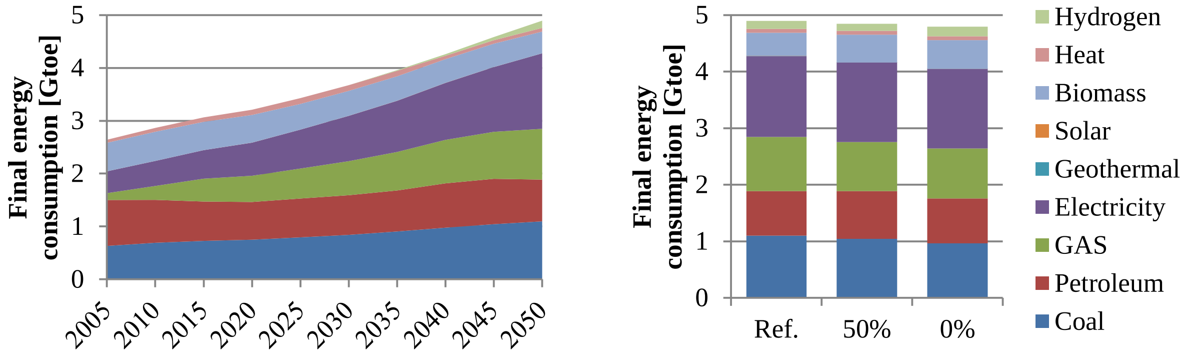
[1] CCS: carbon capture and storage, SB: secondary battery

scenario, the composition of total final energy consumption in 2005 does not change drastically. However, the amount of total final energy consumption decreases. Both the 0% and 50% scenarios reduce gas and electricity consumption compared to the ref. scenario. In the 0% scenario, a total of 1.2 Gtoe of the final energy consumption in the Asian region is saved from 2005 to 2050 .



(a) Ref. scenario (b) in 2050

Fig.7 Final energy consumption in the world



(a) Ref. scenario (b) in 2050

Fig.8 Final energy consumption in the Asian region

(4) CO_2 emission

Fig.9 describes cumulative CO_2 emissions in the Asian region between 2005 and 2050. In the each nuclear constraint scenario, cumulative CO_2 emissions from the Asian region increase 9.8 Gt and 20 Gt, respectively. Especially in the 0% scenario, Chinese cumulative CO_2 emission increase 15.6 Gt compared to the ref. scenario. In order to offset these increases in CO_2 emissions, CO_2 emissions decrease outside the Asian region. Fig.10 discribes emission reduction outside Asia. In the 50% scenario, the USA and AUS reduce their cumulative CO_2 emissions by about 1.8 Gt. In the 0% scenario, the USA and XE15 reduce their cumulative emissions by about 3 Gt and 2Gt, respectively. In these countries, emission reduction are achived by accelerating the introduction of wind power plants and switching fuels for transport from natural gas to biomass. In addition, emission reductions take place not so much in particular countries but in the whole world.

(5) Additional costs

Global total cost from 2005 to 2050 increases to 4.15 billion US dollars and 8.20 billion US dollars in each nuclear constraint scenario. In the Asian region, the global cost increases 2.32 billion US dollars and 4.91 billion US dollars.

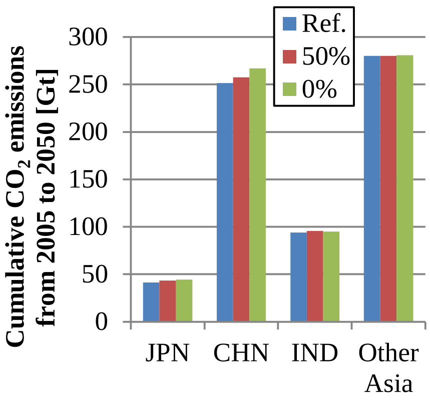


Fig. 9 Cumulative CO_2 emissions in the Asian region

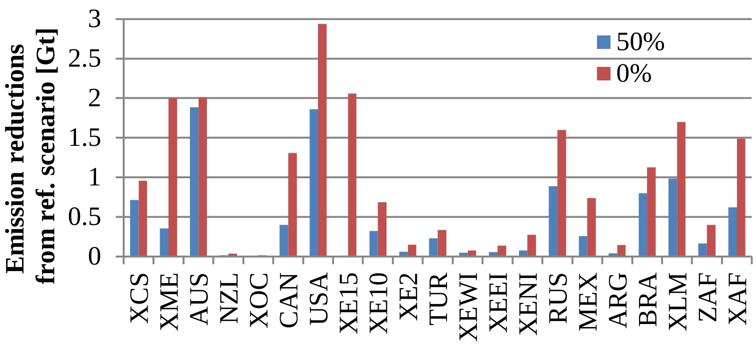


Fig. 10 Emission reductions outside Asia

We analyzed the impact of changes in nuclear policy on energy consumption and CO_2 emissions in the world. As a result of nuclear constraints, coal consumption and CO_2 emissions increase in the Asian region. What kinds of change will then occur at the country scale? In the next section, we focus on Japan, China, and India, which are significantly affected by nuclear constraints.

