Feasibility of Low-Carbon Development in China

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Abstract

This study analyses the energy system and macro-economic responses to emissions reduction in China from 2005 to 2050 using a dynamic recursive Computable General Equilibrium (CGE) model. To explore plausible climate mitigation measures, two socioeconomic scenarios are assumed: Advanced (ADV; active acceptance of innovations and changes) and Conventional (CNV; conservative and passive response to innovations and changes). The assumed emissions reduction target is a 68% reduction from the 2005 level by 2050 derived from a target to halve global emissions. In total, four cases are considered, including two reference cases without emissions reduction and two mitigation cases with emissions reduction. The results, especially in the mitigation cases, are as follows:

In the ADV scenario, the GDP in 2050 is thirteen times larger than that in 2005 even with emissions constraint. The maximum emissions price is \$375/tCO_2eq in 2036, and the maximum GDP loss is 4.6% in 2035. Electrification is accelerated, and electricity is supplied by various power sources including renewable energies. In the CNV scenario, the GDP in 2050 is 7.5 times larger than that in 2005 even under emissions constraint. The emissions price increases significantly and becomes \$1,932/tCO_2eq, with a GDP loss of 10% in 2050. Unavailability of CCS technology forces to reduce fossil fuel consumption while electrification is accelerated. Electricity is mainly supplied by hydroelectric, biomass and nuclear power.

The results show that there are feasible low-carbon development pathways for China, although great uncertainty exists in China's future development. To achieve these pathways, efficient and appropriate governance is necessary, and the introduction of new technologies can contribute to minimizing the socioeconomic impacts of emissions reduction.

Key words: CGE model, China, economic effects, greenhouse gas (GHG), mitigation

1. Introduction

In recent years, global warming has been one of the most critical problems in the world. The Intergovernmental Panel on Climate Change (IPCC) says that the signs of warming of the climate system are unequivocal, and most of the observed increase in global average temperatures since the mid-20th century are very likely due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations (IPCC, 2007). Emissions reduction, especially in the developing world with rapid economic growth, is crucial for preventing drastic changes in the global climate system. The GHG emissions from China were 3,770 Mt CO_2 eq in 1990, rising to 7,707 Mt CO_2eq in 2005, the largest in the world, overtaking the US. (European Commission, 2011). In order to overcome climate change problems and take steps to acheive a "low-carbon society," one of the most intense future concerns is to see how China achieves a significant emissions reduction. Several studies focusing on the achievement of a low-carbon society in China have been conducted. Liu *et al.* (2009) clarified the main technologies to achieve such a society in China using a bottom-up type model. On the other hand, Ke *et al.* (2009) developed a top-down type model dealing with the relationship between investment and technology improvement, and simulated the effects of reduction measures. Although both studies managed to evaluate China's future quantitatively, neither of them considered both the global emissions halving target and the uncertainties of China's future development. Both international and domestic institutions, which are listed in Appendices 1 and 2, have published various scenarios of China's future development; however, often huge differences are seen among the scenarios, and it clearly shows that there are great uncertainties in terms of socioeconomic assumptions and mitigation measures.

This study takes into account the global emissions halving target and the uncertainties of China's future development. Two different socioeconomic scenarios for China, named advanced (ADV) and conventional (CNV), are assumed. While ADV describes a society that is open to innovation and changes, CNV describes a society that is conservative and passive about innovation and changes. The GHG emissions constraints used for this study are derived from the proposals for a global target of halving emissions and for construction and convergence of emissions, *i.e.*, halving global GHG emissions by 2050 from the 1990 level with equal emissions per capita allowed globally in 2050. Based on these ideas, the emissions reduction target for China in 2050 would become a 68% reduction from the 2005 level. In this study, China tries to achieve this target by utilizing mitigation measures. Combining the two socioeconomic scenarios and the reduction target results in four cases: two pairs of cases with and without achieving the emissions reduction target. The emissions reduction measures are set for the two mitigation cases based on the concepts and characteristics of the scenarios and the country, China. The macroeconomic impacts, especially in the two mitigation cases, caused by emissions reductions from 2005 to 2050 are quantitatively evaluated using a computable general equilibrium (CGE) model. The model is a recursive dynamic CGE model dealing with CO_2, CH_4 and N_2O emissions as GHG emissions in both energy-related and non-energy-related sectors.

An outline of the model is presented in Section 2. Section 3 introduces the scenarios, including detailed settings and emissions reduction targets with mitigation measures. Section 4 shows results from the model and finally Section 5 presents the conclusions.

2. Model Description

The model used in this study is a dynamic recursive CGE model, in which equilibriums are found every year. A detailed description of the model is available in Fujimori *et al.* (2011), Chapter 7 in this journal (Fujimori *et al.*, 2013) and the AIM/CGE [basic] manual (Fujimori *et al.*, 2012). The model encompasses 21 commodities, 30 industrial sectors, government, households and enterprises. A commodity is able to be produced by several different sectors, for example, electricity is generated by sectors including wind and solar photovoltaic power sectors. The total capital investment in a year is determined based on the target GDP growth. The investment in one year becomes the new capital in the next year and is allocated to the production sectors. The amount of new capital for each sector depends on the capital rate of return while old capital is fixed to its original sectors, and each sector has a capital stock with 4% annual depletion. Trade is formulated as per the Armington assumption with constant elasticity of substitution (CES) (Arrow *et al.*, 1961) and constant elasticity of transformation (CET) (Powel & Gruen, 1968) functions for imports and exports, respectively. The international goods price is an exogenous parameter for this model and global CGE model results (Fujimori *et al.*, 2013) are used.

The base year's social accounting matrix (SAM) and the energy balance table were compiled from several sources, for example, national accounts, industry statistics and energy statistics, with adjustments of inconsistencies among these data (Fujimori *et al.* 2011).

