Cost-effectiveness Analysis of CO2 Reduction in the Automobile Sector

Energy Data and Modelling Center (EDMC): Shigeru Suehiro, Ryoichi Komiyama, Yuji Matsuo, Yu Nagatomi, Yuji Morita

Global Environment & Sustainable Development Unit: Zhongyuan Shen

Abstract

Various problems relating to energy and the environment clearly exist, such as global warming and a steep rise in the price fossil fuels, and resources. These problems should be addressed in the medium term or long run. As for the abatement of greenhouse gas emission, active discussions have been held on the stage of world politics to achieve the long-term goal. Although various approaches have been proposed by several research institutions and countries, sufficient studies have not yet been conducted on the roles of individual countries and sectors. Specifically, in the automotive transportation sector wherein oil demand and CO_2 emissions are estimated to rise in the future with the marked progress of motorization in developing countries, it is increasingly important to study these subjects. We focused on the automotive transportation sector and studied the CO_2 abatement potential and its cost performance in this sector. This article reports the results of the study.

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1. Introduction

Various problems relating to energy and the environment clearly exist, such as global warming and a steep rise in the price of fossil fuels, and resources. These problems should be addressed in the medium term or long run and several research institutions have settled long-term foresight and offered proposals toward the resolution of these problems. The long-term goal for the abatement of greenhouse gas emission has been actively discussed on the stage of world politics as well. "Cool Earth 50" (the goal is to halve the global CO_2 emission by 2050) proposed by Japan in 2007 has yet not be agreed to by developing countries, but it has been defined as one of the benchmarks. In the G8 Summit in 2009 in L'Aquila, the participating nations agreed that all the advanced countries shall make efforts to reduce CO_2 emissions by 80% in light of the policy of "Cool Earth 50."

However, these proposals and agreements lack the backing of sufficient studies on the roles of individual countries and sectors at present. Specifically, in the automotive transportation sector wherein the oil demand and CO_2 emissions are estimated to rise in the future with marked progress of motorization in developing countries, it is increasingly important to study these subjects. We focused on the automotive transportation sector and studied the CO_2 abatement potential and its cost performance in this sector. This article reports the results of the study.

2. Outline of the IEEJ2050 Model

2.1 Brief description of the Model

The IEEJ2050 Model has been designed to forecast the world energy demand and energy-related CO_2 emission in the medium term or long run. This Model can analyze, by forward casting, the effects of change in various situation of economic societies or different extents of changes in policies and development of technologies. Each five-year period from 2010 to 2050 is to be studied. 16 countries/regions are covered by the Model. The energy data are based on IEA's "Energy Balances of OECD Countries/Non-OECD Countries."

2.2 Structure of the Model

The Model consists of three calculation groups: final energy consumption, energy conversion, and primary energy consumption (including CO_2 emission). First, the final energy consumption is obtained for each sector (industrial, residential and commercial, and transport). Then, the energy supply that meets each energy demand (electric power, heat, hydrogen, etc.) is determined for each of the energy conversion sectors (power generation, heat supply, hydrogen production, etc.). Finally, the primary energy consumption is obtained as a sum of the final energy consumption and energy conversion, and then, the fossil-fuel-related CO_2 emission is calculated. Such a model is applied to 16 regions in the world.

Table 2-1　Regions covered by the IEEJ2050 Model

Region	Classification in the model
North America	1) USA, 2) Canada
Latin America	3) Brazil, 4) other Latin American countries
Europe	5) European OECD countries, 6) Russia, 7) other European countries
Asia and Pacific	8) Japan, 9) China, 10) India, 11) South Korea, 12) ASEAN, 13) Oceania, 14) other Asian countries
Middle East	15) Middle East
Africa	16) Africa

* Countries underlined are OECD countries (USA, Canada, European OECD countries, Japan, South Korea, and Oceania). Note that Mexico is included in other Latin American countries.