3.2 Country scale (Japan, China, and India)

(1)Electricity

(a) Japan

Fig.11 describes electricity generation by fuel in Japan. In the ref. scenario, electricity demand in the first decade decreases by less than 80 Mtoe because of a service demand reduction by population decline and installation of high-energy-efficient appliances. After that, electricity demand increases gradually due to the expansion of electrification. Wind power increases from 2010 because of cheap generation costs. As a result of the installation of coal power plants with CCS from 2020 and expansion of solar power plants after 2035, the CO_2 emission factor of the Japanese electricity sector is reduced by 220 g/kWh. This reduction in the CO_2 emission factor is one of the reasons that electrification expands after 2020. In the nuclear constraint scenario, generated electricity from natural gas increases instead of nuclear power generation. All available renewable energy sources in Japan have already been used, even in the ref. scenario; therefore the Japanese electricity sector cannot use renewables instead of nuclear power generation. Reduction in electricity demand compared to the ref. scenario is not great.

(b) China

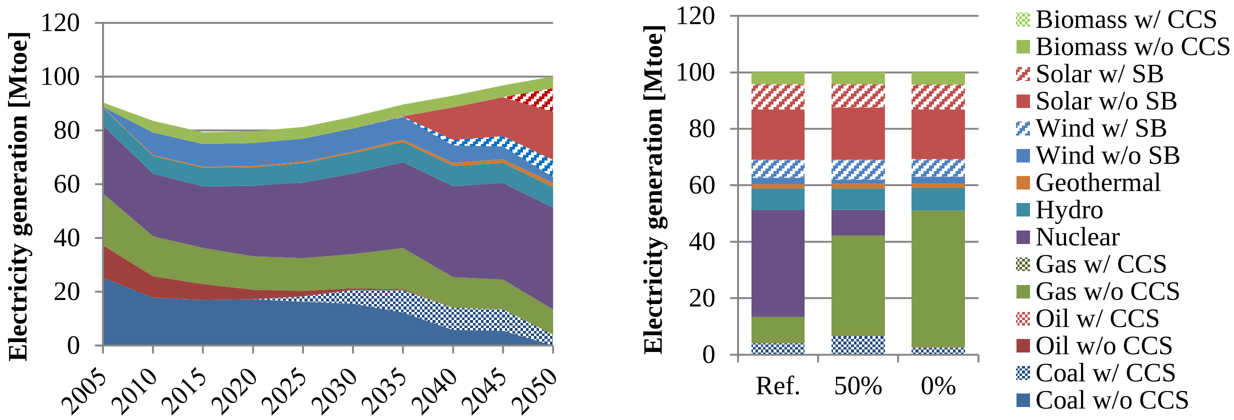
Fig.12 describes electricity generation by fuel in China. Against a background of population and economic growth, electricity demand increases widely. In the ref. scenario, electricity demand increases by 580Mtoe, which is 2.88 times as much as that in 2005. Specifically, nuclear and wind power generation increase, while coal power generation declines. Wind power generation with secondary battery and solar power generation with and without secondary battery increase drastically after 2040. Expansion of the share of renewables and nuclear power causes reduction of CO_2 emission factor of Chinese electricity sector in 2005 by almost 0 g/kWh. In the nuclear constraint scenario, wind power generation and coal power generation increase instead of nuclear power generation. As a result, CO_2 emissions in 2050 in the 0% scenario increase to 300 Mt from the ref. scenario. Electricity demand is reduced by a total of more than 220 Mtoe in each nuclear constraint scenario from 2005 to 2050.