3. Scenarios

3.1 Two socioeconomic scenarios

This study assumes two different socioeconomic scenarios, advanced (ADV) and conventional (CNV). The concept of "ADV" is a society that is proactive and willing to take risks to innovate social systems, institutions and technologies for realizing next-generation societies. In contrast, "CNV" is a society that is cautious about changing social systems, institutions and technologies, putting more focus on transition costs for realizing next-generation societies.

3.1.1 Population

Figure 1 shows population estimates in China. The assumptions range between 1.1 billion (United Nations, 2010, low scenario) and 2.0 billion (Netherlands Environmental Assessment Agency, 2006, A2 scenario) in 2050. In our study, we have used the medium scenario from United Nations Population Prospects 2010 (2010). In this scenario, the population growth shows a downward trend after 2027, with the total population in 2050 finally becoming almost same as that in 2005. Although the scenario is slightly lower than the average of all the collected scenarios, the latter references assume lower scenarios, so this study reflects the latest trend in scenarios.

3.1.2 GDP

Assumed GDP scenarios range between 9.2 trillion (Japan Center for Economic Research, 2007) and 44.6 trillion US dollars (China Energy Research Institute, 2009a, reference scenario in Chapter 2). This study refers to Kawase and Matsuoka (under review), using an econometric model associated with a governance index (Kaufman *et al.*, 2010), average education period, and labor participants for target GDPs. The study assumes

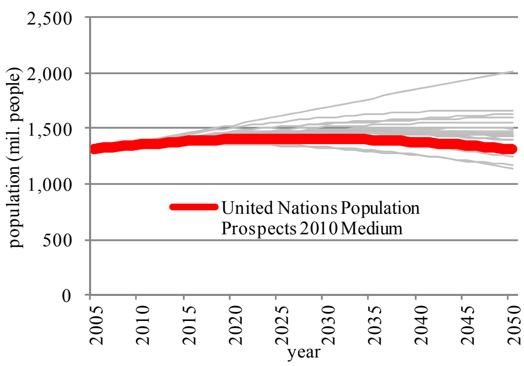

Fig. 1 Population prospects (references listed in Appendix 1).

that in ADV, the governance index would improve from –2.5 in 2005 to –1.4 in 2050 and the average education period would improve from 7.1 years in 2005 to 12.0 years in 2050. On the other hand, in CNV, the governance index would improve to –1.7 and the average education period would improve to 9.7 years in 2050. The average annual GDP growth rates in the period between 2005 and 2050 would be 6.1% and 4.9% in ADV and CNV, respectively, and with these growth rates, the total GDP in 2050 can be assumed to be around 14 and 8 times greater than the 2005 level in ADV and CNV, respectively when emissions constraints are not considered. The two scenarios almost trisect the other scenarios (Fig. 2).

3.1.3 AEEI

This study assumes autonomous energy efficiency improvement (AEEI), which is energy efficiency improvement that occurs in the absence of any energy price change or emissions constraints. According to various references, in 2050, China's total primary energy supply and total final energy consumption are assumed to be 2,400-5,400 and 1,700-3,600 Mtoe per year, respectively. This study sets the AEEI parameter values at 0% to 4% per year depending on the energy sources (Table 1). The current energy efficiency in China is relatively low: in 2007, China's energy intensity was 50% below the world average (IEA, 2010). This implies the possibility that energy efficiency can be improved significantly in China; therefore, this study assumes a relatively high AEEI value, especially for ADV. With the high AEEI value and without considering emissions reduction, in both ADV and CNV total primary energy supplies would be 3,800 and 3,400 Mtoe per year, respectively, and total final energy consumption would be 2,400 and 2,000 Mtoe per year, respectively, in 2050.

3.1.4 Intermediate input efficiency improvement

Although material demand used for social capital like steel and cement grows with economic development, this demand gradually decreases following the maturation of a society. This study reflects this through constant reduction of the input coefficients for iron and steel, mineral products including cement, and non-ferrous products. The reduction rates are determined based on the directory of iron and steel statistics (The Japan Iron and Steel Federation, 2010).

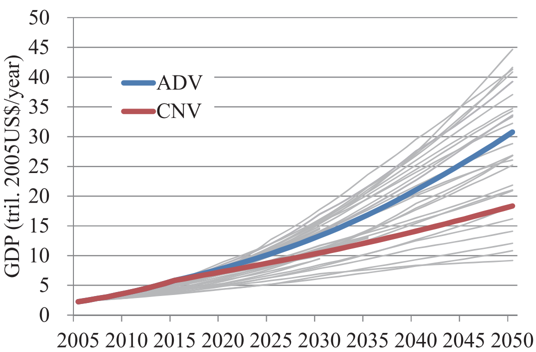

Fig. 2 GDP scenarios (references listed in Appendix 2).

3.1.5 Power generation (fossil fuel)

According to an IEA report (2010), the investment costs for coal and natural gas fuel-burning plants are expected to decrease by 0.5%-0.6% per year during 2010 to 2050. This study assumes the cost reduction to be 0.6% per year.

3.1.6 Power generation (non-fossil fuel)

Although the costs for introducing solar photovoltaic and wind power are relatively expensive currently, they are assumed to decrease drastically in the future. According to IEA (2010), during the period between 2010 and 2050 the cost of investing in solar photovoltaic and wind power is expected to decrease from US$3,500-5,600 to 1,000-1,600/kW and from US$1,450-2,200 to 1,200-1,600/kW respectively. Based on this assumption, this study assumes the cost reduction rates for solar photovoltaic and wind power generation shown in Table 1.

