Long-term Global Energy Supply/Demand Outlook under the Constraints of Atmospheric GHG Concentration

-- Estimating Energy Supply/Demand, CO_2 Emissions and Marginal CO_2 Reduction Cost --

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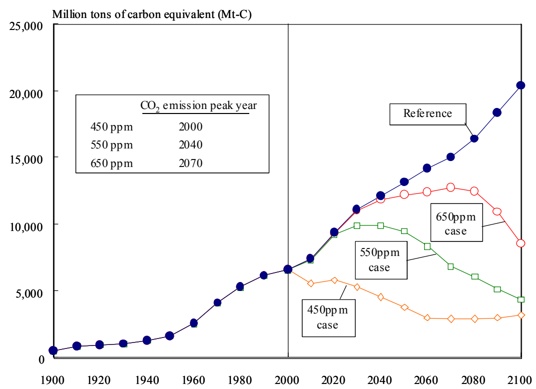
Summary

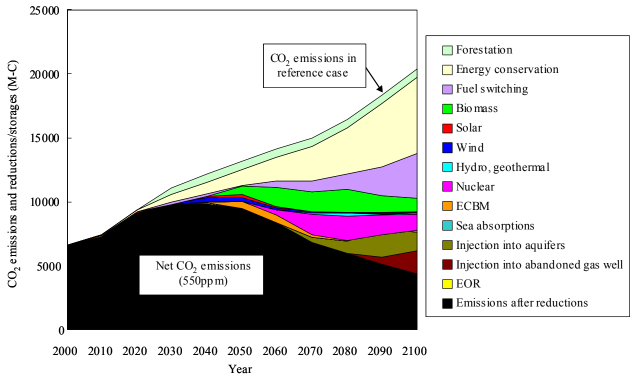
In this study, the author has estimated the world's optimum energy supply/demand structure under the constraints of atmospheric greenhouse gas concentration. According to British and other European governments' targets for stabilizing the atmospheric GHG concentration over a long time, global warming measures will have to be enhanced to stabilize the atmospheric GHG concentration in a 450-550 ppm range in order to hold a temperature rise down to 2 degrees centigrade. The author has developed an long-term economy and energy model, called the WING-LDNE Model, to estimate the optimum energy supply/demand structure for stabilization of the atmospheric GHG concentration at 450 ppm, 550 ppm (double the level before the industrial revolution) and 650 ppm in 2100.

Figure 1
Global CO_2 Emission Estimates (for each CO_2 concentration stabilization target case)



Source: Author's model calculation

Figure 2
CO_2 Emission Reduction Effects of Each Technology (for the 550 ppm case)



*EOR: enhanced oil recovery
ECBM: enhanced coal bed methane recovery
Source: Author's model calculation

One finding is that the world may have to reduce carbon dioxide (CO_2) emissions in 2100 by some 40% from 2000 in order to stabilize the atmospheric GHG concentration at 550 ppm. CO_2 emissions are expected to peak around 2040, although economic and technology prospects are greatly uncertain. The CO_2 emission reduction would require the world to introduce energy conservation and fuel switching technologies as well as CO_2 recovery and storage technologies (including ECBM, forestation, aquifer storage and abandoned gas well storage technologies) and increase the share of non-fossil energy in total primary energy supply to a 30-40% range. Non-fossil energy resources include nuclear energy and biomass. Among the CO_2 emission reduction measures, energy conservation is expected to make great contributions to the reduction over the long run, according to the model calculation results. In order to stabilize the GHG concentration at 550 ppm, the marginal CO_2 reduction cost (CO_2 shadow price) would be about $70 per ton of Carbon in 2030, about $120/tC in 2050 and about $570/tC in 2100.

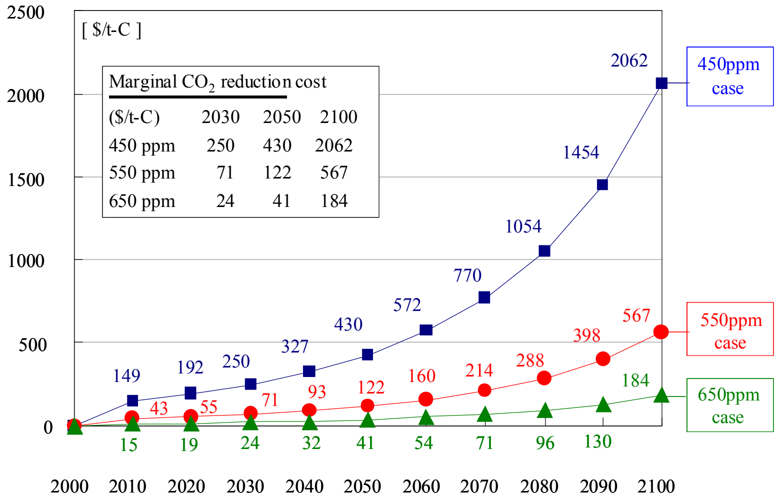
Table 1 World GHG Concentration, Primary Energy Supply, CO_2 Emissions and Marginal CO_2 Reduction Cost in 2100

GHG concentration	Primary energy supply				CO_2 emissions					
	Supply		Breakdown (Share)		Tons of carbon equivalent(t-C)	Comp. with 2000	Peak year	Marginal CO_2 reduction cost ($/t-C)		
	Tons of oil equivalent(Toe)	Comp. with 2000	Fossil resources	Non-fossil resources				2030	2050	2100
450 ppmv	15.7 billion	1.8 times	61%	39%	3.1 billion	+47%	2000	250	430	2,060
550 ppmv	17.2 billion	2.0 times	65%	35%	4.4 billion	+67%	2040	70	120	570
650 ppmv	17.9 billion	2.1 times	73%	27%	8.6 billion	+130%	2070	20	40	180
756 ppmv (reference)	24.9 billion	2.9 times	95%	5%	20.4 billion	+309%	--			

Source: Author's model calculation

In order to stabilize the GHG concentration at 450 ppm in 2100, the world would have to immediately launch a gradual CO_2 emission reduction to cut emissions in the year by about 50% from 2000. The marginal CO_2 reduction cost is estimated at about $250/tC for 2030, about $430/tC for 2050 and about $2,060/tC for 2100. The cost is thus expected to be far more than in the case for the GHG concentration's stabilization at 550 ppm.

Figure 3 Marginal CO_2 Reduction Cost (CO_2 shadow price)



Source: Author's model calculation

In order to manage the global risk of the rising GHG concentration, the world must have long-term perspectives and create a flexible future framework in which both advanced and developing countries can participate. For example, it would be effective for developing countries to include anti-global warming measures into their economic plans and set voluntary targets for CO_2 emission reductions and energy efficiency targets for industrial, transportation, household and other sectors. If these countries grow more conscious of the need for curbing CO_2 emissions through such efforts, the effects of the market mechanism and public policy enhancement may be combined to stimulate autonomous development of technologies for alternative energy and energy conservation. Since the Kyoto Protocol took effect, discussions have grown over the so-called post-Kyoto framework to fight against global warming in and after 2013. In addition to the global framework under the Kyoto Protocol, regional agreements have been being implemented, including the Asia-Pacific Partnership for Clean Development and Climate (APP) seeking to reduce CO_2 emissions under energy efficiency improvement targets. In order to effectively reduce GHG emissions in and after 2013, the world will have to consider a framework allowing developing countries as the future driver of CO_2 emission growth to take part in the reduction. It should build a framework to which these countries can make their positive commitment.

1. Introduction

Over a period of more than 10,000 years before the industrial revolution, the greenhouse effect of CO_2 with the atmospheric concentration of some 280 ppm had contributed to maintaining the global average temperature at about 15 degrees centigrade, an appropriate level for human living. The effect has thus supported human development. But the industrial revolution has led the atmospheric CO_2 concentration to gradually rise since around 1800. The concentration is now close to 370 ppm. As a result, a global average temperature rise of some 0.5 degrees was observed during the 20th century. While scientific knowledge is still inadequate about future temperature changes, global warming is predicted to bring about various developments, if left unresolved. The global warming problem, including the rising atmospheric GHG concentration, has become a matter of great concern to energy policy planners. The world has increasingly appreciated that GHG emissions should be reduced to help prevent global warming.