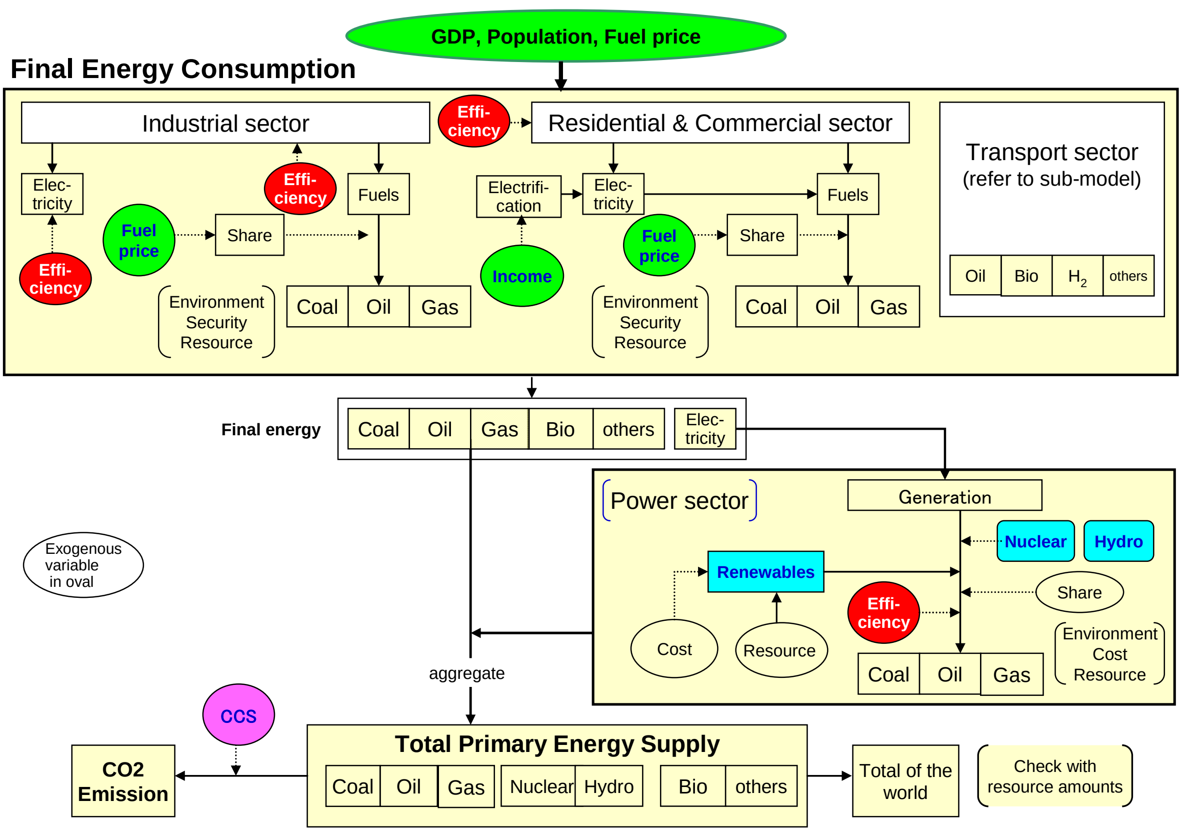

Figure 2-1　Flowchart of the IEEJ2050 Model

2.2.1 Calculation of energy demand per sector

The energy demand per sector is basically calculated from the demand function comprising two elements: activity level (e.g., GDP, power generation, and transportation) and costs (e.g., energy, initial, and maintenance costs). The former determines the energy demand level, while the latter not only influences the demand level through the energy conservation efficiency but also determines the substitution relationship among different energy types. To formulate the demand function, we used the CES (Constant Elasticity of Substitution) production function; logistics curve function, utility preference function, and the like.

For example, the CES production function is one of the demand functions that is widely used in general equilibrium models. This function is based on the assumption that the evaluation of inputs of individual production elements, including energies, are based on the cost minimization action (in other word, so-called optimization action) when the production level and element prices are provided to a company (in the industrial section). Similarly, it is assumed that the consumer goods prices are provided under certain budgetary limitations in the family budget, and the evaluation of consumption is based on the utility maximization action.

2.2.2 Structure of the transport sub-model

The transport sub-model is built to conduct detailed analysis of the road sector. The traffic demand is divided into various sub-demands based on applications (passenger and freight) and transportation (automobile, railroad, ship, and airplane). The traffic demand of automobiles is further broken down on the basis of fuel types and engine technologies. Breaking down the traffic according to transportation and vehicle types as described above makes it possible to, for example, dynamically analyze the influences of shift in demand from motorcycles to passenger cars in developing countries in Asia and the effects on energy demand as a result of development and dissemination of engine technologies for passenger cars.

For engine technologies and improvement of fuel efficiency of passenger cars, the transport model employs the flow-stock replacement structure. That permits to measure more accurate energy and CO2 abatement effects, if providing more realistic assumption at the point of new car sales. With regard to increased demands for electric power and hydrogen as a result of dissemination of electric and fuel cell vehicles, the complete model incorporates the supply system and, therefore, it is possible to measure the so-called Well-to-Wheel CO_2 emission.

