Estimating Global CO_2 Emission Constraints and Energy Supply/Demand Structure in 2050 with MARKAL Model

Yuji Matsuo* Kengo Suzuki** Yu Nagatomi*
Shigeru Suehiro*** Ryoichi Komiyama****

Summary

This study used the MARKAL (MARKet ALlocation) model, a linear programming model for energy system analyses, to find the effects that upper constraints on carbon dioxide emissions will exert on the world's energy supply/demand structure and energy supply costs. Improving the efficiency of energy consumption technologies, promoting renewable energy, switching from coal to natural gas and other co-benefit measures to reduce both CO_2 emissions and fossil fuel consumption may reduce CO_2 emissions in 2050 by up to 40% from the baseline case without these CO_2 emission reduction measures (or may limit the increase from 2005 to 63%) in non-OECD (Organisation for Economic Cooperation and Development) countries and by up to 50% (or up to 36% from 2005) in OECD countries. Given that these measures are effective not only for preventing global warming but also for securing stable energy supply, non-OECD countries are expected to positively introduce these measures. Even in this case, however, global CO_2 emissions in 2050 will still increase by 16% from 2005. If emission constraints are toughened to further reduce emissions, primary energy consumption will increase due to the power generation sector's introducing carbon capture and storage systems.

In order to achieve a tough target of reducing global CO_2 emissions in 2050 by 50% from 2005, developing and industrial countries will have to cut emissions by 70% and 80%, respectively, from the case without emission reduction measures (or by 18% and 74% from 2005). To this end, final energy uses will have to be electrified to an extremely large extent and thermal power generation plants with CCS systems will have to be increased to cover a relevant rise in electricity demand. Total system costs for this case are estimated to rise by $20.5 trillion from the Constraint-free Case. From the abovementioned case where co-benefit measures will be taken to minimize primary energy consumption, primary energy consumption is estimated to increase by 1,900 million tons of oil equivalent and system costs by $15.6 trillion. In the case for reducing global CO_2 emissions in 2050 by 50% from 2005, reduction in the non-OECD countries accounts for 55% of the total system cost increase, whereas the real GDP of the region account for only 45% of the global GDP. Eliminating such cost burden gap accompanying the global CO_2 emission reduction will be important for promoting global warming prevention measures.

1. Introduction

How to share CO2 emission cuts between countries or regions is one of the most important issues involving global warming measures. CO2 emissions from countries other than those covered by Annex I to the U.N. Framework Convention on Climate Change now exceed those from Annex I countries including members of the Organisation for Economic Cooperation and Development1). This trend is expected to continue in the future. However, non-OECD

* The Energy Demand and Modelling Center, the Institute of Energy Economics, Japan
** Graduate School of Engineering, Hokkaido University
*** The International Energy Agency
**** Department of Nuclear Engineering and Management, the University of Tokyo

countries included into non-Annex I countries have yet to advance global warming measures as much as OECD countries. Furthermore, non-OECD countries have a deep-rooted belief that it is unfair for them to accept global warming measures that will impede their economic development. Given that the 17th Conference of Parties to the UNFCCC, known as COP17, in December 2011, agreed to create an international framework that will legally bind all UNFCCC member countries[2)], a discussion on how to share CO_2 emission cuts is expected to grow even fiercer.

The possible effects that CO_2 emission cuts will exert on energy supply/demand structure and energy supply costs in each country or region over a medium to long term are indispensable knowledge for a discussion on how to share CO_2 emission cuts. Energy technology combinations to be selected by countries or regions subject to this analysis will change according to constraints imposed on CO_2 emissions. Changes that global warming measures will trigger in the energy supply/demand structure will include both secondary benefits (co-benefits[3)]) represented by fossil fuel consumption cuts and increases in energy consumption and system costs. The effects of these measures will depend on future economic growth and the current energy supply/demand structure in each country or region and have to be estimated for each country or region.

This study uses the MARKAL (MARKet ALlocation) model[4)], a linear programming model for energy system analyses, to find the effects that upper constraints on CO_2 emissions will exert on the world's energy supply/demand structure and energy supply costs. First, we estimate CO_2 emissions and energy supply/demand structure trends in OECD and non-OECD regions for the case without constraints on CO_2 emissions. Next, we vary CO_2 emission constraint levels to analyze their effects on the energy supply/demand structure and energy supply costs. Finally, we estimate the effects that a 50% cut in global CO_2 emissions will exert on the energy supply/demand structure and energy supply costs.