(c) India

Fig.13 describes electricity generation by fuel in India. Against a background of population and economic growth, electricity demand increases more rapidly than that in China. In the ref. scenario, electricity demand increases to 420Mtoe, which is 6.99 times as much as that in 2005. Most of the increase of electricity demand until 2035 is supplied by coal power generation and nuclear power generation. After 2035, solar power generation increases rapidly and accounts for almost 50% of the generated electricity in 2050. In India, there is a huge potential for solar power, therefore the share of solar power is relatively large. In the nuclear constraint scenario, coal power generation without CCS and hydropower generation increase instead of nuclear power generation. Reduction in the electricity demand from ref. scenario is not great.

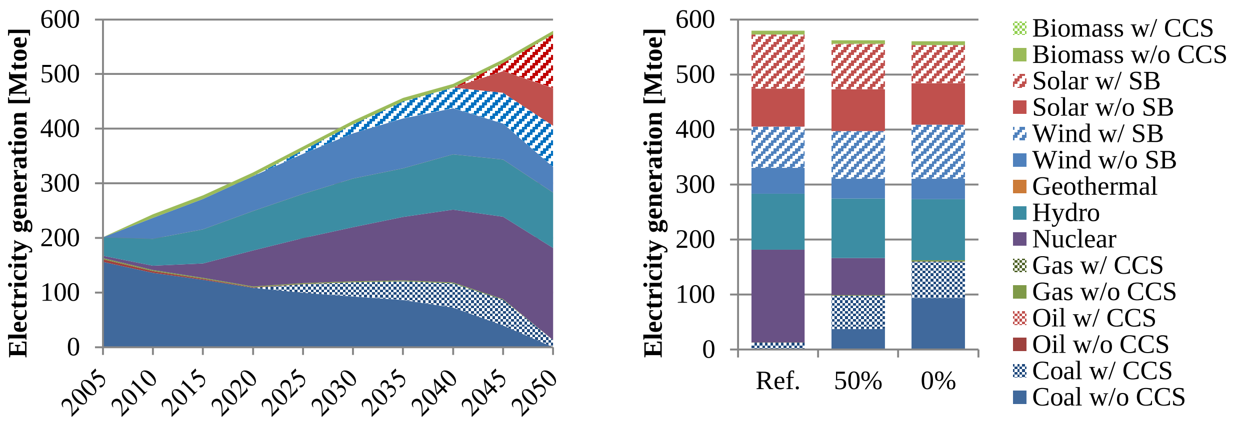
(d) Other Asian region

Fig.14 describes electricity generation by fuel in other Asian regions. In the other Asian regions, electricity demand increases. In the ref. scenario, electricity demand increases by 430Mtoe, which is 4.05 times as much as that in 2005. The share of natural gas is high compared to China and India. In the nuclear constraint scenario, electricity generated by natural gas and biomass increases instead of nuclear power generation. Electricity demand is reduced by more than 146 Mtoe and 263Mtoe in each nuclear constraint scenario, respectively.