Assuming the mixing ratio of bio fuel to gasoline or diesel oil allows analyses in which the region-specific features, for example in Brazil, are considered.

Table 2-2 Fuel types and engine technologies assumed in the transport model

Fuel type	Technology type on power source		
	Internal Combustion Engine Vehicle (ICEV)	ICE & Motor Hybrid Electric Vehicle (HEV)	Motor Zero Emission Vehicle (ZEV)
Gasoline	1) Gasoline-engine Vehicle [GICEV]	5) Gasoline-powered Hybrid Vehicle [GICEHEV] 6) Plug-in Gasoline-powered Hybrid Vehicle [GICEPHEV] (*also using electricity)	
Diesel	2) Diesel-engine Vehicle [DICEV]	7) Diesel-powered Hybrid Vehicle [DICEHEV]	
LPG	3) LPG-powered Vehicle [LPGV]		
CNG	4) CNG-powered Vehicle [CNGV]		
Electricity			8) Electric Vehicle [EV]
Hydrogen			9) Fuel Cell Vehicle [HFCV] 10) Plug-in Fuel Cell Vehicle [HFCPHEV] (*also using electricity)

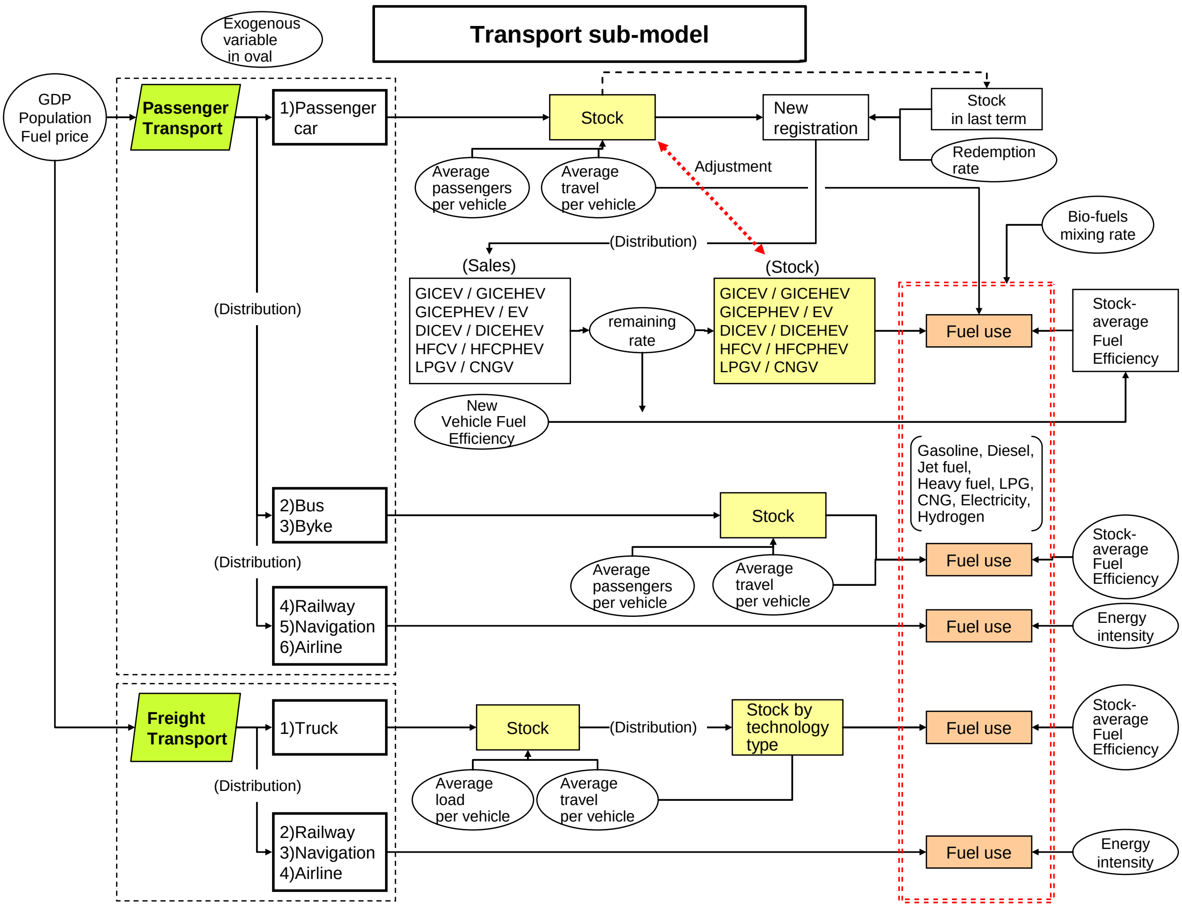

Figure 2-2 Flowchart of the Transport sub-model

3. Future Prospect for World Energy Supply and Demand until 2050 (Reference Case)

3.1 Basic philosophy of the reference case

The reference case estimates the future energy supply and demand profile in the world by using several highly probable assumptions based on the dominant changes, taking into consideration the present economic social situations of individual countries and regions, present international situation, and present technological systems and policies. In this report, these results are used as the reference results that will be compared to other estimation results obtained from, for example, technological development case discussed later in the evaluation process.