The Intergovernmental Panel on Climate Change (IPCC), which was founded in 1988, has so far produced four reports, in 1990, 1996, 2001 and 2007, on scientific knowledge about global warming, setting multiple GHG emission scenarios for consideration regarding global warming in the 21st century. Future global warming scenarios, though subject to great uncertainties, indicate that temperatures will rise steadily. Under the scenario that economic growth will be smooth with energy demand being met mainly by fossil resources, the latest (fourth) IPCC report says, the atmospheric CO_2 concentration could rise to a 540-970 ppm range by the end of this century from the present level of about 370 ppm, with the global average temperature increasing by some 4 degrees (potential increases range from 2.4 degrees to 6.4 degreees). On the rising atmospheric GHG concentration, the so-called Stern Review report in October 2006 noted the stabilization of the concentration in a 450-550 ppm range could help ease the climate change risk. In order to stabilize the atmospheric GHG concentration in this range, the report said, the world would have to reduce GHG emissions by 25% or more from the present level by 2050. Britain's energy white paper said the atmospheric GHG concentration should be stabilized at 550 ppm. France and Germany have noted that the concentration should be stabilized at 450 ppm. Atmospheric GHG concentrations are now being considered as energy policy targets.

The Framework Convention on Climate Change, adopted at the United Nations in May 1992, defines its ultimate objective as "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." At issue are specific levels at which atmospheric GHG concentrations should be stabilized. No international consensus has been reached on specific stabilization targets. In this study, the author has estimated an optimum energy supply/demand relationship for the world under atmospheric GHG concentration limits or targets that have become controversial. Based on these estimates, this study gives implications about an energy policy geared toward the reduction of GHG emissions.

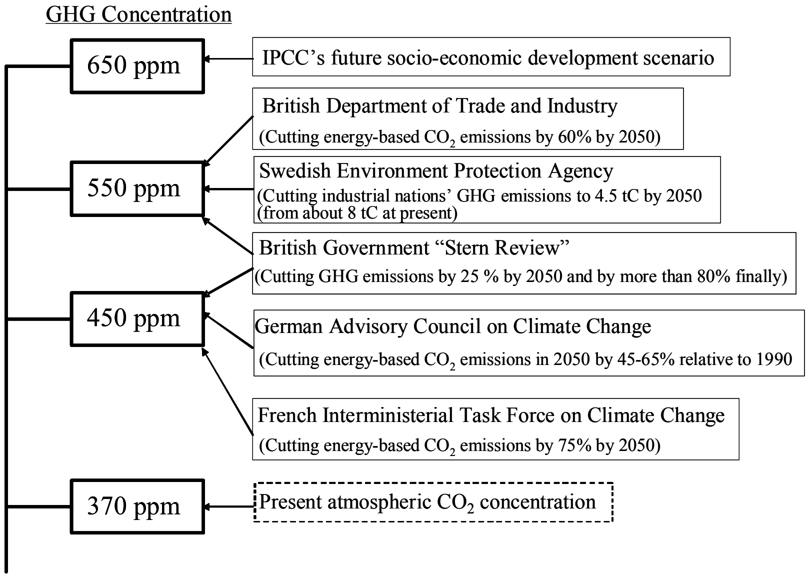
2. Discussions on Stabilization of Atmospheric GHG Concentrations

Stabilization of the atmospheric GHG concentration amounts to balancing GHG emissions with absorptions. The atmospheric CO_2 concentration has risen to some 370 ppm from about 280 ppm at the start of the industrial revolution. The key point is whether the future stabilization target should be set at, above or below 550 ppm, double the pre-industrial level. The stabilization will have to be achieved within a period in which the ecosystem can adapt to climate change with economic development continuing in a sustainable manner. In this sense, how fast the stabilization should be achieved is also a key point. Various studies have been conducted on specific atmospheric GHG concentration levels that would not cause problems. No firm conclusion has been reached, however.

In October 2006, the British government released the "Stern Review" warning that economic losses would amount to 20% of global GDP as global GHGs double with drought and other climate change risks being maximized by 2035. The report was written by a group of economists led by Sir Nicholas Stern under a contract awarded by Chancellor of the Exchequer Gordon Brown. Forecasting economic losses amounting to more than 5% of GDP would emerge if without measures to address global warming, the report concludes spending amounting to 1% of GDP on such measures would be economically reasonable. If the atmospheric GHG concentration were to be stabilized at between 450 ppm and 550 ppm in terms of CO_2, the risk of the worst conceivable effects of climate change might be eased considerably, it says. In order to stabilize the concentration within that range, the report says, the world would have to reduce CO_2 emissions by more than 25% from the present level by 2050 and by 80% in the long run.

Given the Stern Review and long-term government-set targets for stabilization of the atmospheric GHG concentration in Germany, France, Sweden and other European countries, their consensus is that the world will have to cut annual CO_2 emissions by 50-80% from the present level (reduce per capita CO_2 emissions to one-fifth to one-quarter of the present level) in the long run in order to stabilize the atmospheric CO_2 concentration at between 450 ppm and 550 ppm and limit the temperature rise to 2 degrees centigrade.

Figure 2-1 European Atmospheric GHG Concentration Targets



In this study, the author has estimated world energy supply and demand, and CO_2 emissions under the following targets for stabilization of the atmospheric GHG concentration, using the world economy and energy model described in the next chapter. Based on these estimates, the author has considered the optimum world energy supply/demand structure under the atmospheric GHG concentration limits and energy policies for future GHG emission cuts.

Table 2-1 Alternative Cases for Atmospheric GHG Concentration

Case	Notes
Reference	A baseline case in which no regulations will be imposed on CO_2 emissions.
Stabilization at 550 ppm	A case in which the atmospheric GHG concentration in and after 2100 will be stabilized at or below 550 ppm (about double the level before the industrial revolution).
Stabilization at 450 ppm	A case in which the atmospheric GHG concentration in and after 2100 will be stabilized at or below 450 ppm (about 1.6 times the pre-industrial level).
Stabilization at 650 ppm	A case in which the atmospheric GHG concentration in and after 2100 will be stabilized at or below 650 ppm (about 2.3 times the pre-industrial level).

Note: For the three cases for stabilization of the atmospheric GHG concentration at 450, 550 and 650 ppm, CO_2 emissions in 2010 are estimated at a level for a case in which CO_2 emission reduction targets under the Kyoto Protocol are achieved.

3. Outline of World Economy and Energy Model (WING-LDNE Model)

In this study, the author has used a world economy and energy model to make estimates for the world economy, population, energy supply and demand, and CO_2 emissions for the long period through 2100. Here is an outline of the model. The model, called WING-LDNE, consists of two modules -- the WING module[1] to endogenously estimate economic growth, population and final energy demand through 2100 and the LDNE module[2] to determine energy supply on the precondition of the final energy demand estimate and under the standard of minimized costs. For this study, the author divides the world into 10 regions -- (1) North America, (2) Western Europe, (3) Japan, (4) Oceania, (5) China, (6) other Asian nations, (7) the Middle East and North Africa, (8) other African nations, (9) Central and South America, and (10) the countries of the former Soviet Union and Eastern Europe. Annex I countries under the Kyoto Protocol are (1) North America, (2) Western Europe, (3) Japan, (4) Oceania, and (10) the countries of the former Soviet Union and Eastern Europe.