Hydroelectric and nuclear power are often managed by governments. Therefore, this study has established fixed amounts of introduction of the two exogenously. According to China Energy Research Institute (2009a, 2009b) and Chinese Academy of Engineering (2011), in 2050, the amounts of hydroelectric and nuclear power introduced will range from 106 to 378 and 40 to 452 Mtoe per year, respectively. This study assumes that 206 and 210 Mtoe per year of hydroelectric power and 156 and 378 Mtoe per year of nuclear power are introduced in ADV and CNV, respectively, in 2050. Note that the assumed rates of introducing hydroelectric and nuclear power are strongly intense. The domestic scenarios referred to assume strong extension of hydroelectric and nuclear power utilization, at least twice and 30 times larger, respectively, by 2050 than the current level.

3.1.7 Household energy consumption

This study assumes that households increase their energy consumption as income increases and energy prices decrease. Households decide which energy types to consume based on the price of each energy type while satisfying their total energy needs using the logit function (Clark & Edmonds, 1993).

3.1.8 Industrial sector energy consumption

Except in the case of energy transformation sectors such as power generation, industrial sectors have production functions in which value-added and energy composite are aggregated by the CES function and the energy composite is determined using the logit function. Energy commodities consumed by industrial sectors are selected depending on their prices, just as with households.

3.1.9 Transport

According to China Energy Research Institute (2009a, 2009b) and Chinese Academy of Engineering (2011), in 2050 passenger transport volumes by road, rail and aviation are expected to become 3.1-4.4, 3.1-5.0 and

9.8-23.8 times those in 2010, respectively, and freight transport volumes by road, rail and navigation transport will become 2.1-6.3, 3.4-4.0, 3.1-5.0 times those in 2010, respectively. We considered not only the above transport volume assumptions but also GDP and population assumptions presented in the reports, and set the scenarios for transport in ADV and CNV as below.

Household passenger transport by private car increases as household income rises, and its sensitivity to income increase would be lower in ADV than in CNV. China Energy Research Institute (2009a) assumes that the economic efficiency of transport energy consumption improves by 30%-60% from 2010 to 2050. This study assumes that the improvement in energy efficiency for household passenger car use will be 2% per year in ADV and 1.3% per year in CNV. The energy types consumed by each form of transport are determined based on energy prices, using the logit function.

Other passenger transport also increases with an increase in GDP. In ADV, bus and rail passenger transport would exhibit higher sensitivity to increasing GDP while car transport would have lower sensitivity to such increases, compared with in CNV. The freight transport volume was calculated based on transport service demand from institutions.

3.2 Emissions reduction targets

Although currently China has a reduction target only for 2020, this study considers both that target and the global halving target by 2050 to obtain the emissions constraints used here. The emissions constraint for 2020 is determined on the basis of China's national reduction target (Department of Climate Change, China, 2010), a 40%-45% reduction of CO_2 intensity in 2020 compared with the 2005 level. The emissions constraint in 2050 is assumed based on the global halving target, with the idea of construction and convergence, *i.e.*, halving global GHG emissions by 2050 from the 1990 level, allotting each country's emissions allowance based on equal emissions per capita all over the world in 2050. Based on the two targets, this study assumes China's emissions reduction target in 2020 to be a 43% reduction of GHG intensity and the target in 2050 to be a 68% reduction of GHG emissions compared with the 2005 level. China is

Table 1 Scenario catalog.

<table>
<tr><th></th><th>Advanced (ADV)</th><th>Conventional (CNV)</th></tr>
<tr><td>Concept</td><td>A society that is proactive and willing to take risks to innovate social systems, institutions and technologies for realizing next-generation societies</td><td>A society that is cautious of changing social systems, institutions and technologies, putting more focus on transition costs for realizing next-generation societies</td></tr>
<tr><td>GHG emissions reduction targets</td><td colspan="2">In 2020: 43% reduction of GHG emissions per GDP from the 2005 level
In 2050: 68% reduction of GHG emissions from the 2005 level</td></tr>
<tr><td>Population</td><td colspan="2">Peak in 2027 with 1.4 billion people and gradually reducing after 2027</td></tr>
<tr><td>Potential GDP growth rate (% per year)</td><td>2006-2015: 10.0, 2016-2030: 5.7, 2031-2050: 4.2</td><td>2006-2015: 10.0
2016-2030: 4.0
2031-2050: 2.9</td></tr>
<tr><td>AEEI (% per year)</td><td>Coal: 4.0, Oil: 3.0, Gas: 2.0, Electricity: 1.0</td><td>Coal: 3.0, Oil: 2.0, Gas: 1.0
Electricity: 0.0</td></tr>
<tr><td>Intermediate input efficiency improvement (% per year)</td><td>Construction
Iron and steel: 4.0
Mineral products (cement): 4.0
Other manufacturing
Iron and steel: 5.9
Non-ferrous metals: 2.0</td><td>Construction
Iron and steel: 2.1
Mineral products (cement): 2.0
Other manufacturing
Iron and steel: 4.0
Non-ferrous metal: 2.0</td></tr>
<tr><td>Power generation (fossil fuel)</td><td colspan="2">Cost reduction rate: 0.6% per year</td></tr>
<tr><td colspan="3">GHG emissions mitigation measures</td></tr>
<tr><td>Household energy consumption</td><td colspan="2">Demand decreases as energy prices rise and increases as household income grows. The energy commodities consumed are determined using the logit function.</td></tr>
<tr><td>Industrial energy consumption (non-energy transformation sector)</td><td colspan="2">Energy demand is determined by the CES function and the energy commodity share is determined by the logit function.</td></tr>
<tr><td>Transport</td><td colspan="2">Household passenger transport volume by private car rises as household income increases and the sensitivity to increases in ADV is smaller than that in CNV. The energy efficiency change in ADV is 2% per year while that in CNV is 1.3% per year.
Other passenger transport volume rises as GDP increases, and the sensitivity to this for bus and train transport is higher in ADV than in CNV, while the sensitivity for car transport is lower in ADV than in CNV.
The freight transport volume is calculated based on transport service demand from industrial sectors and institutions. The energy efficiency improves by 0.8% per year for cars, buses and trucks, and 0.2% per year for the other transport types. Depending on the energy price, additional energy efficiency improvement may occur.
Energy commodity allocation is determined by the logit function.</td></tr>
<tr><td>Power generation</td><td colspan="2">The rate of cost reduction for solar photovoltaic energy is 3.7% per year in ADV and 2.0% per year in CNV, while the rate of cost reduction for wind power is 2.0 per year in ADV and 0.8% per year in CNV.
The amount of nuclear power introduced in 2050 is 210 Mtoe per year in ADV and 206 Mtoe per year in CNV while the amount of hydro power introduced in 2050 is 156 Mtoe per year in ADV and 378 Mtoe per year in CNV.
CCS technology is available only in ADV from 2020 with a 3% per year maximum introduction rate. The assumed additional costs for introducing CCS technology are shown below.
CCS technology introduction costs
<table>
<tr><td></td><td colspan="4">Fuel-burning power plants</td></tr>
<tr><td></td><td>Coal</td><td>Oil</td><td>Gas</td><td>Biomass</td></tr>
<tr><td>$/tCO₂</td><td>50</td><td>70</td><td>70</td><td>70</td></tr>
<tr><td></td><td colspan="4">Industry</td></tr>
<tr><td></td><td>Mineral products</td><td>Paper and pulp</td><td>Coal Refineries</td><td></td></tr>
<tr><td>$/tCO₂</td><td>200</td><td>150</td><td>100</td><td></td></tr>
</table></td></tr>
<tr><td>Non-energy-related GHG</td><td colspan="2">The reduction of non-energy-related GHG is determined depending on the GHG emissions price or scenarios.</td></tr>
</table>