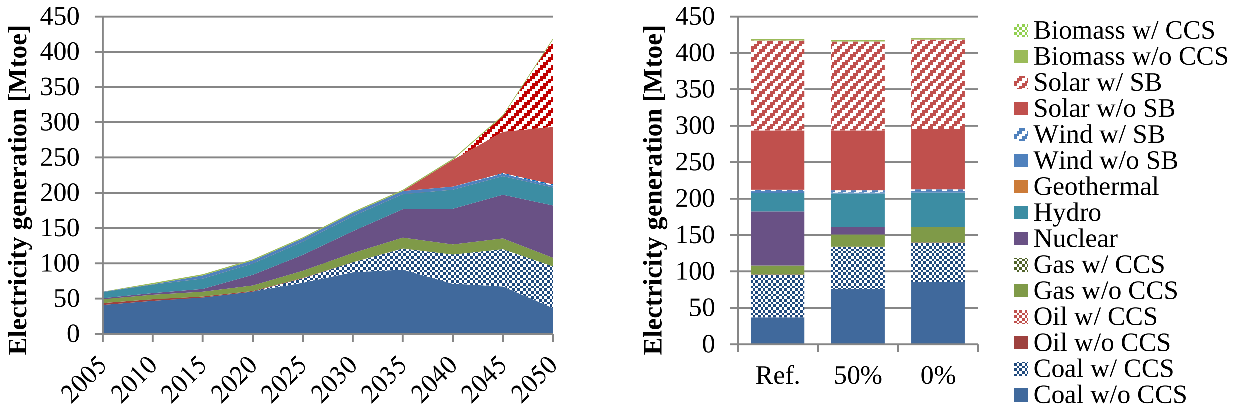
(a) Ref. scenario (b) in 2050

Fig.11 Electricity generation by fuel in Japan



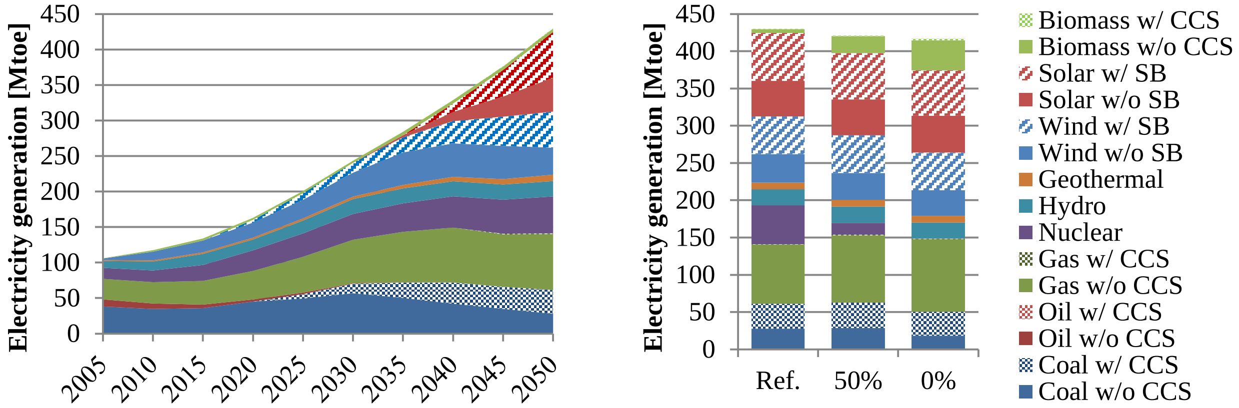
(a) Ref. scenario (b) in 2050

Fig.12 Electricity generation by fuel in China



(a) Ref. scenario (b) in 2050

Fig.13 Electricity generation by fuel in India



(a) Ref. scenario (b) in 2050

Fig.14 Electricity generation by fuel in other Asian regions

(2)Final energy consumption

Fig. 15 discribes final energy consumption in each region.

(a) Japan

Final energy consumption in Japan drops by about 30% from the level of 2005 in 2050. Oil consumption in particular is reduced by about 0.2 Gtoe. The impact of nuclear constraint is not great.

(b) China

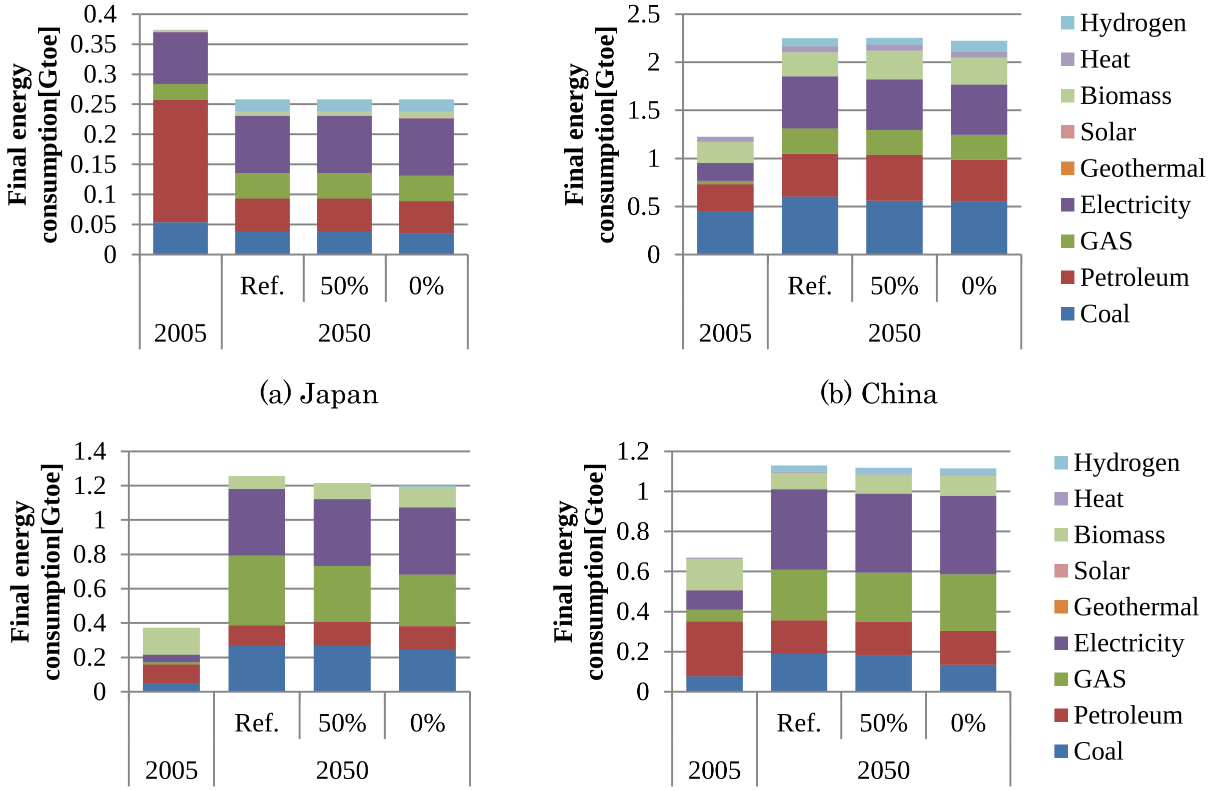
Final energy consumption in China increases to 2.2 Gtoe in 2050, which is 1.84 times as much as that in 2005. Oil and biomass consumption increase because service demand in the transport sector increases. In addition, natural gas consumption in other industry sectors increases by more than 16 times compared to that in 2005. The impact of nuclear constraint is not great. However, in the transport sector, hydrogen consumption increases instead of oil consumption in the 0% scenario.