3.2 Major assumption

The population estimate is based on the United Nation's "Population Estimates and Projections: The 2008 Revision." However, the population estimate in Japan is based on "Population Projection for Japan" (published in December 2006; estimates the standard birth and death in Japan) from the National Institute of Population and Social Security Research while that in Taiwan is based on "Population Projection for Taiwan Areas: 2008-2056" from the Council for Economic Planning and Development (published in September 2008; estimates the medium variant).

In 2050, the world population is estimated to be 9 billion, or about 1.4 times as large as the present level. The increase in the population is mostly contributed by developing countries. The population of Japan, Korea, Russia, and many European countries is expected to decrease, while the population of India, Middle East, and Africa is expected to grow sharply. It is forecast that the population of China will reach the peak around 2030 and decreas subsequently due to aging.

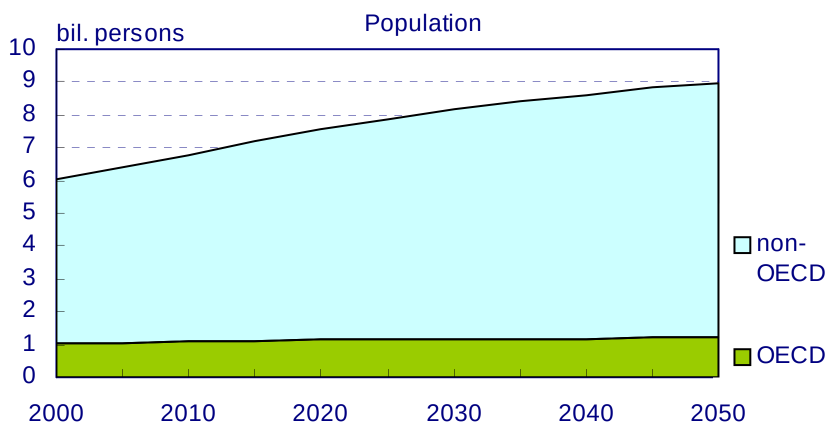

Figure 3-1 Population forecast

The economic growth rate, or GDP (gross domestic product), is estimated under the assumption that it depends on the long-term supply factors, i.e., capital, labor, and technology development (total factor productivity (TFP)). In addition, these factors are forecast one by one. For BRICs (Brazil, Russia, India, and China) that have higher potential of economic growth, the GDP growth rates are estimated mainly by the production functions[1]. For other countries, the growth rates are estimated mainly on the basis of the growth rate of work force under the assumption that a certain technology development is observed. As a result, the world's average GDP growth rate is 2.8% during the target period. The growth rate in advanced countries is 2.0% while that in developing countries is maintained at a high level of 4.1%. The economical performance of these developing countries will grow to the level comparing to advanced countries by 2050. The average GDP growth rate of BRICs is 4.6%.

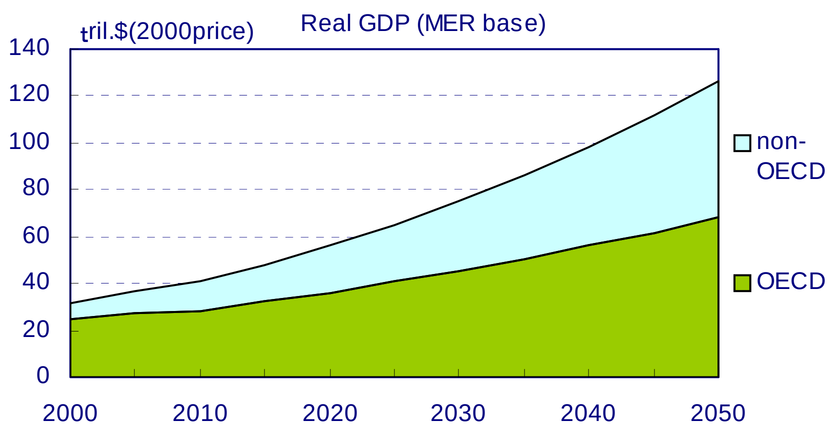

Figure 3-2 GDP forecast (in market exchange rate base)

To forecast the long-term energy demand up to 2050, the assumption of energy prices, particularly oil prices, is a very important factor. However, the estimation of these prices is not an easy task, and thus, it is unavoidable to estimate the oil prices under some assumptions. Rogner[2] has offered the relationship showing that resource mining costs are elevated as the amount of resources mined (cumulative value) increases. In the prospect described in this article, the future oil prices are estimated on the basis of the cost curves offered by Rogner and latest reserves data[3] similarly.