assumed to start reducing its emissions from 2013, and the study assumes a constant rate of reduction of GHG intensity during the periods from 2013 to 2019 and from 2021 to 2049.

By combining the two socioeconomic scenarios and emissions reduction targets, four cases were obtained: two reference cases without the emissions reduction targets and two mitigation cases with the emissions reduction targets. This study considers the four scenarios, focusing mainly on the two mitigation cases.

3.3 Mitigation measures

Several mitigation measures were considered in this study, and the detailed settings differed between the two mitigation cases in accordance with their respective socioeconomic factors.

3.3.1 GHG emissions taxation

A GHG emissions tax is that which is imposed per unit of GHG emissions on the end-use emitter, and hereinafter, this tax price, calculated per ton of GHG emissions in CO_2eq, is called the emissions price. This tax inhibits activities involving GHG emissions, resulting in acceleration of a switch to higher energy efficiency equipment and introduction of lower-carbon energy. In this study, the revenue from the GHG emissions tax is assumed to be allocated to households.

3.3.2 CCS technology

Carbon capture and storage (CCS) technology is techniques of capturing CO_2 from large emissions sources and injecting it into deep geological formations in this study. According to China Energy Research Institute (2009a), CCS is expected to be introduced experimentally starting around 2020, with practical application starting around 2025 in China. This study assumes that such technology will be available only in ADV after 2020. CCS technology can be introduced to conventional fuel-burning power plants, coal refineries, and the mineral products and paper-pulp industries with a maximum introduction speed of 3% per year. The additional cost for the introduction of CCS technology is set based on IEA (2004) assumptions.

3.3.3 Non-energy-related GHG reduction

This study assumes that if emissions are constrained, the GHG emissions from non-energy sources except land use and land use change will decrease depending on the emissions price, and the coefficient is set based on Hasegawa and Matsuoka (2010). Without GHG constraints, GHG emissions from land use and land use change are assumed to follow Riahi *et al.* (2007), and with GHG constraints, the emissions become zero in 2050.

3.4 Overview of the scenarios

The scenarios mentioned above are summarized in Table 1. One of the common characteristics between the two socioeconomic scenarios is a dramatic change in potential GDP growth rate: both scenarios show a rapid slowdown of GDP growth rate, especially between the periods of 2006-2015 and 2016-2030. This means that China is currently facing a dramatic shift in its economic system. Another turning point is the year of 2027, when the population is expected to peak. After 2027, the population will start to decrease. Because the emissions reduction target in 2050 is calculated based on population, a smaller population results in a stricter emissions reduction target as a whole. High energy efficiency improvement, seen especially in the ADV scenario, is also one of the characteristics. Additionally, active introduction of new energy is also an important characteristic in ADV. The power generated from hydroelectric and nuclear sources in 2050 exceeds 6 times and 35 times, respectively, than that of 2005 in ADV. Based on the concepts of the scenarios, the ADV society intends to introduce various renewable energies while the CNV society mainly focuses on utilizing conventional renewables.

4. Results

In this section, cases without GHG emissions reduction are shown under names which include the letters REF (reference), while cases with GHG emissions reduction are shown under names which include MIT (mitigation). All prices below are to be taken at the 2005 value of the US dollar, unless stated otherwise.

4.1 GHG emissions

Without emissions constraints, GHG emissions will become 15 to 16 Gt of CO_2eq in 2050 (Fig. 3, left). Even though ADV does involve more rapid economic development than CNV, the emissions in the REF scenarios are almost same. This is because rapid energy efficiency improvement is assumed for ADV and as a result, the energy consumption in the two cases becomes close: primary energy consumption in ADV_REF is only 1.1 times that in CNV_REF. Another factor is that the emissions in the two REF cases become almost constant because of the slowdown in economic growth and energy efficiency improvement.

In the mitigation cases, the emissions are constrained as mentioned in the previous section, to a 43% reduction in GHG intensity by 2020 and 68% reduction in GHG emissions by 2050 from the 2005 levels. Because this study does not consider emissions trading, the amounts of emissions in the two cases in 2050 are exactly the same, 2.4 Gt of CO_2eq.