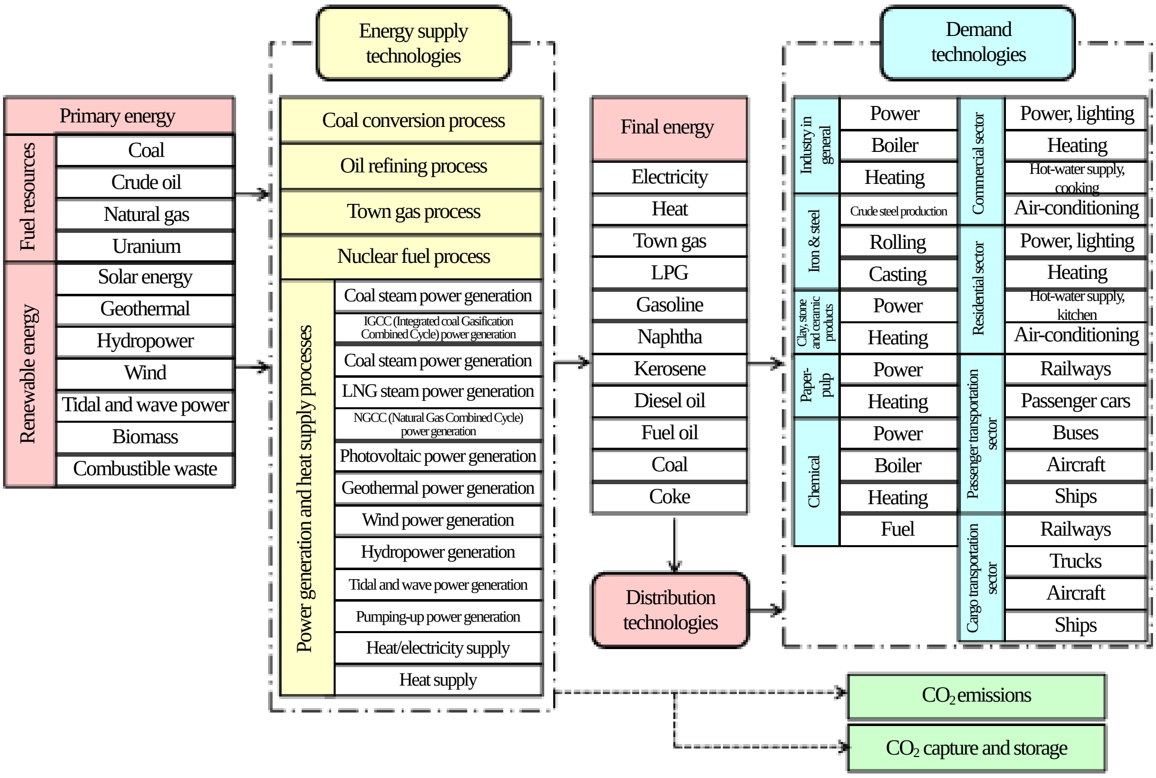
2. Outline of MARKAL Model

2-1 MARKAL Model Structure

The MARKAL model is a linear programming model to estimate a future energy system that can be created and operated at minimum cost under given economic and technological scenarios and constraint conditions. The economic scenario consists of components such as energy service demand, fuel prices and discount rates. The technological scenario covers characteristic data (technological efficiency, capacity utilization ratios, etc.) of available energy technologies. Constraint conditions represent technological, social and political constraints on energy supply and demand, including renewable energy introduction potential, constraints on nuclear power plant locations and upper constraints on CO_2 emissions.

The MARKAL model is structurally similar to actual energy systems, consisting of energy supply and demand technologies. Energy demand technologies consume final energy to provide energy services. Energy supply technologies collect energy sources and transform them into final energy to be provided for energy demand technologies. The total system cost as the objective function for optimization with the MARKAL model is defined as the total sum of equipment, fuel, operation, repair and other costs. Energy technology introduction and operation amounts are determined as the result of optimization calculation to minimize total system costs. By accumulating results of such calculation, we can estimate an energy supply/demand structure, CO_2 emissions and total system costs for a period of time subject to analysis. The MARKAL model structure is given in Figure 2-1.

Figure 2-1 MARKAL Model Structure



2-2 Earlier Studies Using MARKEL Model

Earlier studies that used the MARKAL model to analyze the effects that CO_2 emission constraints will exert on the energy supply/demand structure are roughly divided into two categories. The first category varies the levels of upper constraints on CO_2 emissions for a target year to find the different effects that the different levels of such constraints will exert on the energy supply/demand structure. For example, Shrestha and Pradhan (2010)[5] compared and analyzed the effects that CO_2 emission cuts ranging from 0% to 30% between 2005 and 2050 in Thailand will exert on the energy supply/demand structure. This study found that tougher constraints on CO_2 emissions will result in progress in energy conservation, an increase in marginal emission reduction costs, the diversification of primary energy sources, and other changes. Similar studies have been conducted for other non-OECD countries such as Nepal[6] and Bangladesh[7]. The second category attempted to find the effects of changes in technological, social and political constraints on the achievement of emission targets under fixed upper constraints on CO_2 emissions for a target year. For example, Kannan (2009)[8] analyzed how an upper limit on investment in CCS systems, nuclear power generation and renewable energy will affect future electricity generation and the power mix under the condition of a 60% cut in CO_2 emissions in 2050. This study concluded that the abovementioned investment limit will result in a fall in electricity generation and a rise in marginal CO_2 emission reduction costs. Komiyama (2012)[9] analyzed how a change in Japan's nuclear power generation outlook after the Great East Japan Earthquake will affect the energy supply/demand structure under the condition of a 60% cut in CO_2 emissions in 2050. This study indicated that as constraints on nuclear power generation are toughened, marginal CO_2 reduction costs will expand through an increase in CCS systems.

In general, the first category has been conducted mainly for the non-OECD region and the second category for the OECD region. One apparent reason for this trend may be that discussions have focused on desirable emission reduction levels in the non-OECD region free from any emission reduction requirements under the Kyoto Protocol and on how to achieve emission reduction targets in the OECD region bound by the emission reduction requirements.

While the viewpoints for the first and second categories are both important, this study focuses on the first category viewpoint in analyzing the effects of various CO_2 emission constraint levels on the OECD and non-OECD regions. This is because we believe we must give priority to finding the effects of various emission constraint levels on the energy supply/demand structure in both regions in the absence of numerical emission reduction targets and adopting the effects as a base for future discussions. Since it is also important to pursue a universal target, however, we also analyze the case where global CO_2 emissions in 2050 will be cut by 50% from 2005.

3. Economic and Technological Scenario Assumptions

3-1 Economic Scenario Assumptions

Population, real gross domestic product and fossil fuel prices are assumed as shown in Tables 3-1 and 3-2, based on our Asia/World Energy Outlook 2011 (AWEO2011)[10]. Both population and GDP in the non-OECD region will grow far more rapidly than in the OECD region. As a result, the non-OECD region's share of global population will increase from 82% in 2005 to 85% in 2050. Its share of global real GDP will expand 22% in 2005 to 45% in 2050. Oil prices will rise due to factors such as a production cost increase amid a shift to small- and medium-sized and deep-sea oilfields and oil producing countries' growing market power. Natural gas and steam coal prices will increase in line with crude oil price hikes. As in the past, however, the steam coal price will rise slower than natural gas prices. The discount rate is assumed at 5%.

Table 3-1 Population and Real GDP Assumptions

		Actual	Forecast		Annual growth
		2005	2035	2050	50/05
Population	OECD region	12	14	14	0.3%
[100 million people]	Non-OECD region	53	72	79	0.9%
GDP	OECD region	29	52	64	1.8%
[constant 2000 US$ trillion]	Non-OECD region	8	35	52	4.3%

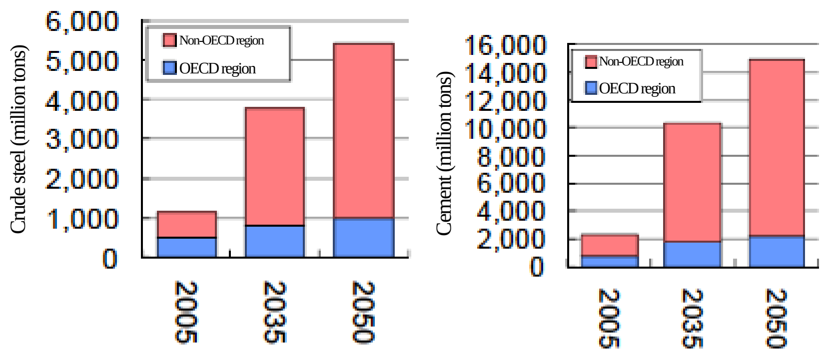
Table 3-2 Fossil Fuel Price Assumptions ($1million per petajoule)