[1] Refer to Goldman-Sachs, "Dreaming with BRICs: The Path to 2050," 2003.
[2] Hans-Holger Rogner, "An Assessment of World Hydrocarbon Resources," May 1996
[3] The BP Statistics 2009 states the proved oil reserves are 1,408,700 million barrels (1,258,000 million barrels for conventional oil and 150,700 million barrels for oil sand in Canada) as of end of 2008 and, therefore, the R/P of single conventional oil is 42 years. The Oil & Gas Journal states the proved oil reserves are 1,342,200 million barrels (including nonconventional oil; the reserves in Canada are 178,100 million barrels) as of January 1st, 2009 and, therefore, the R/P estimated from the oil production result of 72,970,000 B/D in 2008 is 50.4 years. There is a concern that the oil reserves presently confirmed will be exhausted by 2050. These proved oil reserves do not include the reserves that will be discovered in the future or the reserves that will be added to the present reserves after the economic viability is ensured due to increase in oil prices. The prospect determined in this article estimates the future oil prices by adding these reserves to the present proved oil reserves.

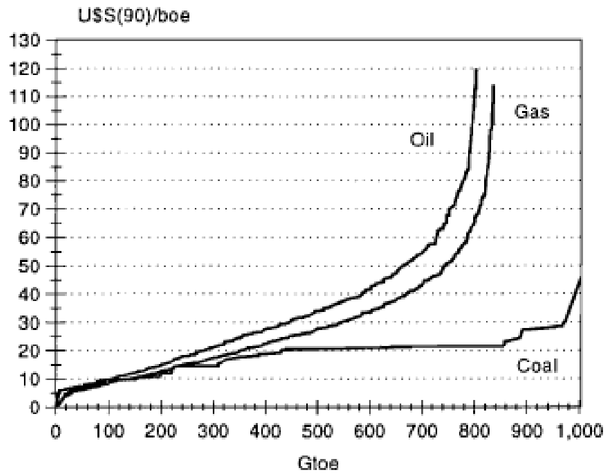

Figure 3-3 Rogner's cost curves (prices in 1990)

It is forecast that with the increase in oil demand, the accumulated oil production will reach 1,800,000 million barrels in the future, and as a result, the oil price (OECD average import price) will be elevated to 200 dollars per barrel (2007 price equivalent) and 469 dollars per barrel (nominal price) in 2050. Although the natural gas price is presently about 0.6 of the crude oil price based on the calorific value, it is forecast that the price will be gradually elevated to 0.7 due to environmental premium and be 1,411 dollars per ton-LNG in 2050. It is forecast that the coal price will be maintained almost at the present level due to rich reserves. (The coal price will be 108 dollars per ton in 2050. The price ratio of coal to crude oil will be decreased to 0.1 from 0.3 of the present level.)

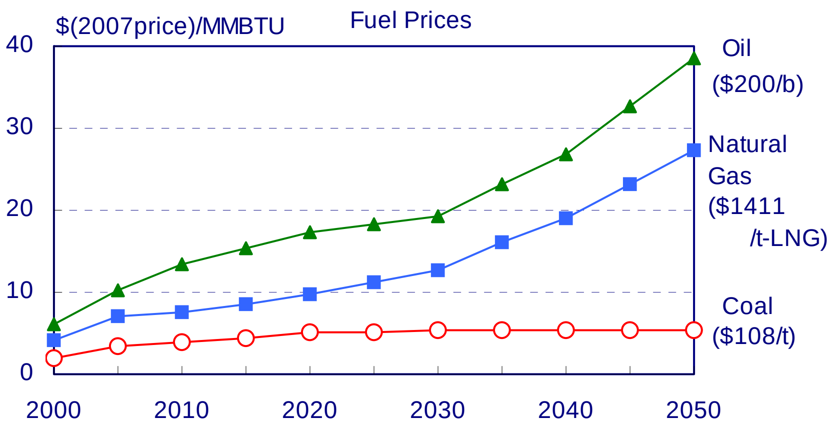

Figure 3-4 Energy prices forecast (prices in 2007)