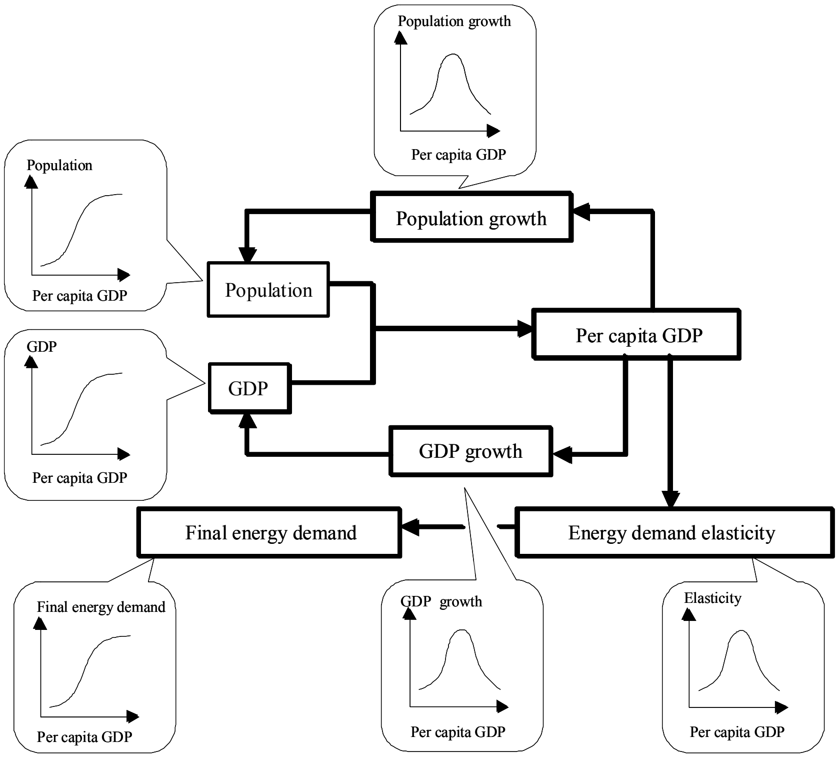
3-1 WING Module

The WING module builds on the stage theory of economic growth to determine economic growth, population and final energy demand through 2100. The stage theory of economic growth indicates a view that the economy transforms itself depending on its growth stages. This means that population growth, economic growth (speed for quantitative expansion) and energy demand are transformed depending on economic growth stages.

[1] The WING module is the economy and energy model that the Energy Data and Modeling Center of the Institute for Energy Economics, Japan, has developed for the estimation for the very long period through 2100.

[2] The LDNE model, the linearized version of nonlinear functions (energy conservation and renewable energy supply functions) of the DNE21 (Dynamic New Earth21) model handling engineering technologies, is adopted as a long-term technology assessment model. See Yamaji, K.et al., Global energy system to maintain atmospheric CO2 concentration at 550 ppm, Environmental Economics and Policy Studies, 3, 159, 2000.

Figure 3-1　　Relations between per capita income and population growth, economic growth and energy elasticity



Most conventional top-down models calculate energy demand and its details under given conditions regarding population and income, with the elasticity assumed as consistent. In contrast, this model uses per capita income to indicate economic growth stages, based on a view that per capita income rises as the economy grows. The basic idea behind the model is that population growth, economic growth and energy elasticity change depending on economic growth stages (per capita income levels).

Final energy demand is classified into four categories -- solid, liquid, gas and electricity. Each category's volume and share are calculated with consideration given to economic growth stages (per capita income levels). This means that a consumption shift from unconventional fuels to petroleum products and other liquid fuels and a shift to electricity (a rise in electricity's share of total final energy demand) are taken into account when each category's share is determined.

Key points of this module follow:

- Population: Population growth may first accelerate on such factors as a decline in infant mortality as per capita income increases. But the growth may later decelerate gradually on a birthrate fall.
- GDP growth: Economic growth may accelerate fast as industrialization starts (with per capita income presumed at some $1,000 for this model). As per capita income reaches $3,000, however, growth may decelerate gradually.
- Energy income (GDP) elasticity: The energy elasticity may also change depending on economic growth stages. It may rise as industrialization accelerates. But it may decline as the economy grows toward a higher stage.

If a specific per capita income level is given, population and GDP may be determined. Then, per capita income may be determined for feedback by dividing GDP by population. Per capita income's relationship with GDP under this system can be indicated by an S-shaped curve. Per capita income's relationship with population or energy demand can also be represented by an S-shaped curve.

The mechanism in which economic growth, population growth and energy income elasticity change in line with changes in per capita GDP as a representative benchmark of economic growth stages is used for determining population, GDP, final energy demand and a category-by-category breakdown of the demand.

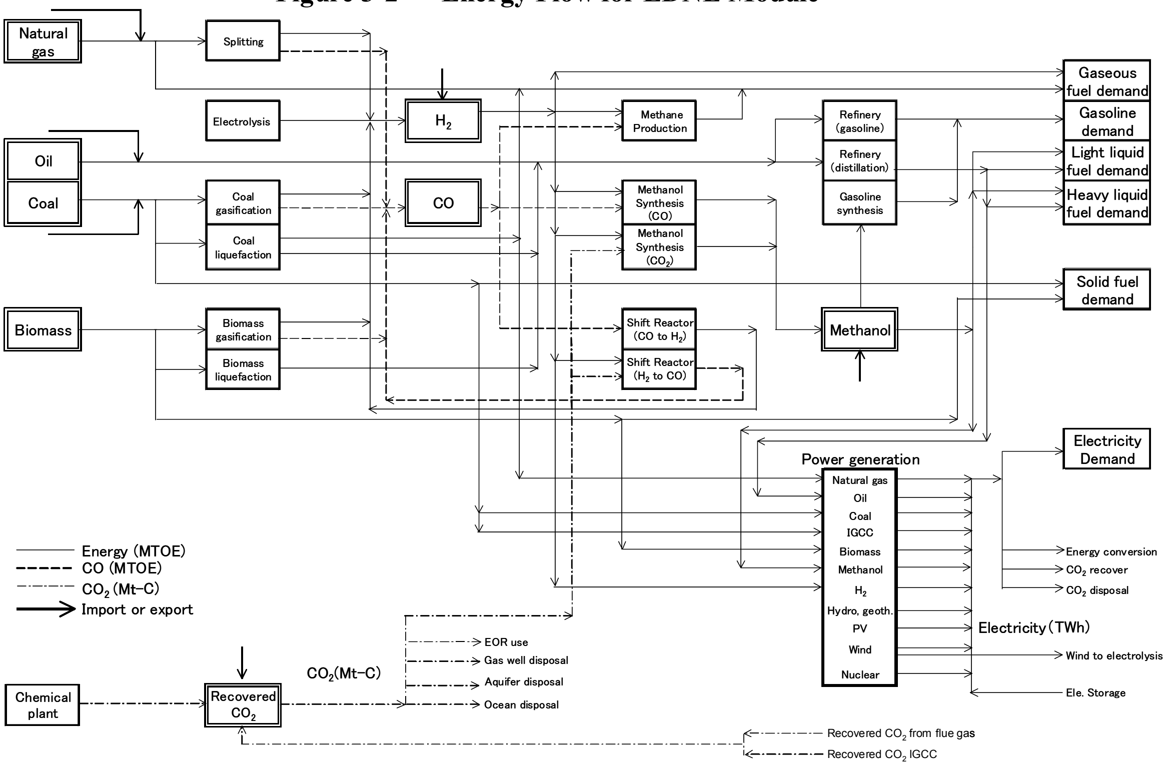
Most conventional models have given population, economic growth and the like as exogenous values, excluding population explosion and other problems from assumptions. These models have also indicated an absence of or moderate structural changes in economic and social environments. Since it is doubtful if these conventional models should be used for predicting effects of the global warming problem on the world over the long period of 100 years under such limited assumptions, this module has been developed.

3-2 LDNE Module

Energy flow is illustrated in Figure 3-2 for the LDNE model, the linearized version of nonlinear functions (energy conservation and renewable energy supply functions) of the DNE21 (Dynamic New Earth21) model handling engineering technologies. Fossil, renewable, nuclear and other primary energy supplies are converted through chemical and electricity generation plants into secondary energy to meet the four categories (solid, liquid, gas and electricity) of final energy demand predicted by the WING module.

This module is an optimization model to minimize total system costs with discount rates taken into account over the target period. It covers 110 years (11 decades) between 1995 and 2105 and gives estimates for 15 decades through 2145 to eliminate end effects. The module encompasses the world as being divided into the 10 regions.