(c) India

Final energy consumption in India in 2050 increases more than 3.3 times compared to that in 2005. Coal, natural gas and electricity consumption increase drastically. In the steel production sector, coal consumption increases bacause steel demand increases. In other industry sectors and the transport sector, the share of natural gas increases and the share of oil decreases after 2015. In the nuclear constraint scenario, natural gas consumption is reduced in transport sector. Specifically, hybid truck which can use biofuel installed instead of natural gas truck. This device change leads to not only a reduction in energy consumprion but also a reduction in CO_2 emissions.

(d) Other Asian region

Final energy consumption in other Asian regions increases by about 1.1 Gtoe. Coal, natural gas and electricity consumption increase similar to India. The impact of nuclear constraint is not great.



(a) Japan (b) China

(c) India (d) Other Asian regions

Fig. 15 Final energy consumption

4. Conclusion

This study estimated the impact of technology selection and energy consumption as a result of changes to nuclear policies using the AIM/BCM[global]. The analysis led to the following conclusions:

✓ *As a result of nuclear policy changes, biomass and coal consumption increase in the world.*

✓ *In the electricity sector, energy sources that offset the decreases of nuclear power generation are different in each country.*

In Japan, natural gas generation increases instead of nuclear power generation.

In China, wind power generation and coal power generation cover the decrease in nuclear power generation. In addition, electricity demand is reduced by a total of more than 220 Mtoe in each nuclear constraint scenario from 2005 to 2050.

In India, hydro power generation and coal power generation increase instead of nuclear power generation.

✓ *As the result of energy source changes, cumulative CO_2 emission from Asian region increase 9 Gt and 20 Gt in each nuclear constraint scenario, respectively.*

Especially in the 0% scenario, Chinese cumulative CO_2 emission increase 15 Gt compared with the ref. scenario.

✓ *In order to offset these increment of CO_2 emission, CO_2 emission reduces outside Asian region.*

USA and AUS have a relatively-large reduction in CO_2 emissions; however, emission reduction takes place more across the world rather than in particular countries.

These results show the availability of technology to achieve GHG emission reductions to stabilize radioactive forces by 2.5–3.0 W/m^2 even without new nuclear power plants in Asia.

References

1) International Energy Agency, Energy Technology Perspective,2010
2) Keigo Akimoto, Toshimasa Tomoda, Yasumasa Fujii and Kenji Yamaji, Assessment of global warming mitigation options with integrated assessment model DNE21, Energy Economics, 2004, vol. 26, issue 4, pages 635-653
3) Intergovernmental Panel on Climate Change, Forth Assessment Report, 2007
4) Kainuma M., Matsuoka Y., Morita T.(Eds.); Climate Policy Assessment: Asia-Pacific Integrated Modeling,2003,Springer
5) Detlef P. van Vuuren and Keywan Riahi, The relationship between short-term emissions and long-term concentration tergets, Climatic Change, Volume 104, Numbers 3-4, 2011, Pages 793-801
6) World Nuclear Association, World Nuclear Power Reactors & Uranium Requirements.