For nuclear power generation, it is forecast that the generating capacity will be increased from 386 GW (in 2006) to 571 GW (in 2030) based on the policies and development trends in individual countries. It is forecast that the generating capacity in Asia, where China and India act as key players, will be drastically increased by about 130 GW and the former Soviet area, where Russia acts as a key player, will represent growth of about 40 GW. It is forecast that the growth in the generating capacity in North America will be as low as about less than 20 GW. In Europe, the net generating capacity will be decreased by more than 10 GW although the execution of "non-nuclear policies" may be considerably delayed in some countries in the future. It is forecast that existing reactors will be replaced with new ones and new plants will be constructed at a pace higher than the decommissioning of existing plants in individual countries from 2030 to 2050, and as a result, the generating capacity is estimated to rise by about 15 GW a year in the world. During the period, China and India will still maintain remarkable growth of generation capacity and a large number of nuclear power plants will be constructed in Southeast Asia and Middle East.

Renewable energies are forecast on the basis of the present introduction level, the status of the policies that assist the introduction of those energies, and introduction plans promoted by individual governments and other institutions. While hydro power will also remain a key player in renewable energies in the future, biomass, municipal waste, wind power, and solar power generation will be gradually increased as a result of improvement in applicability and economy of resources. In the USA, the largest energy consuming country in the world, the present share of the renewable energies (excluding hydro and geothermal power) will be increased from 2% in 2005 to 8% in 2050 with the spread of wind power generation. In developing countries where the power demand will substantially grow due to sharp industrialization and urbanization, the share of the renewable energies (excluding hydro and geothermal power) is estimated to be around 1 to 3% even in 2050 since the existing thermal power generation still acts as a key player.

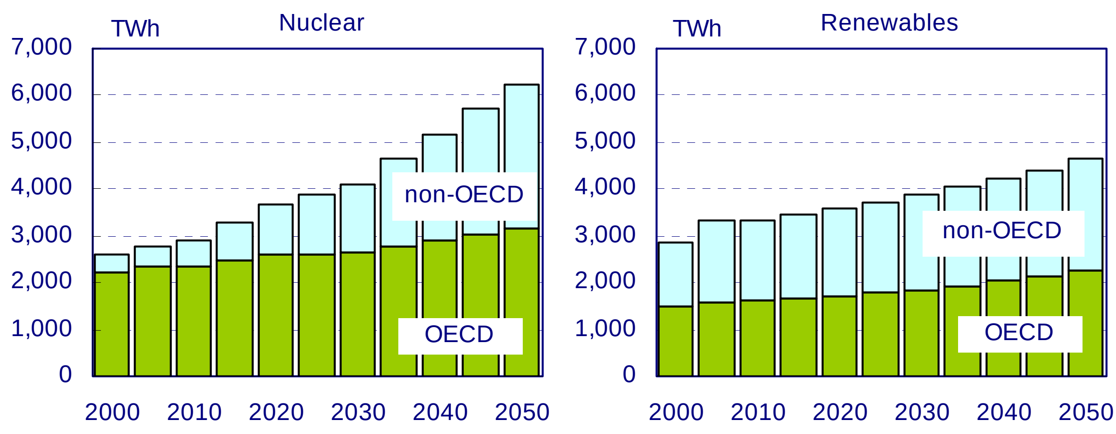

Figure 3-5 Estimated power generation by nuclear and renewable energies

3.3 Future prospect for primary energy supply and demand

The world's total primary energy supply calculated according to the assumptions discussed above is estimated to rise to 18,500 million tons oil equivalent in 2050, which is about 1.8 times as large as the present level. The increment is mostly brought by developing countries. Although efforts toward energy conservation is included in this forecast, the energy consumption in developing countries is estimated to rise to 2.5 times the present level due to expansion of population, development of industry, and improvement of income.

Seeing by sector, growth rates of industrial, transport, and residential & commercial sectors are 1.6, 2.0, and 1.9 times, respectively. The growth of the transportation sector is brought by the increased transport demand as discussed later, particularly by a sharp increase in automotive transport. The growth in the residential & commercial sector is brought by the increased population and improved living standard in developing countries. Electrification in energy use will be remarkably developed mainly in the residential & commercial sector, and as a result, the share of the electricity use in the final energy consumption will rise to 24% from 19% of present level. Therefore, the energy demand in the power generation sector will be drastically increased.