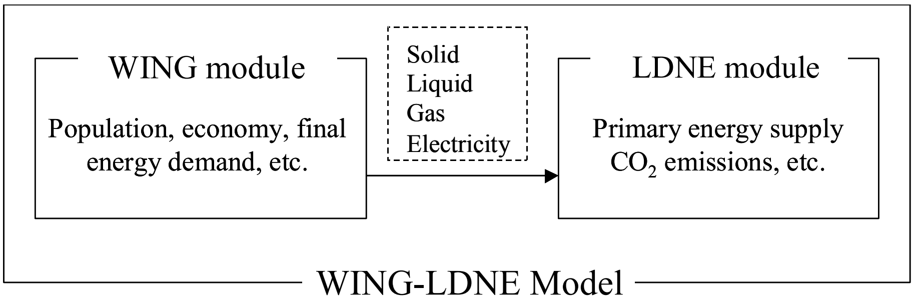
Figure 3-2 Energy Flow for LDNE Module



3-3 WING-LDNE Model

The WING-LDNE Model integrating the WING and LDNE modules is explained below. First, the WING module is used for determining economic growth, population and final energy demand (solid, liquid, gas and electricity) endogenously under the stage theory of economic growth. Then, the LDNE module determines the energy supply (coal, oil, gas, nuclear energy, etc.) to meet the final energy demand under the standard of minimized costs. Next, CO_2 emissions from the energy system are estimated.

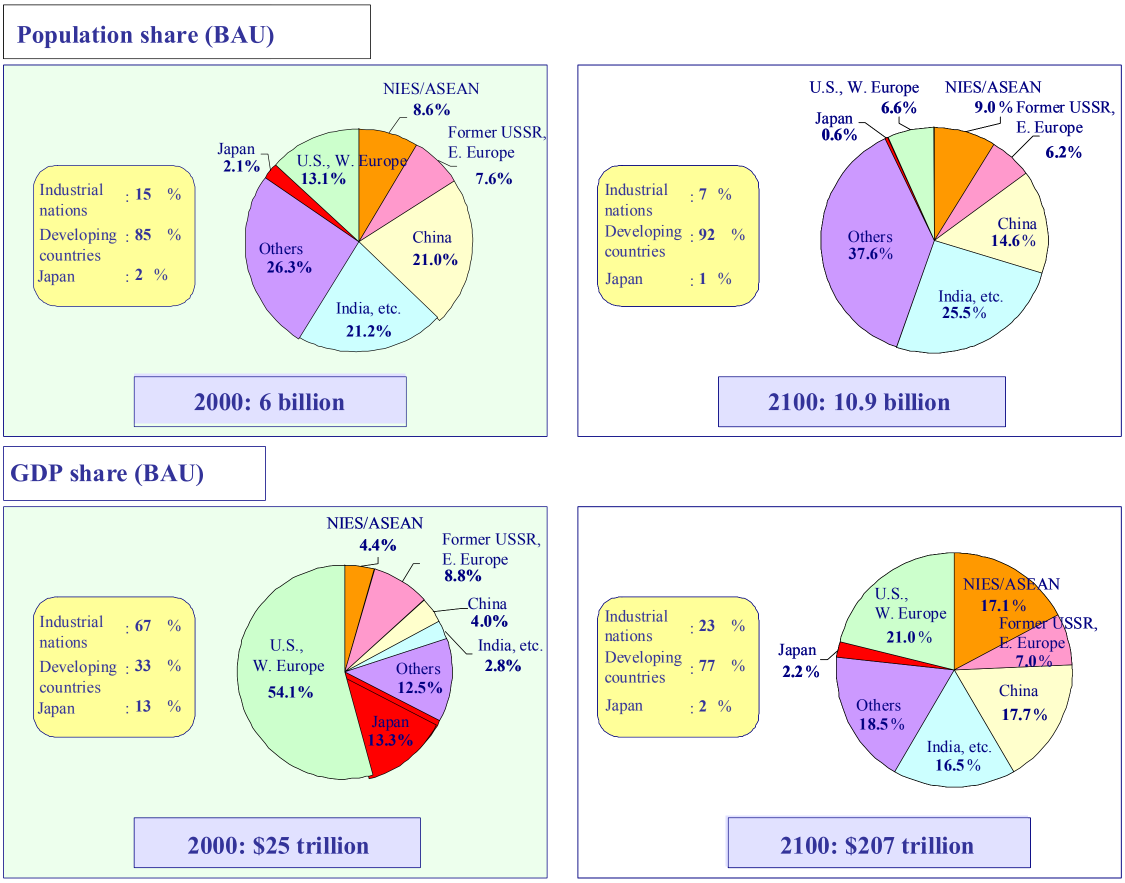
Figure 3-3 Overview of WING-LDNE Model



(a) Economic growth, population

Estimates indicate that world population is expected to almost double from some 6 billion in 2000 to 11 billion in 2100. In 2000, advanced nations accounted for some 20% of the world population and developing countries for about 80%. In 2100, the share will fall to some 10% for advanced nations and rise to about 90% for developing countries. World population growth will thus center on developing countries.

Figure 3-4 World GDP and Population Estimates for 2100



Source: Author's model calculation

World GDP is expected to grow at an annual pace of 2.1% from $25 trillion in 2000 to about $210 trillion in 2100. The total growth in the century is estimated at 10-fold. Per capita GDP in the world is estimated to expand some five-fold from $4,000 in 2000 to $19,000. In 1990, advanced countries accounted for about 70% of world GDP in 1990 and developing countries for about 30%. In 2100, the share may fall to some 20% for advanced countries and rise to about 80% for developing countries. World GDP growth may thus be led by developing countries, including China, India and other Asian nations.

(b) Final energy demand

Final energy demand estimates are given below, as made by the WING module. World final energy consumption is estimated to increase at an annual pace of 1.1% from about 6.1 billion tons oil equivalent in 2000 to 17.6 billion tons in 2100.

Figure 3-5 Final Energy Demand (World)

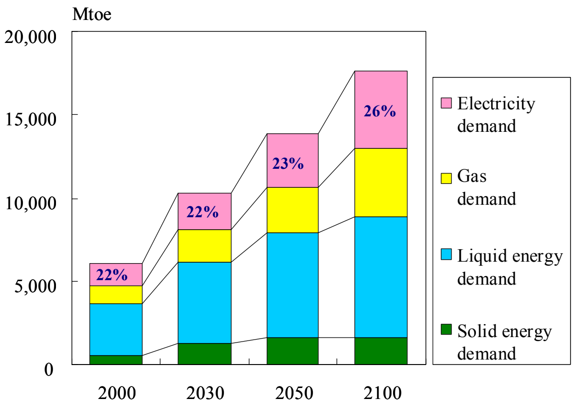
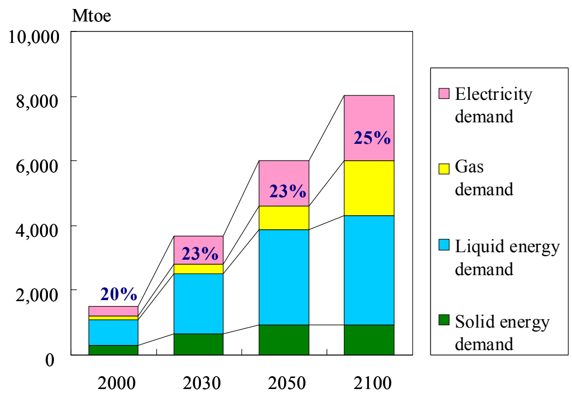


Figure 3-6 Final Energy Demand (Asia)



Source: Author's model calculation

Of final energy consumption, electricity is estimated to expand at an annual pace of 1.2% from 1.3 billion TOE (about 15 trillion kWh) in 2000 to 4.6 billion TOE (about 53 trillion kWh). Electricity's share of primary energy consumption may rise from 22% in 2000 to 26% in 2100. Asian final energy consumption is estimated to rise at an annual rate of 1.7% from some 1.5 billion TOE in 2000 to 8 billion TOE in 2100. Of the consumption, electricity is expected to increase at an annual pace of 1.9% from 300 million TOE (about 3.6 trillion kWh) in 2000 to 2 billion TOE (about 23 trillion kWh). Electricity's share of primary energy consumption in Asia may thus rise from 20% in 2000 to 25% in 2100.

Asia's share of world final energy consumption may increase from 25% in 2000 to 45% in 2100. Its share of world electricity consumption may also expand from 23% in 2000 to 44% in 2100.

Over the long period through 2100, Asia's share of world energy consumption is thus expected to steadily increase.