	2005	2035	2050	50/05
Steaming coal	2.4	4.7	4.9	1.6%
Crude oil	8.4	19.8	20.6	2.0%
Natural gas	5.7	13.8	14.4	2.1%

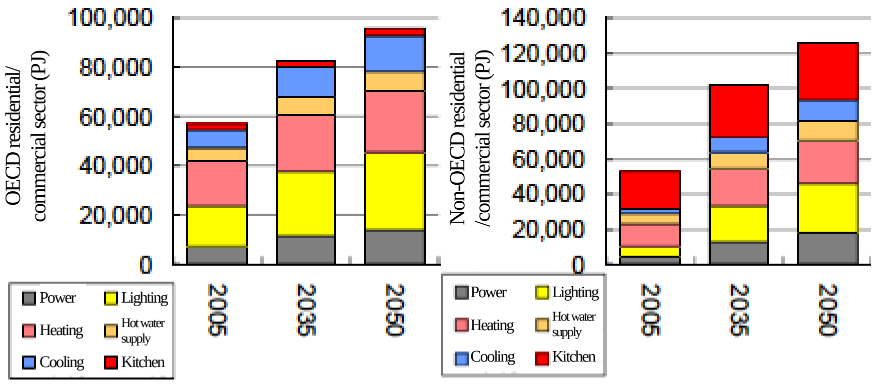
Energy service demand put into the MARKAL model is roughly divided into three sectors – industrial, residential/commercial and transportation. The future industrial sector demand scenario is estimated in line with real GDP growth and each industry's actual production records[11)12)13)14)15)]. Residential/commercial sector demand is estimated according to population and per capita GDP growth and actual records for each sector[16)]. Transportation sector demand is cited from the IEEJ2050 model database[17)] that has been developed for a detailed analysis of the transportation sector. Since GDP forecasts in the AWEO2011 are different from those in the IEEJ2050 model, however, this study uses estimates corrected with the GDP elasticity of transportation sector demand. Each sector's energy service demand assumptions based on the abovementioned method are shown in Table 3-1.

The industrial sector's energy service demand, while increasing moderately in the OECD region, will expand substantially in the non-OECD region. This is because energy-intensive industry bases will shift from the OECD region to the non-OECD one. Crude steel, cement and ethylene output in the non-OECD region in 2050 will overwhelm OECD region levels. The non-OECD region will raise its share of global paper-pulp production close to 50%. The residential/commercial sector's energy service demand will increase both in the OECD and non-OECD regions. But the non-OECD region's growth at 140% will be far higher than 68% for the OECD region. Power, lighting and air-conditioning demand will increase remarkably in line with living standard improvements accompanying economic development. The transportation sector's energy service demand will also increase mainly in the non-OECD region. In the passenger transportation sector, the use of passenger cars will increase rapidly in line with living standard improvements. Passenger cars' share of total passenger transportation will rise from 18% in 2005 to 29% in 2050. In the cargo transportation sector, the use of convenient trucks will increase. Trucks' share of total freight transportation will go up from 36% in 2005 to 40% in 2050.

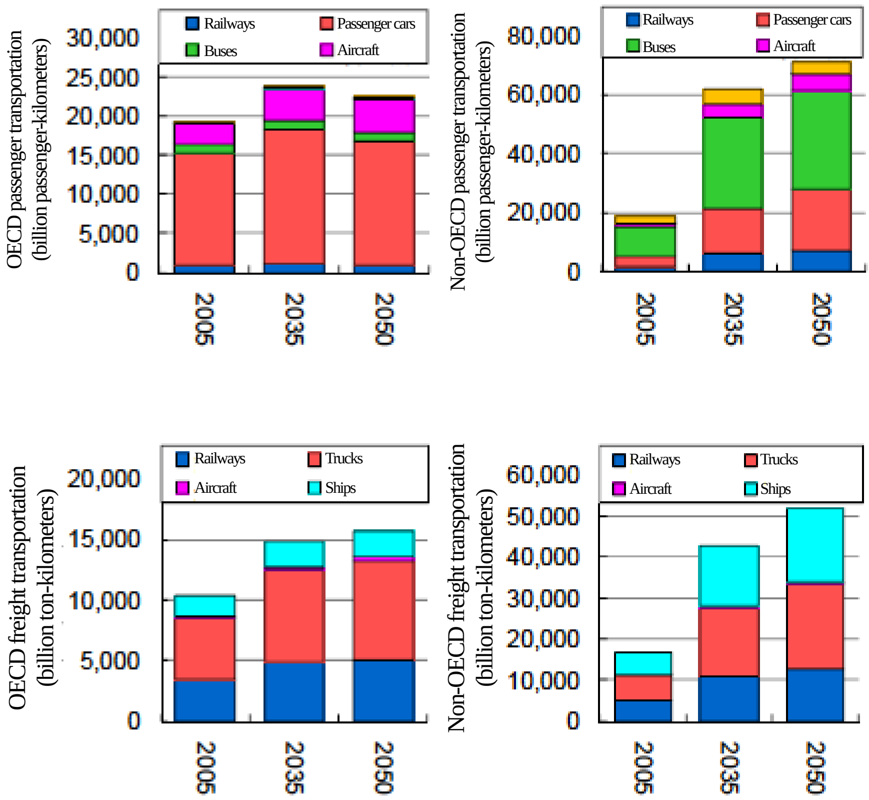
Figure 3-1Energy Service Demand Outlook



(a) Representative Industries' Energy Service Demand



(b) Residential/Commercial Sector's Energy Service Demand



(c) Transportation Sector's Energy Service Demand

3-2 Technological Scenario Assumptions

As for supply and demand side energy technologies, differences in efficiency, cost and other technological levels between the OECD and non-OECD regions are taken into account only for the first year of the period for this analysis. For the rest of the period, however, both the OECD and non-OECD regions are assumed to be able to choose from all available technologies. This means that this study does not assume any tariff or other barriers that may impede the transfer of cutting-edge technologies developed in a certain region to other regions.

From the viewpoint of CO_2 emission cuts, a power generation technology assumption is the most important among various assumptions for the technological scenario. This has been indicated by many earlier studies (e.g., Kannan (2009), Mondal & Denich (2010)) that gave priority to analyzing the power generation sector. Power generation technology assumptions for this study are given in Table 3-3, based on EIA (2010)[18], IEA (2010a,b)[19][20], IEA (2011)[21], etc.