4.2 The GHG emissions price

The maximum emissions price in ADV_MIT is \$375/tCO_2eq in 2036 and the price finally decreases to \$223/tCO_2eq in 2050 (Fig. 3, right). The price in CNV_MIT is lower than that in ADV_MIT until 2036, because the GHG emissions of CNV_REF are almost constant while those of ADV_REF are continuously increasing. After 2036, the emissions price in CNV_MIT continuously increases while that in ADV_MIT decreases gradually. In the year 2050, the emissions price in

CNV_MIT grows to \$1,932/tCO_2eq. The emissions price of ADV_MIT decreases because new technologies will have matured enough and their introduction will be accelerated. On the other hand, in CNV_MIT without CCS technology, consumption of fossil fuel, especially coal, is strictly constrained. To consume less fossil fuel, electrification is accelerated; however, thermal power plants, except those burning biomass, are again strictly constrained. In addition, the introduction of hydroelectric and nuclear power is exogenously managed; therefore, in CNV_MIT, relatively expensive renewable energies would need to be utilized while reducing energy demand and increasing the price of electricity. That would result in a significant increase in the emissions price.

4.3 GDP and GDP loss

The total GDP achieved in ADV_MIT in 2050 is almost twice as large as that in CNV_MIT (Fig. 4, left). Figure 4 (right) shows that the GDP loss in CNV_MIT is greater than that in ADV_MIT throughout the period. Ultimately, the GDP loss in CNV_MIT reaches 10% in 2050. The maximum GDP loss in ADV_MIT is 4.6% in 2035, declining to 4.3% in 2050.

These trends in GDP loss are similar to those in the GHG emissions price (Fig. 3, right). In CNV_MIT, strict emissions reduction without efficient mitigation measures like CCS technology results in high emissions and electricity prices. These increases would cause a decrease in production in some industries. The overall effects of strict emissions reduction eventually result in a significant GDP loss. On the other hand, ADV_MIT reaches a turning point in 2035: the GDP loss starts to decrease after that point almost the same as the GHG emissions price.

4.4 Total Primary Energy Supply

The primary energy supply in ADV_MIT is greater than that in CNV_MIT during the entire period (Fig. 5). This is mainly because the GDP in ADV_MIT is much higher than that in CNV_MIT. In both scenarios, the biomass and nuclear energy supply increase while the fossil fuel energy supply decreases. Because CCS technology is not available in CNV_MIT, coal consumption in CNV_MIT decreases to near zero in 2050 while 13% of primary energy supply in ADV_MIT would be coal.

4.5 Total Final Energy Consumption

The share of final energy consumption in the two scenarios is similar throughout the period (Fig. 6). After 2012, GHG emissions constraints are applied to both scenarios and final energy consumption starts to decrease. Although consumption in ADV_MIT increases after 2035, the consumption in CNV_MIT continuously decreases through to 2050. The reason why final energy consumption increases in ADV_MIT after 2035 is because several mitigation technologies like CCS become available and practical.

4.6 Household energy consumption

Household energy consumption decreases drastically in both scenarios, especially in 2035, after which it increases in ADV_MIT while it continuously decreases in CNV_MIT (Fig. 7, left). This follows the same trend as the other energy parameters, as CNV_MIT is required to achieve its emissions reduction target by decreasing energy demand and fossil fuel dependence. In both scenarios, electricity becomes the main energy source for households in 2050, while biomass, often called traditional biomass, decreases significantly. The decrease in traditional biomass is a common trend among developing countries.

4.7 Industrial energy consumption

Similar to household energy consumption, electricity penetration in the industrial sectors is accelerated, especially in the CNV_MIT scenario after 2035 (Fig. 7, right). In 2050, electricity would account for more than 80% of total industrial energy consumption in CNV_MIT.

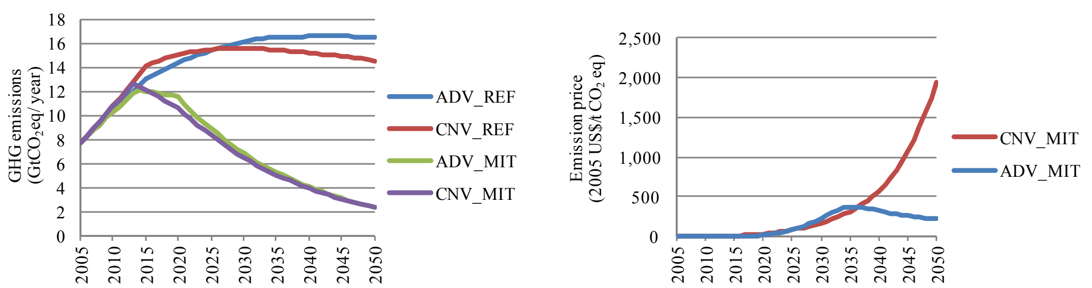

Fig. 3 GHG emissions (left: GHG emissions, right: GHG emissions price).

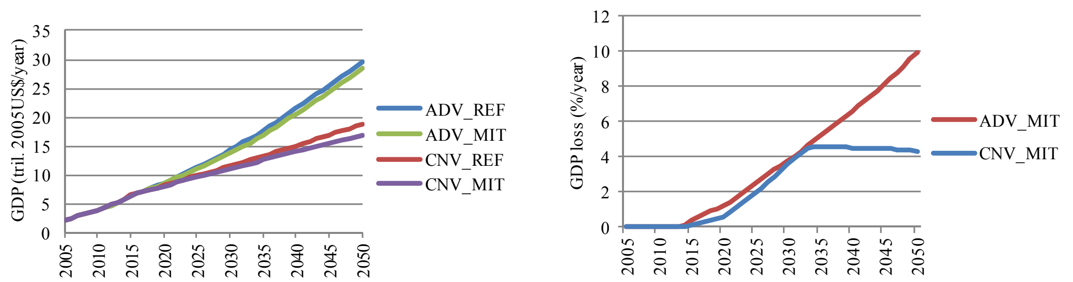

Fig. 4 GDP (left: GDP, right: GDP loss).