Figure 3-7 Final Energy Consumption (by region)

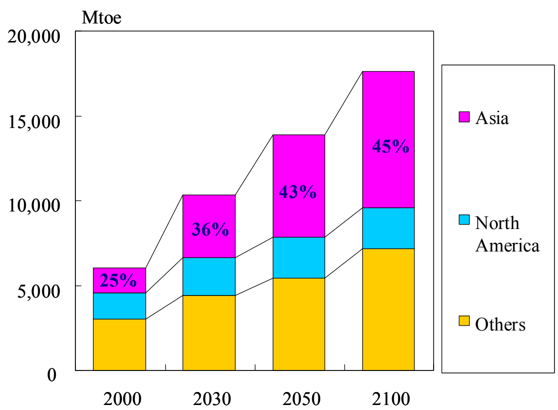
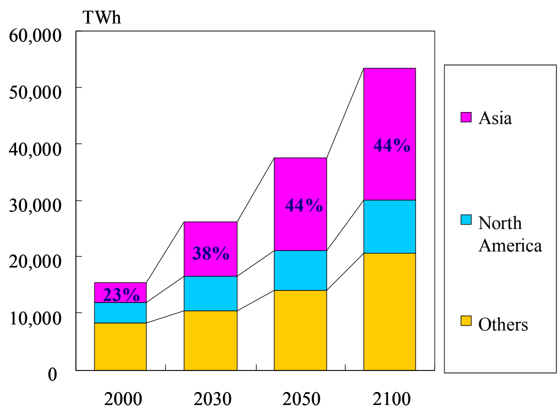


Figure 3-8 Electricity Demand (by region)



Source: Author's model calculation

4. Calculation Results

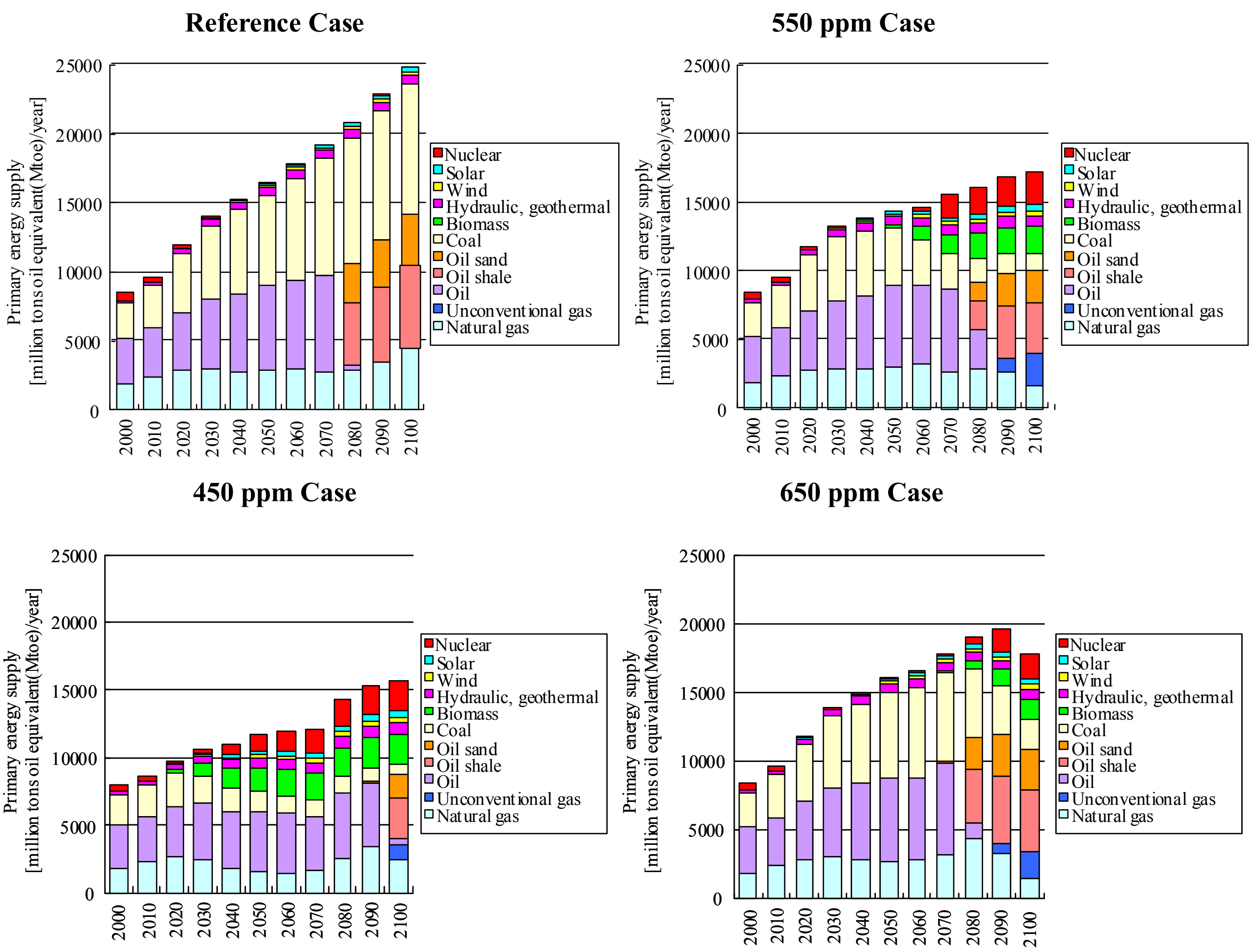
4-1 Primary energy supply

In the reference case free from constraints regarding stabilization of atmospheric GHG concentrations, the world would depend on coal and oil for most of the primary energy supply over the long term. Specifically, the world would depend on fossil resources for about 90% of energy supply through 2100. Oil supply from 2080 would rely on unconventional resources such as oil sand and shale.

In the case for stabilizing the atmospheric GHG concentration at 550 ppm, energy consumption would be saved substantially, with energy supply being far less than in the reference case. In the middle of this century, the introduction of biomass, nuclear and other clean energy would expand. In the case for stabilizing the atmospheric GHG concentration at a lower level of 450 ppm, the expansion of the clean energy introduction and the implementation of full energy conservation efforts would start earlier, or in 2030. In the case for stabilizing the atmospheric GHG concentration at a higher level of 650 ppm, such measures would start in 2080.

In the reference case, primary energy supply in 2100 would be 2.9 times as high as in 2000. Primary energy supply growth would fall to 2.0 times for the case for stabilizing the atmospheric GHG concentration at 550 ppm, 1.8 times for the 450 ppm case and 2.1 times for the 650 ppm case. As for the primary energy supply mix, the ratio of fossil resources to non-fossil resources would be about 9 to 1 for the reference case in 2100, about 7 to 3 for the 550 and 650 ppm cases and 6 to 4 for the 450 ppm case. In the 450ppm case, non-fossil energy would be introduced faster.

Figure 4-1 Primary Energy Supply (World)