In addition to power generation volumes, constraints on non-fossil energy technology introduction volumes are important. Since the potential for introducing these technologies depends on natural conditions, social constraints and policy trends, assumptions about the potential must be specified before an analysis. This study uses non-fossil energy introduction volumes for the Reference Scenario in the AWEO2011 as a lower constraint and those for the Advanced Technologies Scenario as an upper constraint. In the Reference Scenario, "countries are assumed to implement no additional energy conservation or low-carbon measures, and ambitious targets vowed by various countries for introducing energy conservation and low-carbon technologies are assumed to fail due to financial or other difficulties." The Advanced Technologies Scenario assumes that "countries implement a series of energy and environmental policies and measures aimed at securing stable energy supply and reducing global warming, and accelerate the development and introduction of innovative technologies." Constraints on non-fossil energy introduction volumes are given in Table 3-4, based on projections for the two scenarios.

Table 3-3 Power Generation Technology Assumptions

	Year for introduction	Service life	Operating rate	Power generation efficiency	Equipment cost	Fixed operation & maintenance cost	Variable operation & maintenance cost
		[Years]	[%]	[%]	[US$/kW]	[US$/kW]	[US$/PJ]
Conventional coal thermal	2005	40	85	33-36	817-987	28	1.2
Pulverized coal thermal	2005	40	85	39-43	2076-2502	28	1.2
Pulverized coal thermal+CCS	2020	40	85	29-31	3337-4028	61	2.5
IGCC	2015	40	85	39-43	2639-2816	47	1.9
IGCC+CCS	2020	40	85	32-35	3296-4224	55	2.2
Coal CHP	2005	20	70	33	880.2	79	1.2
Oil thermal	2005	40	85	33-36	1160-1340	94	1.0
Nuclear (light water reactor)	2005	60	76–84	33	3491-4214	70	0.6
Hydropower	2005	60	45	100	3076	11	0
Geothermal	2005	30	73	10	2335-3208	179	2.7
Biomass thermal	2005	40	85	33-36	1584-2031	90	1.2
Wind (onshore)	2005	20	30	100	1056-1381	41	0
Wind (offshore)	2005	20	30	100	1511-2437	78	0
Wave power	2010	20	70	100	1807-3249	97	0
Solar thermal power generation	2010	20	25	100	2010	24	0
Photovoltaic power generation	2005	20	17	100	650-3249	41	0
Pumping-up power generation	2005	60	0	70	4420	10	0
Conventional gas thermal	2005	40	85	32-38	869-974	5.5	4.1
NGCC	2005	40	85	53-63	895-1003	12	1.0
NGCC+CCS	2020	40	85	46-53	1499-2060	24	1.8
Natural gas CHP	2005	20	70	27-32	978	11	1.0

Table 3-4 Constraints on non-fossil Energy Introduction Volumes (unit: GW)

	2005		2035		2050	
	OECD	Non-OECD	OECD	Non-OECD	OECD	Non-OECD
Hydropower generation	342	430	342-432	430-1031	342-480	430-1538
Geothermal power generation	0	0	0-14	0-11	0-17	0-14
Biomass thermal power generation	40	9	132-142	69-81	167-175	88-99
Wind power generation (onshore)	55	6	415-593	313-572	432-788	483-924
Wind power generation (offshore)	0	0	87-125	66-120	140-255	156-299
Wave power	0	0	6-7	1-1	13-21	1-3
Solar thermal power generation	0	0	39-75	19-38	58-221	45-205
Photovoltaic power generation	4	0	232-407	57-205	332-688	116-551

3-3 CO_2 Emission Constraint Assumptions

This study estimates a case without upper constraints on CO_2 emissions (hereinafter referred to as "Constraint-free Case") and another case where CO_2 emissions will be cut by X% from the constraint-free case in 2050 (hereinafter referred to as "-X% Case"). The X value will be increased by increments of 10 percentage points until the model calculation becomes impossible. For each case, emissions in 2050 and their percentage decline from 2005 will be indicated after emissions for the Constraint-free Case are estimated.

4. Analysis Results

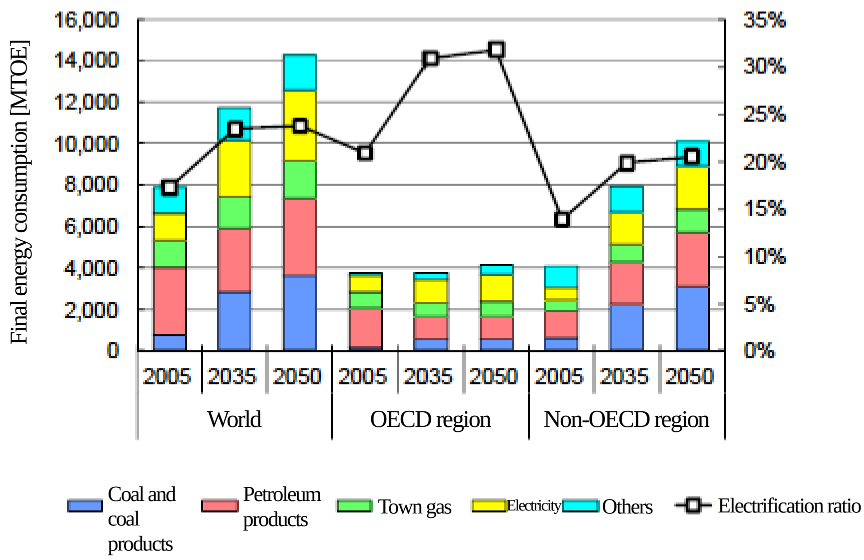
4-1 Energy Supply/Demand Structure for Case without CO_2 Emission Constraints

4-1-1 Final Energy Mix

Global final energy consumption for the Constraint-free Case is given in Figure 4-1. Consumption is specified each for the OECD and non-OECD regions. The white square indicates the electrification ratio, or electricity's share of final energy consumption. Global final energy consumption in 2050 will increase by 6,400 MTOE (million tons of oil equivalent) (80%) from 2005 to 14,200 MTOE. The non-OECD region accounts for more than 90% or 6,000 MTOE of the increase. As a result, final energy consumption will total 4,100 MTOE in the OECD region and 10,100 MTOE in the non-OECD region. Thus, the non-OECD region will account for more than 70% of global consumption.

Among energy categories, coal (up 2,900 MTOE) and electricity (up 2,000 MTOE) post particularly large increases. The world's electrification ratio will rise by 7 percentage points from 2005 to 24% in 2050. In the OECD region, the electrification ratio will increase by 11 points from 21% to 32% despite the low growth in total energy demand, indicating that a switch from oil to other energy categories will make progress. In the non-OECD region, however, all energy categories will increase to support the fast expansion in energy demand. The electrification ratio will rise by 6 points from 14% to 20%.