4.8 Power generation

Total power generation follows almost identical trends in the two scenarios (Fig. 8). In ADV_MIT, however, electricity is generated by a variety of power sources, for example, not only conventional energies but also wind power and biomass fire power with CCS technology. On the other hand, in CNV_MIT, hydroelectric, biomass fire and nuclear power generate more than 80% of total power in 2050. Although both cases are under emissions reduction targets, ADV_MIT would still be able to utilize fossil fuel energy because of CCS technology, so the share of renewable power in ADV_MIT is lower than that in CNV_MIT.

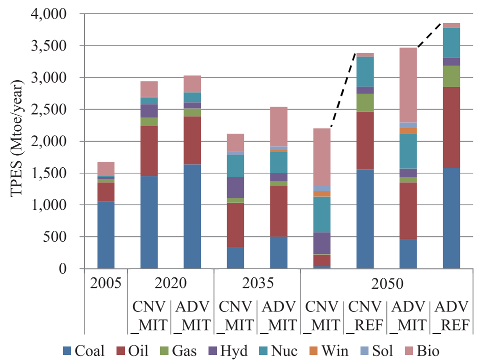

Fig. 5 Total primary energy supply.

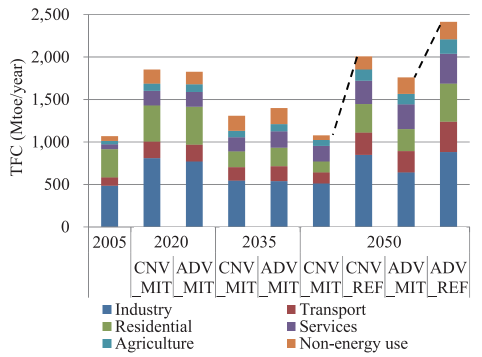

Fig. 6 Total final energy consumption.

4.9 GHG emissions reduction measures

Figure 9 shows shares of GHG emissions reduction measures in ADV_MIT and CNV_MIT. In ADV_MIT, in addition to renewable power and non-energy-related GHG reduction, CCS technology accounts for a large share. CCS technology would become one of the main reduction measures from around 2035, as mentioned in previous sections. In CNV_MIT, the introduction of renewable power is the largest contributor, and non-energy-related GHG reduction is the second.

4.10 CCS

It seems that CCS technology would have a significant economic effect in China; therefore, this study has also assumed several additional CCS settings to compare with the original scenario results.

Although originally CCS would not be available in CNV_MIT, if it were possible to introduce it after 2020 at maximum speed of 3% per year as in the case of ADV_MIT, the GHG emissions price would decrease significantly. The maximum emissions price would be \$270/tCO_2eq in 2038, and in 2050, it would become \$170/tCO_2eq. The GDP loss would decrease to 5.0% from the original 10% in the CNV_MIT without CCS. On the other hand, if the maximum speed of CCS introduction were 1% per year instead of the 3% per year in ADV_MIT, the GHG emissions price increase and the maximum price would become \$625 in 2041, up significantly from \$375 in 2036.

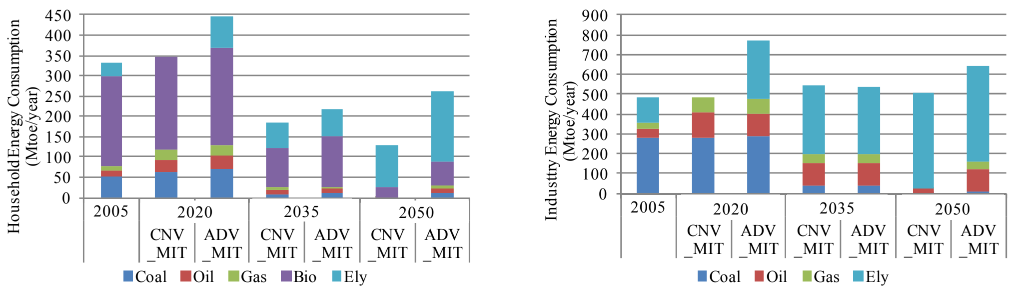

Fig. 7 Energy consumption (left: household, right: industry).

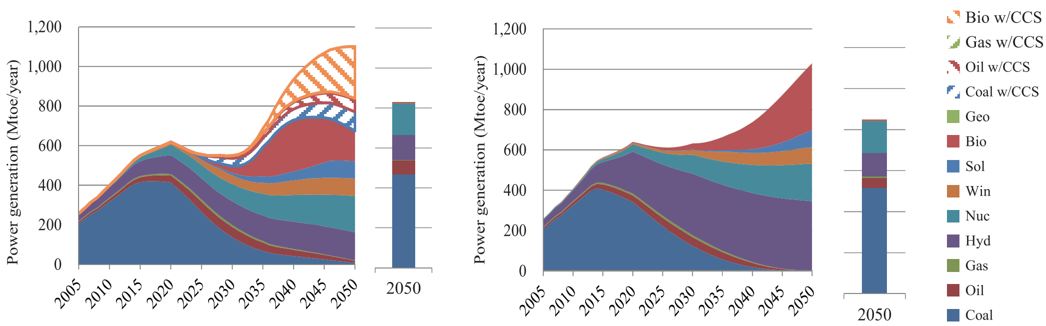

Fig. 8 Power generation.

(from left: ADV_MIT 2005-2050, ADV_REF 2050, CNV_MIT 2005-2050, CNV_REF 2050).