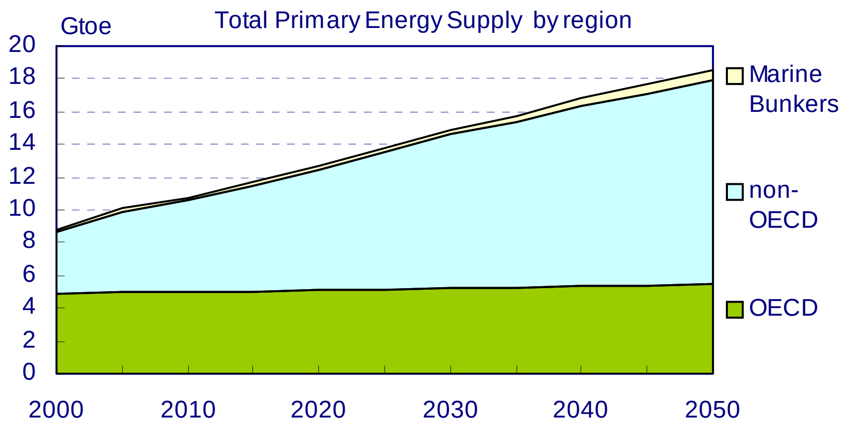

Figure 3-6 Future prospect for total primary energy supply (by region)

Seeing by fuel type, growth rates of oil, coal, and gas are 1.6, 1.9, and 1.9 times, respectively, and the share of fossil fuel will be decreased from 89% of the present level to 86%, but it will still act as a key player. Transportation by automobiles and airplanes contributes to increased oil demand, while coal and gas are increasingly used for power generation. Although it is forecast that nuclear energy will be increased 2.3 times and renewable energies such as hydro and wind power will be increased 2.3 times, shares of these energies in the total primary energy are only 9% and 5%, respectively.

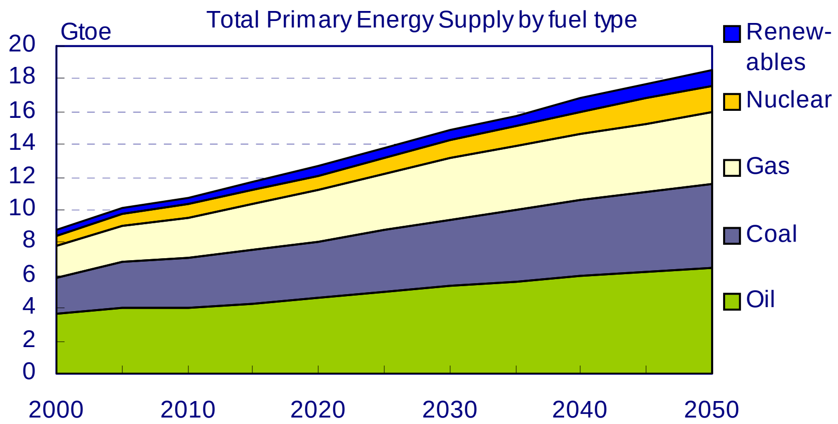

Figure 3-7 Future prospect for total primary energy supply (by fuel type)

3.4 Future prospect for power generation mix

With the increased demand for the electricity, the power generation in 2050 will be 2.2 times as high as the present level. Concretely, the share of the thermal power generation will rise to 73% in 2050 from the present level of 67%, meaning that the dependency on thermal power generation will be increased. The reason why the share of the thermal power generation will be increased is that the share in developing countries will rise from 73% to 81% due to their increased electricity use, although the share in advanced countries will drop from 62% to 54%. Although the power generation by renewable energies will grow 1.4 times as large as the present level, the share in the total power generation will drop from 18% to 12%.