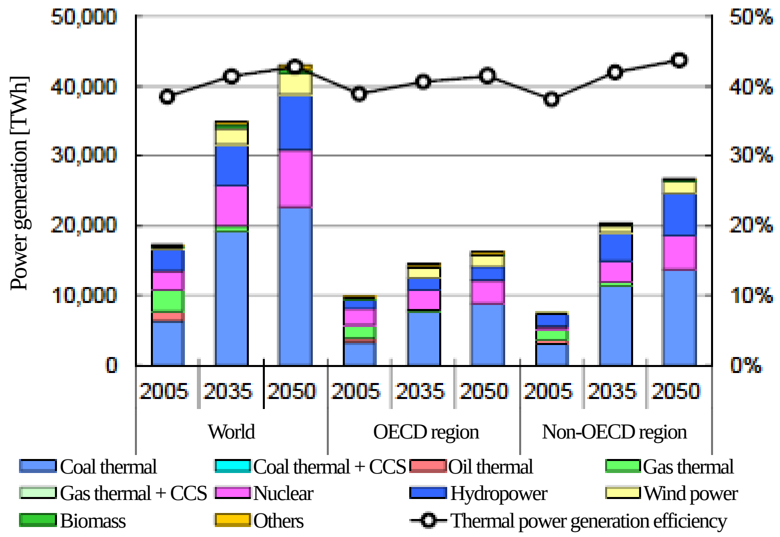
Figure 4-1Final Energy Mix for Constraint-free Case



4-1-2 Power Generation Mix

Figure 4-2 shows power generation in the world, the OECD region and the non-OECD region for the Constraint-free Case. Global power generation in 2050 will increase by 26,100 TWh (or 153%) from 2005 to 43,100 TWh. The total includes 16,300 TWh for the OECD region and 26,800 TWh for the non-OECD region. By power generation category, coal thermal power generation will score the largest growth of 16,200 TWh (150%) during the analysis period. Nuclear power generation will increase by 5,300 TWh, hydropower generation by 4,900 TWh and other renewable energy-based power generation by 3,000 TWh. These changes will result from a fuel switch to relatively cheaper coal and non-fossil energy sources from oil and natural gas for which price hikes are expected to continue. The electrification of final energy consumption, as given in Figure 4-1, will be attributed to a power generation cost decline caused by the fuel switch.

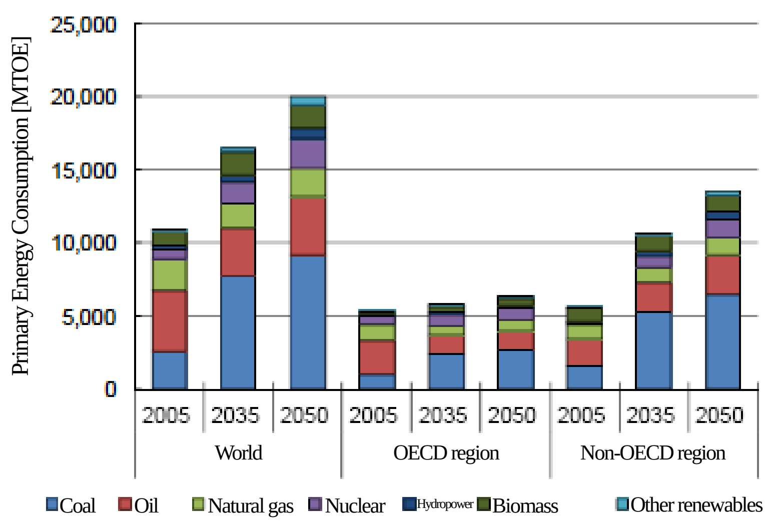
Figure 4-2 Power Generation Mix in Constraint-free Case



4-1-3 Primary Energy Mix

Figure 4-3 shows primary energy consumption in the world, OECD region and non-OECD region in the Constraint-free Case. The world's primary energy consumption in 2050 will increase by 9,100 million tons of oil equivalent or 84% from 2005 to 20,000 MTOE. Some 8,000 MTOE or nearly 90% of the increase will come from the non-OECD region. As a result, primary energy consumption in 2050 will total 6,400 MTOE in the OECD region and 13,600 MTOE in the non-OECD region. In this way, the non-OECD region will account for nearly 70% of global primary energy consumption. Of the global increase at 9,100 MTOE, coal will account for 6,600 MTOE. Coal's share of primary energy consumption in 2050 will expand by a substantial 22 percentage points from 2005 to 46%. Non-fossil fuel consumption will increase by 2,900 MTOE, leading its share of primary energy consumption in 2050 to rise by 6 points from 2005 to 25%.

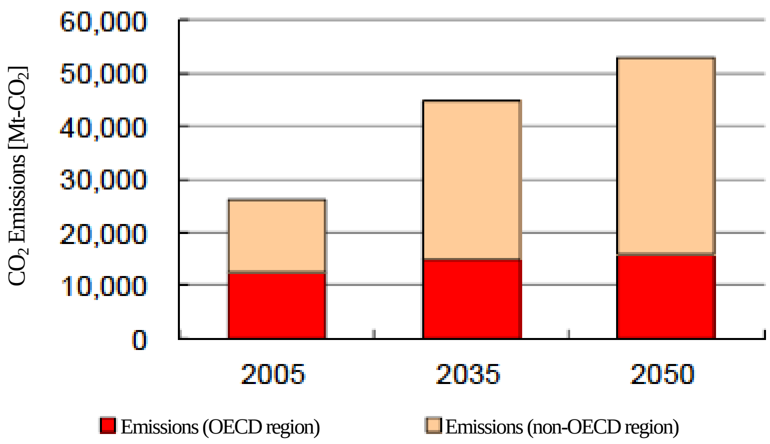
Figure 4-3 Primary Energy Mix in Constraint-free Case



4-1-4 CO_2 Emissions

Figure 4-4 shows global CO_2 emissions estimated for the Constraint-free Case. Global CO_2 emissions will increase by 26.9 billion tons or 104% from 26 billion tons in 2005 to 52.9 billion tons in 2050. By region, the OECD region will expand CO_2 emissions by 3.6 billion tons or 29% from 2005 to 16 billion tons and the non-OECD region by 23.3 billion tons or 172% from 2005 to 36.8 billion tons.

Figure 4-4 CO_2 Emission Trends



4-2 Energy Supply/Demand Structure Changes under CO_2 Emission Constraints

4-2-1 Case Assumptions

As explained in Section 3-3, this study represents an analysis where CO_2 emissions in 2050 are reduced by increments of 10 percentage points from 100% for the Constraint-free Case. As a result, estimates have been made for a reduction of up to 80% in the OECD region and up to 70% for the non-OECD region. Table 4-1 shows assumptions for each region in each case. We must take note of a point that even the same percentage reduction for the OECD and non-OECD regions results in a wide gap in their reduction volumes as non-OECD CO_2 emissions are assumed to more than double the OECD level in the Constraint-free Case.