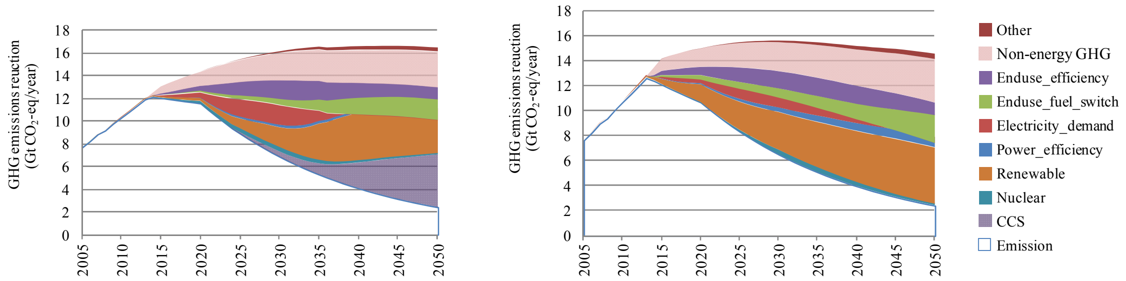

Fig. 9 GHG emissions reduction measures (left: CNV_MIT, right: ADV_MIT).

5. Discussion and Final Remarks

This study analysed the economic effects of GHG emissions reduction in China during the period from 2005 to 2050 using a CGE model. Two socioeconomic scenarios were assumed for China: ADV, which describes a society open to innovation and changes, and CNV, which describes a society conservative and passive about innovation and changes. The emissions reduction target in 2050 calls for a 68% reduction from the 2005 level and is based on the idea that the global halving target and equal emission amounts per capita all over the world. GHG mitigation measures were set in accordance with the two socioeconomic scenario concepts. A dynamic recursive CGE model was applied and the economic impacts of GHG emissions reductions were analyzed quantitatively.

Based the results, the two societies are described as below:

<ADV scenario>

– Rapid economic growth is achieved and the GDP in 2050 is $28 trillion, 12.6 times greater than that in 2005.
– GHG emissions reduction results in a maximum emissions price of $375/tCO_2eq in 2036, and the GDP loss becomes 4.6% in 2035.
– CCS introduction is accelerated and renewable energy technologies become economically practical, especially after 2035, so energy consumption starts to increase again and the economic loss gradually decreases.
– The electricity supply is supported by various power sources including renewable energies, and in 2050, 67% of total electricity is supplied by renewable energies.

<CNV scenario>

– In 2050, China achieves a GDP of $17 trillion, 7.5 times as large as that in 2005.
– Emissions reductions have a significant economic impact, and the GDP loss is 10% in 2050 with an emissions price of $1,932/t CO2eq.
– Because CCS technology is unavailable, fossil fuel consumption decreases and electrification is accelerated rapidly.
– Electricity is mainly supplied by hydroelectric, biomass fire and nuclear power, which supply 84% of the total in 2050.
– In the case that CCS technology is available, there is a possibility of reducing these economic effects significantly.

The descriptions of the two scenarios bring up three points for discussion: energy system shift, energy efficiency improvement and economic impacts.

One of the characteristic of China's energy system is its dependence on fossil fuels, especially coal. Fossil fuels account for more than 80% of its total primary energy supply, and 75% of those fossil fuels was provided by coal in 2005. In order to achieve a low-carbon society, China needs to realize a significant energy system change, from a system relying on fossil fuel to one relying on renewable and nuclear power. CCS technology would be able to ease the change because with it, fossil fuel could be utilized even under strict emissions constraints. The results from the model clearly show the importance of CCS technology in China.

This study assumes a relatively high degree of energy efficiency improvement, especially for the ADV_MIT case. This assumption is based on reports from Chinese domestic institutes including one from the China Energy Research Institute (2009b). In order to achieve this assumed energy efficiency improvement, appropriate government plans and strategies will be necessary.

The final point for discussion is the economic impacts of emissions reduction. The results show that the GDP loss ranges between 4% and 10%. Taking into account the total GDP growth, there may be compensation for this loss; however, there is still room to consider strategies to minimize the negative impacts. This study does not consider some of the emissions reduction measures that might be available, for example, international emissions trading, which would allow China to buy and sell emission credits internationally. Although they might be essential countermeasures for China, appropriate efforts should be made and support should be provided by the government to realize other countermeasures such as concrete international carbon market systems.

In conclusion, this study has analyzed the feasibility of low-carbon development in China. Although great uncertainty exists, especially in China's future development, there are feasible low-carbon development pathways. In order to achieve these pathways, efficient and appropriate governance is necessary, and the introduction of some new technologies can contribute to minimizing the impacts of emissions reduction in China.

Acknowledgments

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Michiko NAMAZU

Michiko NAMAZU is a master's degree student at the Department of Urban and Environmental Engineering, Kyoto University. Ms. Namazu got her Bachelor's of Engineering from the Department of Global Engineering, Kyoto University. She has been conducting research for the Asian-pacific Integrated Modeling (AIM) team since her senior year. Her field of study is climate change modeling, especially computable general equilibrium (CGE) modeling. Currently she is working on quantitative evaluation of the impact of greenhouse gas emission reduction in Asian regions, using the AIM/CGE [basic] model. She has applied the CGE model to Japan, India and China so far, and will apply it to other Asian regions as well. Through application of the model, she is developing scenarios for Asian regions toward a reduced GHG emissions society, *i.e.*, the so-called low-carbon society.

Shinichiro FUJIMORI

Shinichiro FUJIMORI is a researcher at the National Institute for Environmental Study in Japan. Dr. Fujimori got his Bachelor's, Master's and PhD degrees from the Department of Environmental Engineering, Kyoto University. Now he is a member of the AIM (Asia-Pacific integrated Assessment Model) team, where he is working on development and application of a CGE model. In the early period of his career, he tackled development of a method to create a consistent social accounting matrix and energy balance table. He later applied that method to the world, classifying it into more than 100 regions spanning the last three decades, and using more than 30 international data sets, *e.g.*: national accounts, trade statistics, energy statistics, etc. The reconciled data are used in the CGE model or a bottom-up-type energy model. During the last couple of years, he has been working on development and application of a CGE model. The model will find wide use, for instance, in global climate mitigation assessment, development of new IPCC socioeconomic scenarios, and national level climate mitigation policy.