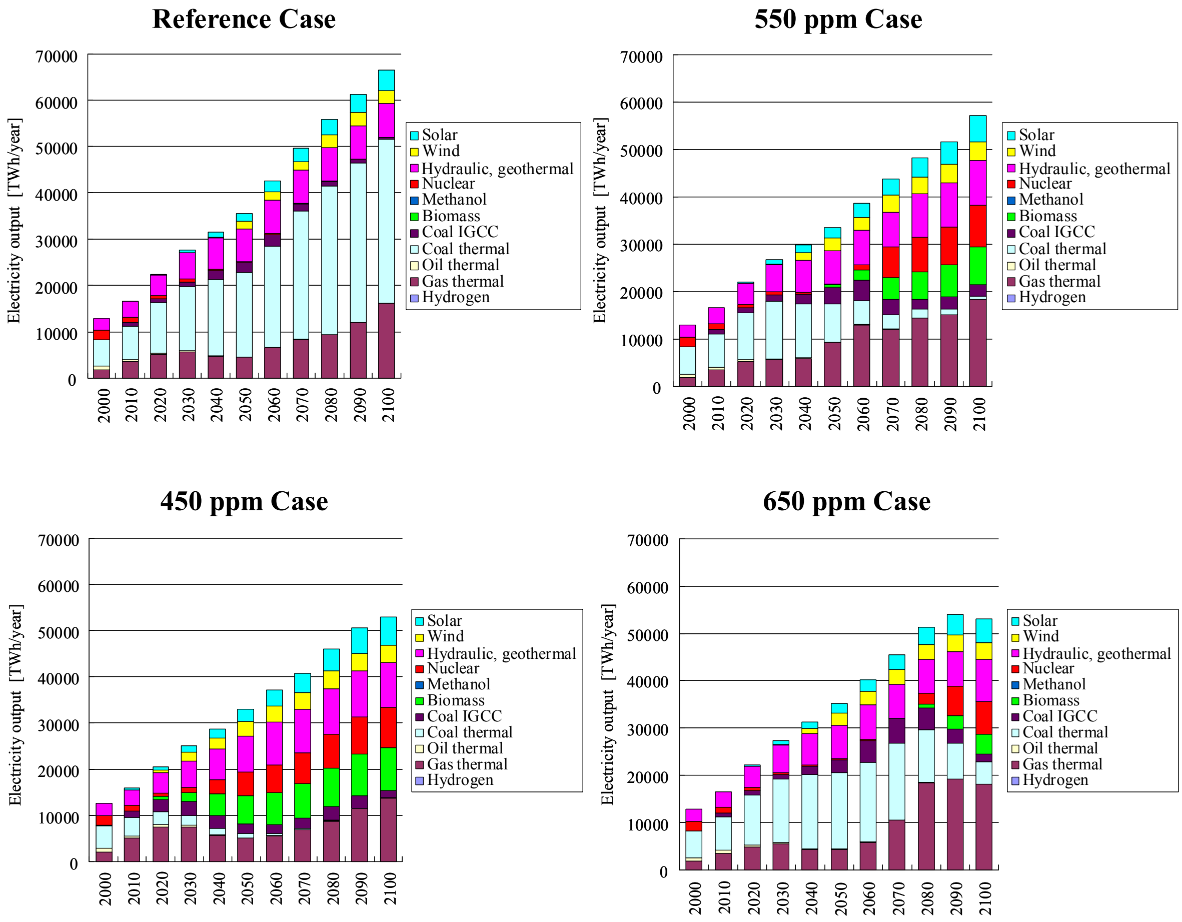


Source: Author's model calculation

4-2 Electricity output mix

In the reference case free from constraints regarding stabilization of atmospheric GHG concentrations, the world would depend on economically competitive coal thermal power generation for most of the electricity supply. In the case for stabilizing the atmospheric GHG concentration at 550 ppm, electricity output would be less than in the reference case due to energy conservation efforts. In the middle of this century, the introduction of gas thermal, biomass, nuclear, wind, photovoltaic and other clean electricity generation systems to replace coal thermal power plants that feature higher unit CO_2 emissions would expand. Power generation using coal IGCC (integrated gasification combined cycle) systems in this case would be greater than in the reference case. In the case for stabilizing the concentration at a lower level of 450 ppm in 2100, the expansion of clean power generation systems and full energy conservation efforts would have to start in 2030. In the case for a higher concentration level of 650 ppm, such measures would be launched in 2080.

Figure 4-2　Electricity Generation Mix

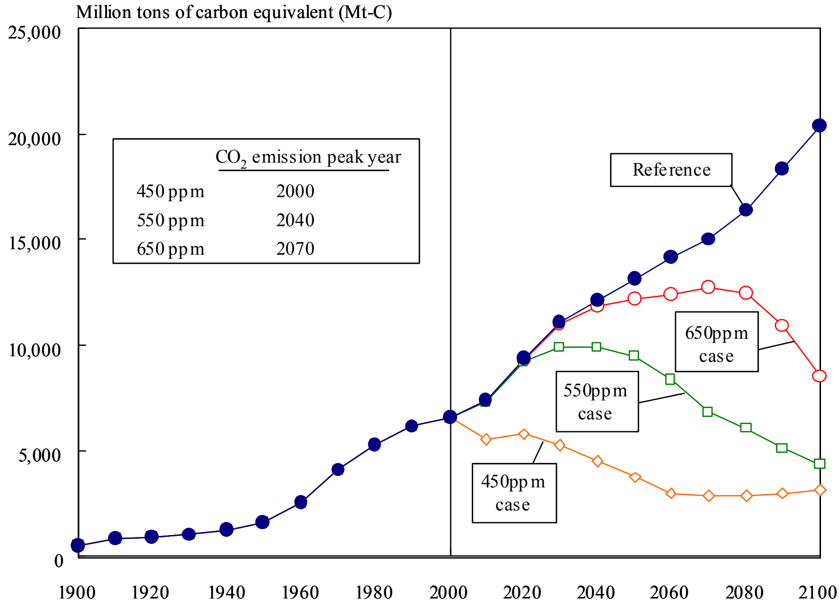


Source: Author's model calculation

4-3 CO_2 emissions

Figure 4-3 indicates changes in estimated CO_2 emissions for each case. In the reference case, CO_2 emissions are estimated to triple from the equivalent of 6.6 billion tons of carbon in 2000 to 20.4 billion tC. In the case for stabilizing the atmospheric GHG concentration at 550 ppm in 2100, CO_2 emissions would have to be reduced after peaking in 2040. CO_2 emissions in 2100 would have to be cut to some 70% of the present level. In the case for stabilizing the atmospheric GHG concentration at 450 ppm in 2100, CO_2 emissions would have to be reduced immediately after a peak in 2000. CO_2 emissions in 2100 would have to be limited to some 50% of the present level. In the case for stabilizing the atmospheric GHG concentration at 650 ppm in 2100, CO_2 emissions would have to be cut after peaking in 2070. CO_2 emissions in 2100 would have to be limited to about 130% of the present level.

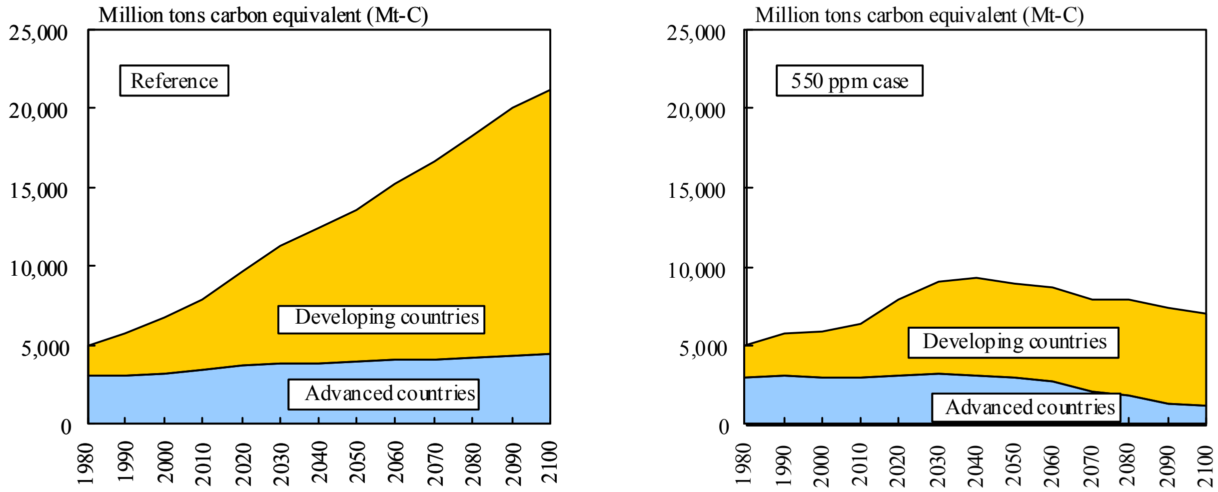
Figure 4-3 CO_2 Emissions (worldwide, by case)



Source: Author's model calculation

Figure 4-4 indicates CO_2 emissions in advanced and developing countries. CO_2 emission changes for the reference case show that developing countries would lead the global expansion of emissions. While emissions in advanced countries would increase 1.4-fold from 3.2 billion tC in 2000 to 4.4 billion tC in 2100, those in developing countries would quintuple from 3.6 billion tC to 16.8 billion tC. Since emissions in advanced countries are thus expected to expand far slower than in developing countries, it is important for developing countries to reduce CO_2 emissions to resolve the global warming problem. In the case for stabilizing the atmospheric GHG concentration at 550 ppm in 2100, an increase in CO_2 emissions from 2000 to 2100 would have to be limited to some 40% in advanced countries and about 100% in developing countries.