Table 4-1 Case Assumptions for CO_2 Emission Constraints

Case	Emissions in 2050 [Mt-CO_2]		Change from 2005 [%]	
	OECD	Non-OECD	OECD	Non-OECD
-10%	14,436	33,131	16%	145%
-20%	12,832	29,450	3%	118%
-30%	11,228	25,769	-10%	91%
-40%	9,624	22,087	-23%	63%
-50%	8,020	18,406	-36%	36%
-60%	6,416	14,725	-48%	9%
-70%	4,812	11,044	-61%	-18%
-80%	3,208	-	-74%	-

(Note) The cases indicate CO_2 emission cuts from the case without constraints on CO_2 emissions.

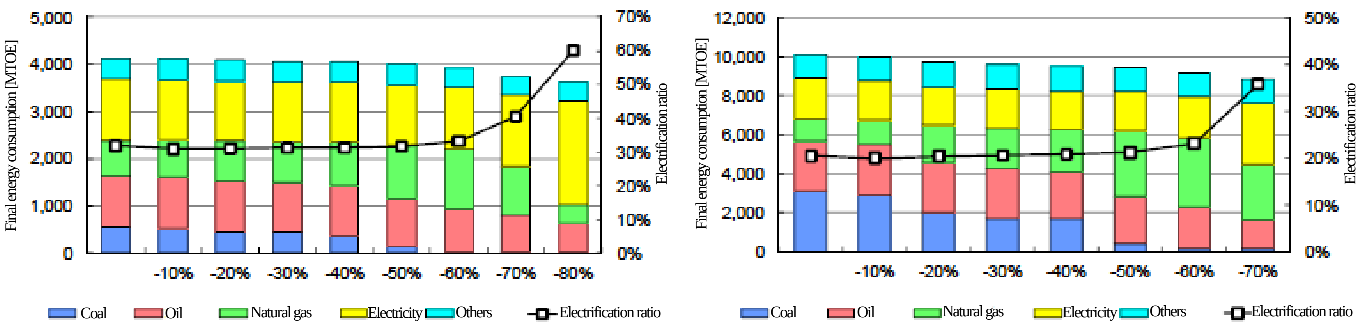
4-2-2 Final Energy Mix

Figure 4-5 shows a final energy mix in 2050 for each case. The white square indicates the electrification ratio. In each region, final energy consumption will decline monotonically as the CO_2 emission constraint is toughened. In the OECD region, final energy consumption in 2050 for the 80% CO_2 emission reduction case will be 500 MTOE or 12% less than for the Constraint-free Case. In the non-OECD region, consumption in 2050 for the 70% CO_2 emission reduction case will be 1,300 MTOE or 13% less than for the Constraint-free Case. The results indicate that energy demand technologies will grow more efficient as the CO_2 emission constraint is toughened.

However, we must take note of a point that the declines in final energy consumption for the -70% and -80% cases in the OECD region and for the -60% and -70% cases in the non-OECD region will originate from electrification progress. Energy demand technologies using electricity as an energy source have higher energy utilization efficiency than those using other energy sources. But lifecycle-based energy utilization efficiency depends on electricity generation and transmission/distribution efficiency. Therefore, whether electrification leads to efficient energy utilization cannot be decided based on final energy consumption alone.

Energy mix changes indicate that as the CO_2 emission constraint is toughened in each region, a fuel switch from coal to natural gas, from oil to natural gas, and fossil fuels to electricity will make progress. The electrification ratio in each region will begin to rise in -60% and tougher-constraint cases after a fuel switch from coal to natural gas is completed. The electrification ratio will rise from 32% for the -50% case to 60% for a tougher-constraint case in the OECD region and from 21% to 42% in the non-OECD region. The results indicate that emission cuts through a fuel switch from coal cost less than cuts through electrification and that emission cuts after a fuel switch from coal will have to be made through electrification that costs more. We will have to decide how much electrification contributes to reducing fossil fuel consumption after checking the electricity generation mix.

Figure 4-5 Final Energy Mix in 2050 for Each Case



OECD region   Non-OECD region

4-2-3 Electricity Generation Mix

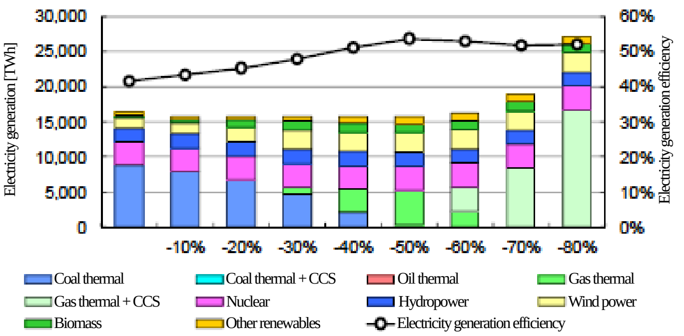
Figure 4-6 shows the electricity generation mix in 2050 for each case. The white circle indicates the thermal power generation efficiency. In each region, total electricity generation will remain unchanged toward the -50% case and turn up in the -60% or tougher-constraint case. In the OECD region, electricity generation in the -80% case will increase by 10,800 terawatt hours or 66% from the Constraint-free Case to 27,100 TWh. In the non-OECD region, electricity generation in the -70% case will increase by 14,200 terawatt hours or 52% from the Constraint-free Case to 41,000 TWh.

The electricity generation mix indicates that as the emission constraint is toughened, both regions will first replace thermal power generation with wind power etc. and then switch fuel from coal to natural gas for electricity generation, replace non-CCS-equipped natural gas thermal power plants with CCS-equipped plants and increase CCS-equipped natural gas power plants to expand electricity generation.