Kejun JIANG

Kejun JIANG began researching climate change relative to energy policy analysis, with a focus on energy technology policy assessment, energy supply policy assessment, renewable energy development and energy conservation. Since 1994, he has worked on integrated assessment model development for energy and GHG emission policy scenarios, focusing on analysis of China and the world. At present he is mainly working on energy and environment policy assessment, serving as leader of the Integrated Policy Assessment Model for China (IPAC) team. His major focus includes energy and emissions scenarios, energy policy energy systems, energy market analysis, and climate change. Started from 1997, he has worked with the IPCC on the Special Report on Emission Scenario and Working Group III Third Assessment Report, serving as lead author for IPCC WGIII AR4 Chapter 3, and lead author for GEO-4 Chapter 2. Now he is the Coordinating Lead Author for IPCC AR5. His recent research projects include energy and emissions scenarios for 2030, low-carbon emissions scenarios up to 2050, assessment of energy taxes and fuel taxes, the potential of energy targets in China, development of an integrated policy assessment model, and other projects. He got his Ph.D. from the Social Engineering Department of the Tokyo Institute of Technology.

Yuzuru MATSUOKA

Yuzuru MATSUOKA is a Professor at the Graduate School of Engineering, Kyoto University. He specializes in environmental engineering. He started researching global environmental issues in the late 1980s. He has developed various kinds of integrated models, including bottom-up and top-down models. Recently he has been leading projects for development of Asian low-carbon societies.

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Appendices

Appendix 1 Reference list for Fig. 1.

Title	Year	Author
2050 China Energy and CO_2 Emission Report (CEACER)	2009a	China Energy Research Institute, National Development and Reform Commission
China's Low-Carbon Development Pathways by 2050: Scenario Analysis of Energy Demand and Carbon Emissions (CEACES)	2009b	China Energy Research Institute, National Development and Reform Commission
Transportation Energy Intensity and Consumption Forecasts.	2012	China Energy Research Institute, National Development and Reform Commission
Energy Science & Technology in China: A Roadmap to 2050	2010	Chinese Academy of Sciences
Energy Revolution Sustainable Energy Global Energy Outlook 2nd Edition	2010	Greenpeace
The GGI Scenario Database (version 2.0)	2006	International Institute for Applied Systems Analysis
Downscaling Drivers of Global Environmental Change – Enabling Use of Global SRES Scenarios at the National and Grid Levels	2006	Netherlands Environmental Assessment Agency
Development of Long-term Socioeconomic Scenarios –Population, GDP –	2011	Research Institute of Innovative Technology for the Earth
China's Low-Carbon Development Scenario in 2050, 2050 China Energy and CO_2 Emissions Report	2009	Study Team of 2050 China Energy and CO_2 Emissions Report
World Population to 2300	2004	United Nations Population Division
World Population Prospects 2008	2008	United Nations Population Division
World Population Prospects 2010	2011	United Nations Population Division
US Census International Database	2010	United States Census Bureau

Appendix 2 Reference list for Fig. 2.

Title	Year	Author
Energy Outlook for Asia and the Pacific 2009	2009	Asia-Pacific Economic Cooperation, Asian Development Bank
Country-level GDP and Downscaled Projections	2002	Center for International Earth Science Information Network
CEPII BASELINE V1.0 GDP	2009	Centre D'etudes Prospectives et D'infomarions Internationales (CEP)
The Long Term Growth Prospects of the World Economy-Horizon 2050	2006	Center D'etudes Prospectives et D'infomarions Internationales (CEP)
2050 China Energy and CO_2 Emission Report (CEACER)	2009a	China Energy Research Institute, National Development and Reform Commission
China's Low-Carbon Development Pathways by 2050 Scenario Analysis of Energy Demand and Carbon Emissions (CEACES)	2009b	China Energy Research Institute, National Development and Reform Commission
China's Mid- and Long-term (2030, 2050) Energy Development Strategy	2011	Chinese Academy of Engineering
Energy Science & Technology in China: A Roadmap to 2050	2010	Chinese Academy of Sciences
The Prospects of China's Economic Development in 2030-Based on the DRC-CGE Model	2010	Development Research Center of State Council, P. R. China
International Energy Outlook 2010.	2010	Energy Information Administration
Potential Secure, Low-Carbon Growth Pathways for the Chinese Economy	2011	Energy Research Institute, National Development and Reform Commission
The GGI Scenario Database (version 2.0)	2006	International Institute for Applied Systems Analysis
Energy Technology Perspectives.	2010	International Energy Agency
Long-term Forecast of Global Economy and Population 2006-2050 Demographic Change and the Asian Economy	2007	Japan Center for Economic Research
Downscaling Drivers of Global Environmental Change-Enabling use of Global SRES Scenarios at the National and Grid Levels	2006	Netherlands Environmental Assessment Agency
Development of Long-term Socioeconomic Scenarios –Population, GDP–	2011	Research Institute of Innovative Technology for the Earth
China's Low-Carbon Development Scenario in 2050, 2050 China Energy and CO_2 Emissions Report	2009	Study Team of 2050 China Energy and CO_2 Emissions Report
Asia/World Energy Outlook 2009 –The role of Technology towards the Resolution of Energy & Environmental Issues in Asia–	2009	The Institute of Energy Economics, Japan
Asia/World Energy Outlook 2010 –The Role of Technology Towards the Resolution of Energy & Environmental Issues in Asia and the World–	2010	The Institute of Energy Economics, Japan
Asia/World Energy Outlook 2011 –Growing Uncertainty over International Energy Trends and the Future of Asia–	2011	The Institute of Energy Economics, Japan