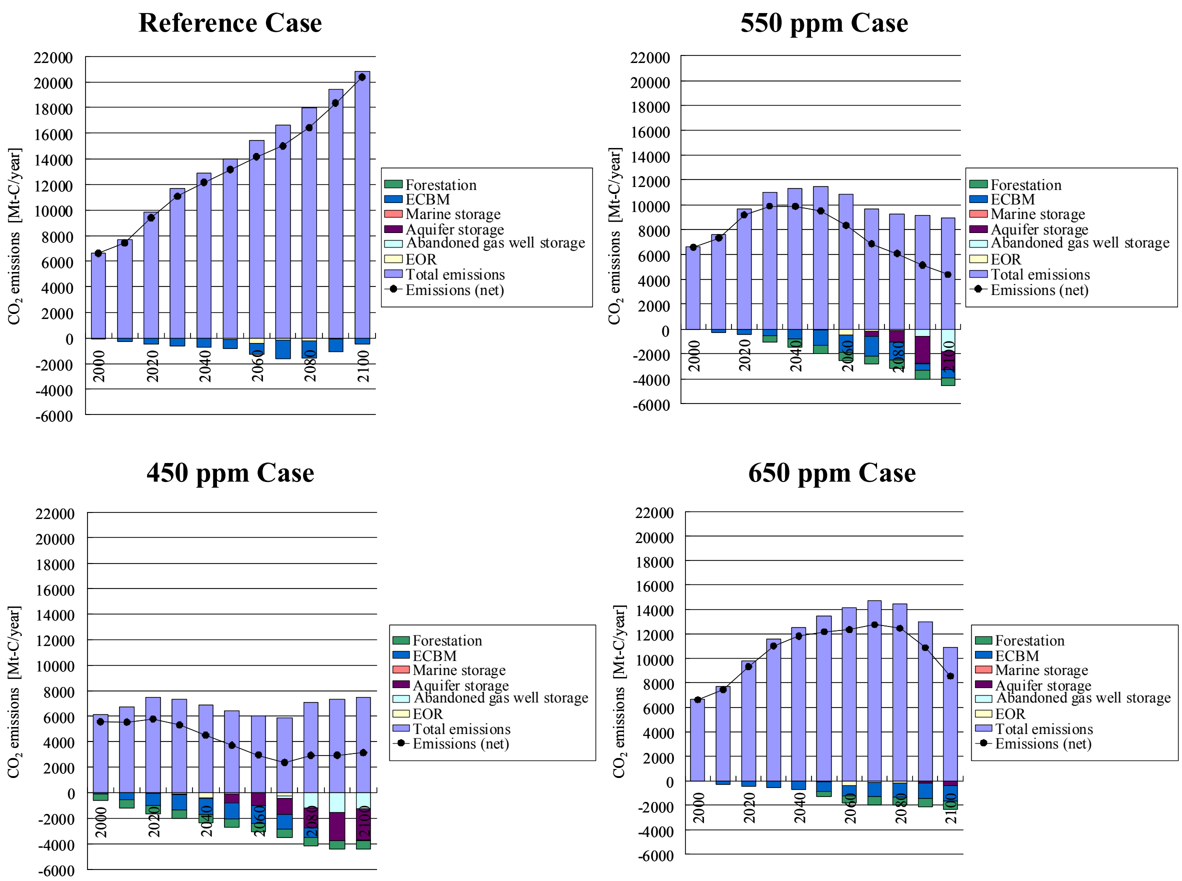
Figure 4-4 CO_2 Emissions (worldwide, by country category)



Source: Author's model calculation

Figure 4-5 shows the balance between CO_2 emissions and storages. In the reference case, limited ECBM (enhanced coal bed methane recovery) operations would be implemented along with EOR (enhanced oil recovery) operations. CO_2 would be utilized for increasing oil and methane gas recovery through EOR and ECBM operations. In the case for stabilizing the atmospheric GHG concentration at 550 ppm in 2100, ECBM operations would be promoted along with forestation. In the second half of this century, CO_2 storages in aquifers and abandoned gas wells would be promoted. In the case for stabilizing the atmospheric GHG concentration at 450 ppm, CO_2 fixation and storage technologies would be introduced faster than in the 550 ppm case. In the case for stabilizing the atmospheric GHG concentration at 650 ppm, ECBM and forestation operations for CO_2 fixation and storage would be sufficient to achieve the stabilization.

Figure 4-5 CO_2 Emissions and CO_2 Storages (World)



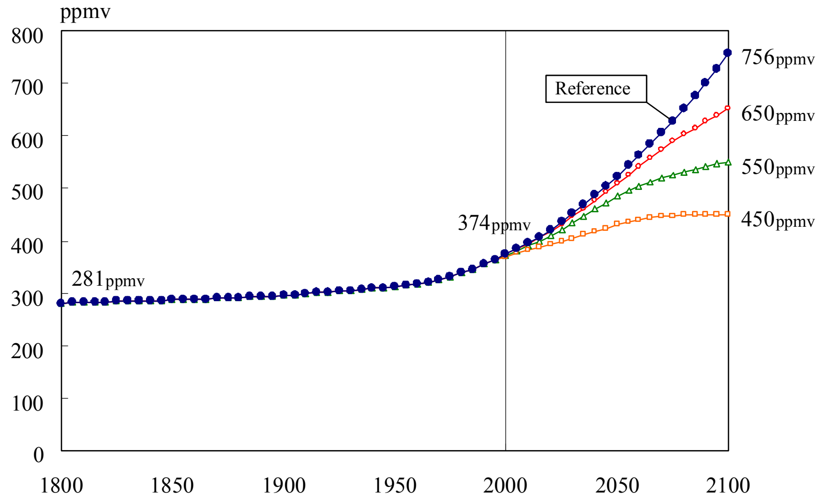
EOR: enhanced oil recovery

ECBM: enhanced coal bed methane recovery

Source: Author's model calculation

Figure 4-6 indicates changes in the atmospheric GHG concentration for each case. In the reference case, the concentration in 2100 would double from about 370 ppm at present to 760 ppm. For converting CO_2 emissions into the atmospheric concentration in this estimation, the author has exploited the MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), which has been widely utilized by the IPCC and other relevant organizations. This model uses the liner response function to estimate sea and onshore plant absorptions of CO_2 against emissions, deducts estimated absorptions from emissions and calculates the remaining emissions' atmospheric concentration.

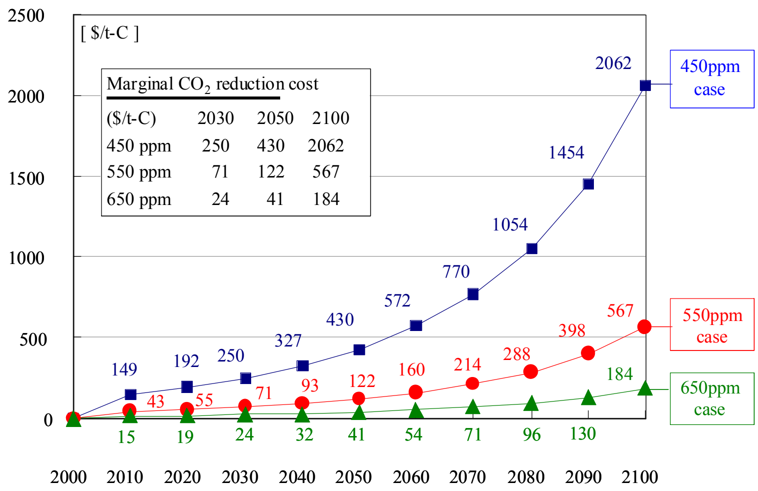
Figure 4-6 Projected GHG Concentration (by case)



Source: Author's model calculation

Figure 4-7 shows changes in the marginal CO_2 reduction cost (CO_2 shadow price). The marginal CO_2 reduction cost means the cost for a one-unit additional reduction of CO_2 emission. The marginal CO_2 reduction cost in 2030 is estimated at about $70/tC in the case for stabilizing the atmospheric GHG concentration at 550 ppm in 2100. The cost would rise to about $250tC in the 450 ppm case and fall to about $20/tC in the 650 ppm case. The gap between the cases would widen toward 2050 and 2100. In the 550 ppm case, the marginal CO_2 reduction cost would rise from about $120/tC in 2050 to about $570/tC in 2100. In the 450 ppm case, the cost would rise fast from $430/tC to $2,060/tC.