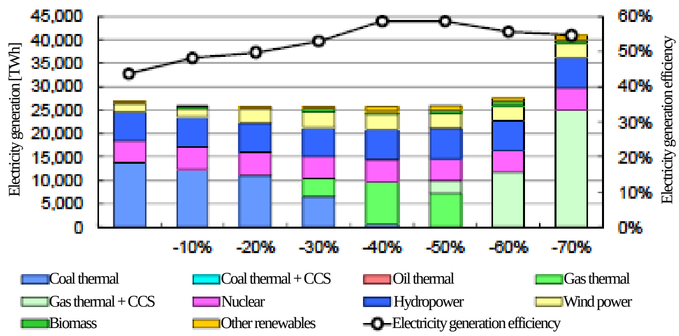
In both regions, renewable energy-based electricity generation will increase for the -10-40% cases and level off for the tougher-constraint cases. In the -40% case, renewable energy-based electricity generation (combining hydropower, wind power, biomass and other renewable energy generation) will increase by 2,900 TWh or 69% from the Constraint-free Case to 7,100 TWh in the OECD region and by 2,900 TWh or 35% to 11,100 TWh in the non-OECD region. A switch from coal to natural gas for thermal electricity generation will be completed in the -50% case for the OECD region and in the -40% case for the non-OECD region. Non-fossil electricity generation will account for 66% of total generation in the -50% case for the OECD region and for 62% of total generation in the -40% case for the non-OECD region. CCS-equipped natural gas thermal power plants will replace non-CCS-equipped ones in the -50-70% cases for the OECD region and in the -40-60% cases for the non-OECD region. If CO_2 emission cuts through the replacement fall short of allowing emission reduction targets to be achieved, the final measure to combine electrifying final energy consumption with constructing additional CCS-equipped natural gas power plants will be implemented. If this measure is implemented substantially, non-fossil electricity generation's share of total electricity generation will fall substantially from the cases before the CCS introduction to 38% in the -80% case for the OECD region and to 33% in the -70% case for the non-OECD region.

Of the four abovementioned measures, the renewable energy diffusion and the switch from coal to natural gas for thermal power generation can improve the electricity generation efficiency. But CCS-equipped thermal power plants' replacement with non-CCS-equipped ones and the construction of additional CCS-equipped thermal power plants can lower the efficiency. Electricity generation efficiency will rise to 54% in the -50% case and fall to 52% in the -80% case for the OECD region. For the non-OECD region, the efficiency will rise to 59% in the -40% case and fall to 54% in the -70% case.

Figure 4-6 Case-by-case Electricity Generation Mix in 2050



OECD region



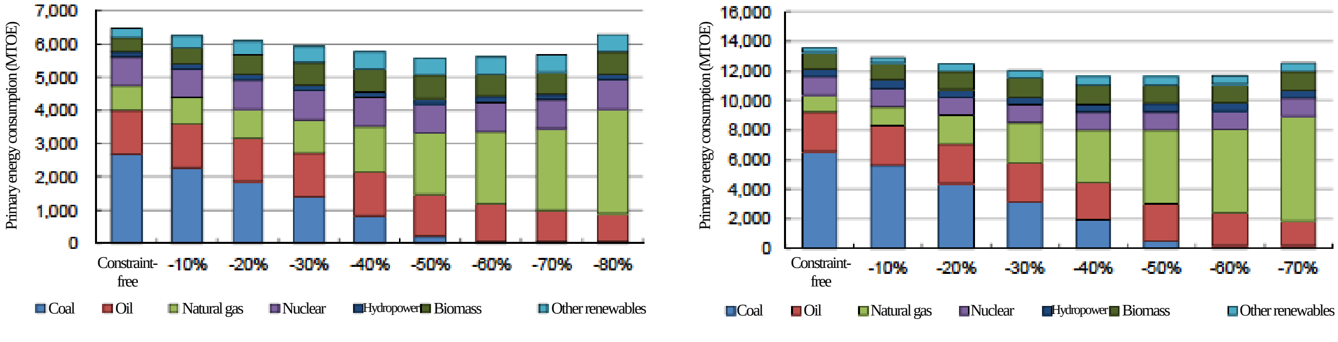
Non-OECD region

4-2-4 Primary Energy Mix

Figure 4-7 shows a primary energy mix in 2050 for each case. In the OECD region, primary energy consumption will fall to the lowest level of 5,600 MTOE (down 14% from the Constraint-free Case) in the -50% case and turn up in tougher-constraint cases. Consumption will post small growth in the -60-70% cases and rise sharply to 6,300 MTOE (down 3% from the Constraint-free Case) in the -80% case. In the non-OECD region, primary energy consumption will fall to the lowest level of 11,600 MTOE (down 15% from the Constraint-free Case) in the -40% case and turn up in tougher-constraint cases. Consumption will post small growth in the -50-60% cases and rise sharply to 12,500 MTOE (down 8% from the Constraint-free Case) in the -70% case. These results indicate that the electrification of final energy consumption in tougher-constraint cases will contribute to reducing CO_2 emission while working to boost primary energy consumption through a decline in the lifecycle energy utilization efficiency.

Non-fossil energy consumption will almost hit the ceiling in the -30% case. Therefore, primary energy consumption changes in tougher-constraint cases will reflect fluctuations in fossil fuel consumption. In the OECD region, non-fossil fuels' share of primary energy consumption will rise to 40% in the -50% case and fall to 35% in the -80% case. In the non-OECD region, the share will increase to 31% in the -40% case and fall to 27% in the -70% case.

Figure 4-7 Primary Energy Mix in 2050 for Each Case



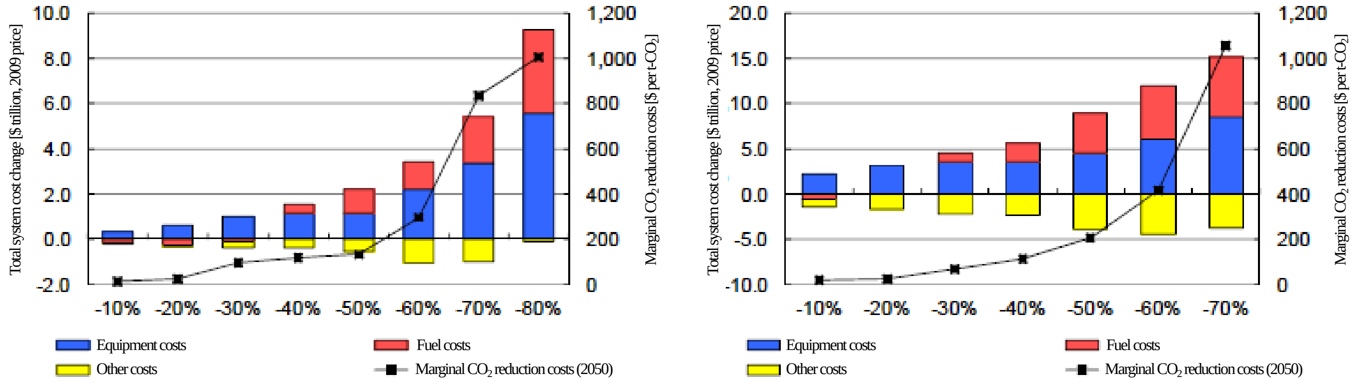
OECD region Non-OECD region

4-2-5 Total System Costs

Figure 4-8 shows a total system cost increase from the Constraint-free Case and marginal CO_2 reduction costs in 2050 for each case. In the OECD region, total system costs will increase by $1.6 trillion for the -50% case with the lowest primary consumption and by $9.2 trillion for the -80% case with the toughest constraint. In the non-OECD region, total system costs will increase by $3.3 trillion for the -40% case with the lowest primary consumption and by $11.3 trillion for the -70% case with the toughest constraint. As indicated by the results, more emission cuts from the Constraint-free Case will lead to greater additional costs per unit emission reduction. Marginal CO_2 reduction costs in 2050 will increase sharply for cases with tougher constraints than in the least primary energy consumption case each in the OECD and non-OECD regions. In the toughest-constraint case, such costs will exceed $1,000 per ton each in the OECD and non-OECD region.