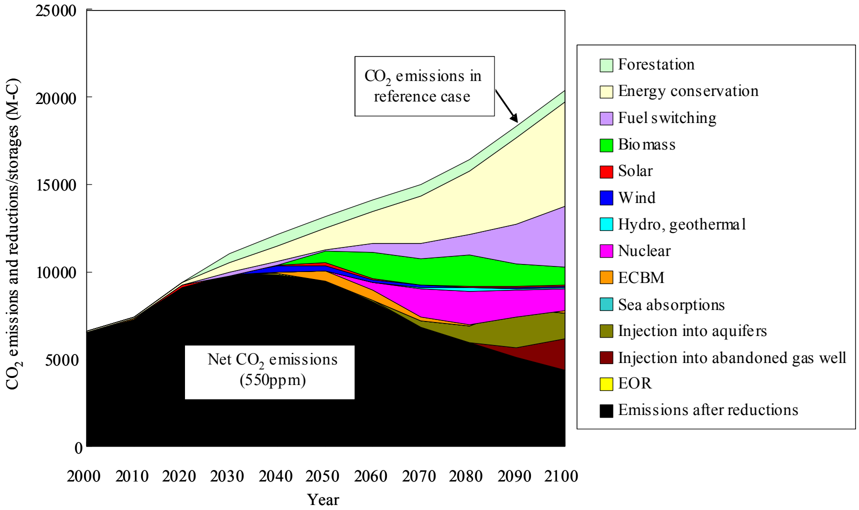
Figure 4-7 Marginal CO_2 Reduction Cost (CO_2 shadow price)



Source: Author's model calculation

Figures 4-8 and 4-9 indicate CO_2 emission reduction effects of each technology or measure in the world for each case. Over the long term, energy conservation would make the greatest contribution to reducing CO_2 emissions among the measures and technologies, followed by fuel switching (from coal to gas), introduction of non-fossil energy (including nuclear energy and biomass) and CO_2 recovery and storage (including storage in abandoned gas wells and aquifers). In particular, CO_2 absorption and storage technology would be required for the cases for stabilizing the atmospheric GHG concentration at 450 ppm and 550 ppm in 2100.

Figure 4-8　CO_2 Emission Reduction Effects of Each Technology (for the 550 ppm case)



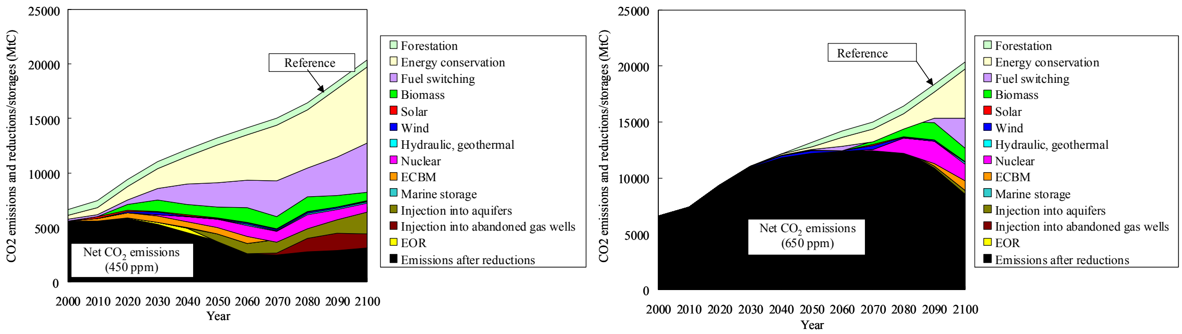
EOR: enhanced oil recovery

ECBM: enhanced coal bed methane recovery

Source: Author's model calculation

Figure 4-9 CO_2 Emission Reduction Effects of Each Technology (for the 450 ppm and 650 ppm cases)

450 ppm case　　　　**650 ppm case**



Source: Author's model calculation

5. Conclusion

In this study, the author has estimated the world's optimum energy supply/demand structure under GHG concentration limits. According to British and other European governments' targets for stabilizing the atmospheric GHG concentration over a long time, measures against global warming will have to be enhanced to stabilize the atmospheric GHG concentration in a 450-550 ppm range in order to limit the temperature rise to 2 degrees centigrade. In this respect, the author has estimated the optimum energy supply/demand structure for stabilization of the atmospheric GHG concentration at 450 ppm, 550 ppm (double the level before the industrial revolution) and 650 ppm in 2100.

One finding is that the world may have to substantially reduce CO_2 emissions toward 2100 in order to stabilize the atmospheric GHG concentration at 450 or 550 ppm in that year, although economic and technology prospects are greatly uncertain. A specific reduction from 2000 is estimated at about 50% for the 450 ppm case and about 40% for the 550 ppm case. The emission reduction should start in 2040 for the 550 ppm case and immediately for the 450 ppm case. The CO_2 emission reduction would require the world to introduce and diffuse energy conservation and fuel switching technologies and non-fossil energy sources (non-fossil energy sources' share: 39% for the 450 ppm case and 35% for the 550 ppm case) as well as CO_2 recovery and storage technologies (including ECBM, forestation, aquifer storage and abandoned gas well storage technologies). Among the CO_2 emission reduction measures and technologies, energy conservation is expected to make great contributions to the reduction over the long run as indicated by the model calculation results. The marginal CO_2 reduction cost (CO_2 shadow price) in 2030 would be about $70/tC for the 550 ppm case and about $250/tC for the 450 ppm case. The cost in 2100 would be about $570/tC for the 550 ppm case and about $2,060/tC for the 450 ppm case.

Table 5-1 World GHG Concentration, Primary Energy Supply, CO_2 Emissions and Marginal CO_2 Reduction Cost in 2100

GHG concentration	Primary energy supply				CO_2 emissions					
	Supply		Breakdown (Share)		Tons of carbon equivalent (t-C)	Comp. with 2000	Peak year	Marginal CO_2 reduction cost ($/t-C)		
	Tons of oil equivalent (Toe)	Comp. with 2000	Fossil resources	Non-fossil resources				2030	2050	2100
450 ppmv	15.7 billion	1.8 times	61%	39%	3.1 billion	+47%	2000	250	430	2,060
550 ppmv	17.2 billion	2.0 times	65%	35%	4.4 billion	+67%	2040	70	120	570
650 ppmv	17.9 billion	2.1 times	73%	27%	8.6 billion	+130%	2070	20	40	180
756 ppmv (reference)	24.9 billion	2.9 times	95%	5%	20.4 billion	+309%	--			

Source: Author's model calculation

In order to manage the global risk of the rising GHG concentration, the world must have long-term perspectives and create a flexible future framework in which both advanced and developing countries can participate. For example, it would be effective for developing countries to include anti-global warming measures into their economic plans and set voluntary targets for CO_2 emission reductions and energy efficiency targets for industrial, transportation, household and other sectors. If these countries grow more conscious of the need for curbing CO_2 emissions through such efforts, the effects of the market mechanism and public policy enhancement may be combined to stimulate autonomous development of technologies for alternative energy and energy conservation. Since the Kyoto Protocol took effect, discussions have grown over the so-called post-Kyoto framework to fight against global warming in and after 2013. In addition to the global framework under the Kyoto Protocol, regional agreements have been being implemented, including the Asia-Pacific Partnership for Clean Development and Climate (APP) seeking to reduce CO_2 emissions under energy efficiency improvement targets. In order to effectively reduce GHG emissions in and after 2013, the world will have to consider a framework allowing developing countries as the future leader of CO_2 emission growth to take part in the reduction. It should build a framework to which these countries can make their positive commitment.

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