A total system cost breakdown indicates that equipment costs increase as the emission constraint is toughened. The increase stems from investment in higher-efficiency equipment, renewable energy equipment, the electrification of energy demand equipment and CCS-equipped electricity generation plants. Fuel costs will decline temporarily as the introduction of renewable energy expands in the -10-20% cases and increase substantially as fuel is switched from coal to natural gas, electricity generation efficiency declines accompanying the CCS introduction, and electrification progresses in tougher-constraint cases. Other costs will decline in accordance with a shift from coal to natural gas for thermal electricity generation and a decline in operation and maintenance costs through the energy demand side's advanced technology introduction.

Figure 4-8 Total System Cost Increase in Each Case



OECD region Non-OECD region

4-3 Compiling and Analyzing Results

In the case without constraint on CO_2 emissions, global final energy consumption in 2050 will increase by about 80% from 2005, with the increase concentrating in the non-OECD region. Coal and electricity will cover about three quarters of the increase. Given that coal thermal electricity generation will cover some 60% of an electricity generation increase, coal will account for about 70% of a primary energy consumption increase. Nuclear, renewable and other non-fossil energy sources will have a cost advantage over oil, natural gas and other fossil fuels and account for about 30% of the primary energy consumption increase. The non-OECD region's share of global primary energy consumption will rise from about 50% in 2005 to nearly 70% in 2050.

In line with the substantial coal consumption growth, global CO_2 emissions in 2050 will almost double the 2005 level. Given that about 90% of the emission growth will originate from the non-OECD region, global warming measures will urgently be required to be implemented mainly in the non-OECD region. If CO_2 emissions in 2050 were to be halved from 2005, emissions would have to be cut to about one quarter of the Constraint-free Case level.

If the target of CO_2 emission reduction from the Constraint-free Case is 50% for the OECD region and 40% for the non-OECD region, it may be achieved through enhancing the efficiency of energy demand technologies, promoting the introduction of renewable energy, switching fuel from coal to natural gas, and other co-benefit measures to reduce both CO_2 emissions and fossil fuel consumption. Given that these measures are effective for preventing global warming and securing stable energy supply, the non-OECD region is expected to positively introduce such measures.

If an emission constraint exceeding the above levels is imposed, primary energy consumption will increase slightly due to the electricity generation sector's CCS introduction. This is because the efficiency of fossil thermal electricity generation will decline due to additional electricity consumption for powering CCS systems. If a higher emission reduction target of 70% or 80% were to be achieved, the electrification of final energy would have to be combined with the introduction of CCS-equipped fossil thermal power plants. Given that these measures are expected to substantially expand primary energy consumption through a decline in the lifecycle energy utilization efficiency, non-OECD countries are not expected to positively introduce CCS-equipped plants.

The results indicate that it will be difficult to achieve the ambitious target of reducing global CO_2 emissions in 2050 by 50% from 2005 by using co-benefit measures alone. According to Table 4-1, CO_2 emissions in the -50% case with the least primary energy consumption for the OECD region will be 8 billion tons (down 8 billion tons from the Constraint-free Case). Emissions in the -40% case with the least primary energy consumption for the non-OECD region will be 22.1 billion tons (down 14.7 billion tons from the Constraint-free Case). If the two cases are combined, global primary energy consumption will decline by a substantial 14% from 2005 to 17,100 MTOE. But CO_2 emissions will increase by 16% from 2005 to 30.1 billion tons. Total system costs for this case will increase only by \$4.9 trillion from the Constraint-free Case.

If CCS-equipped natural gas thermal power plants are increased to the maximum level, CO_2 emissions in 2050 may be reduced by nearly 50% from 2005. According to Table 4-1, CO_2 emissions will total 3.2 billion tons (down 12.8 billion tons from the Constraint-free Case) in the -80% case for the OECD region and 11 billion tons (down 25.8 billion tons from the Constraint-free Case) in the -70% case for the non-OECD region. If these cases are combined, global CO_2 emissions in 2050 will total 14.2 billion tons, down 45% from 2005. In this case, however, global primary energy consumption will total 19,000 MTOE, up 1,900 MTOE from the least primary energy consumption case. A total system cost increase from the Constraint-free Case will come to \$20.5 trillion, up \$15.6 trillion from the least primary energy consumption case.

If the world seeks to achieve the above target of reducing CO_2 emissions 2050 by 45% from 2005, how to treat a sense of unfairness emerging from a gap in emission cuts between the regions will be a challenge. Even in 2050, the non-OECD region will account for only 45% of real global GDP. Nevertheless, this study indicates that the CO_2 emission reduction in the non-OECD region will account for 68% of the total reduction and 55% of the total system cost increase. Eliminating the sense of unfairness emerging from such sharing of the burdens is important for future global warming measures.

5. Conclusion

This study is significant in that it built an environment for analyzing the impact of global warming measures on the energy supply/demand structure and energy supply costs quantitatively, proposed the relevant analysis procedure, and provided a gap between burdens on the OECD and non-OECD regions in halving CO_2 emissions in 2050 from 2005.

Our study uses more conservative assumptions than those by other organizations such as the International Energy Agency on non-fossil energy introduction potential and innovative technology introduction in order to provide knowledge that could become a starting point for discussions on how to share emission cuts. This is because we believe that an analysis based on more conservative assumptions is more convenient for identifying impediments to achieving targets. Any analysis based on initial optimistic assumptions could lead to a conclusion that any difficult target may be achieved.

In expanding this study, as a matter of course, it may be significant for us to analyze cases where various constraints are eased in accordance with actual technology development and political trends. Greater non-fossil energy introduction potential or the introduction of innovative technologies such as biomass-CCS plants, biofuel for aircraft and artificial photosynthesis could be subjected to an analysis in accordance with progress in efforts for their realization or commercialization.

In addition, in order to deepen knowledge about the non-OECD region, we should analyze Asian countries that are expected to achieve particularly rapid economic development among non-OECD nations. Deepening knowledge not only about China and India but also about the Association of Southeast Asian Nations that is developing as much as those two countries is indispensable for considering a low-carbon society for Asia.

Contact: report@tky.ieej.or.jp

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