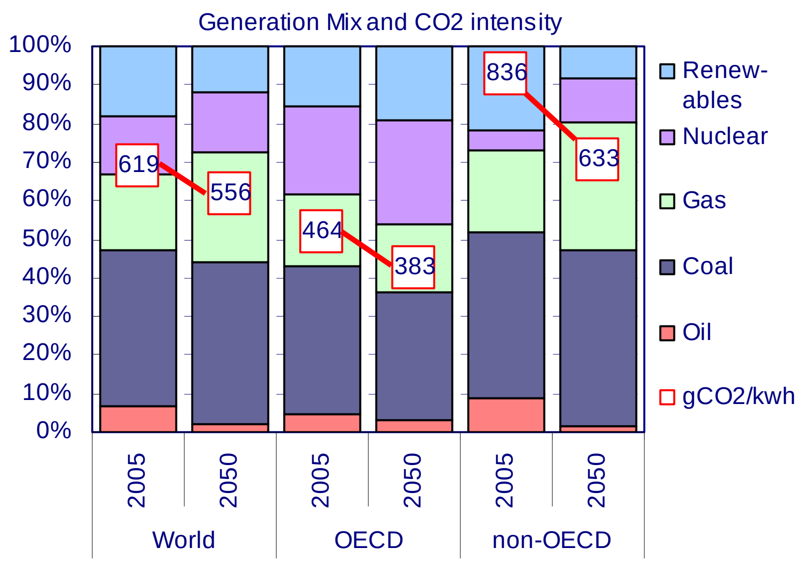

Figure 3-8 Future prospect for generation mix and CO_2 emission intensity

Although the share of the fossil-fuel-based power generation will be increased, the share of gas-fired power generation will be relatively increased and, therefore, the CO_2 emission intensity (end use electricity) will be slightly decreased to 556 g/kWh from the present level of 619 g/kWh. The emission intensity will be considerably decreased from 836 g/kWh to 633 g/kWh in developing countries. This improvement is greatly brought by the decreased loss in the power transmission and distribution system, as well as further introduction of gas-fired power generation.

3.5 Future prospect for energy-related CO_2 emission

In 2050, CO_2 emissions resulting from the combustion of fossil fuels will be 47,500 million tons, which is about 1.8 times as large as the present level. It is forecast that CO_2 emissions will be generally decreased from the present peak in advanced countries, but that in developing countries will be increased 2.4 times as large as the present level, making up 74% of the total CO_2 emission in the world (excluding the emission from international marine bunkers).

Seeing by sector, industrial, transport, and residential & commercial sectors feature 1.5-, 1.8-, and 1.6-times increases, respectively, and the conversion sector, including power generation, features a 1.9-times increase. However, these figures are slightly underestimated in the residential & commercial sector, where electrification has been promoted. When CO_2 emissions are proportionally distributed to final demand sectors the industrial, transportation, and residential & commercial sectors will feature a 1.6-, 1.8-, and 2.1-times increase, respectively.

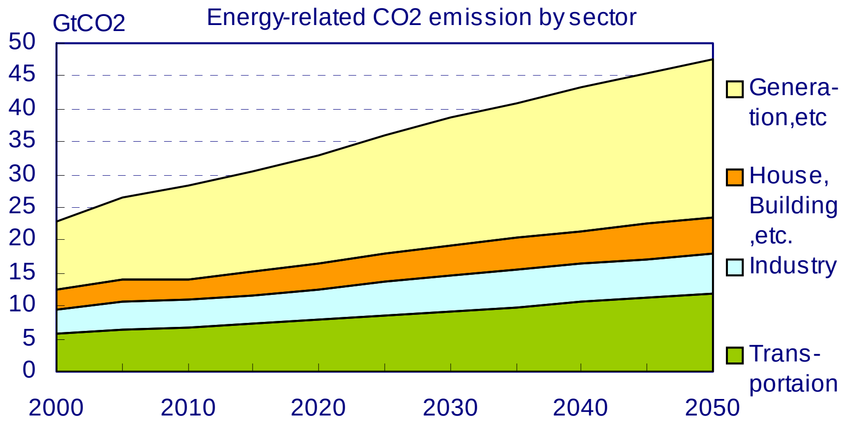

Figure 3-9 Future prospect for energy-related CO_2 emission (by sector)

4. Detailed Analysis on the Transportation Sector (Reference Case)

4.1 Future prospect for transport demand

The passenger transport demand (in person-kilometer base) will rise to 2.5 times of the present level by 2050 due to improvement of living standard. About 90% of the increment would be observed in developing countries. Growth rates of transportation by passenger cars, buses, trains, and airplanes would be 2.2-, 2.9-, 3.0-, and 2.8-times increases, respectively. It is forecast that the share of the road transport will drop to 80% from 83% of the present level, but the shares of transportation by trains and airplanes will rise to 8% and 11%, respectively.

In developing countries where the living standard has been markedly improved, motorization has been sharply developed, and as a result, transportation by passenger cars will be increased 5.1 times by 2050. The transportation by buses will be decreased from 52% to 45% and motorcycles will drop the share from 13% to 6%, while the transportation by passenger cars will be increased from 19% to 30%.

The freight transport demand (in ton-kilometer base) will rise to 2.5 times of present level as a result of expanded economic activities. Trucks are highly convenient modes of transportation and, therefore, their share will be increased from 41% to 45% while the share of trains will be decreased from 32% to 27%. Transportation by ships will stay at almost the same level (from 26% to 27%).

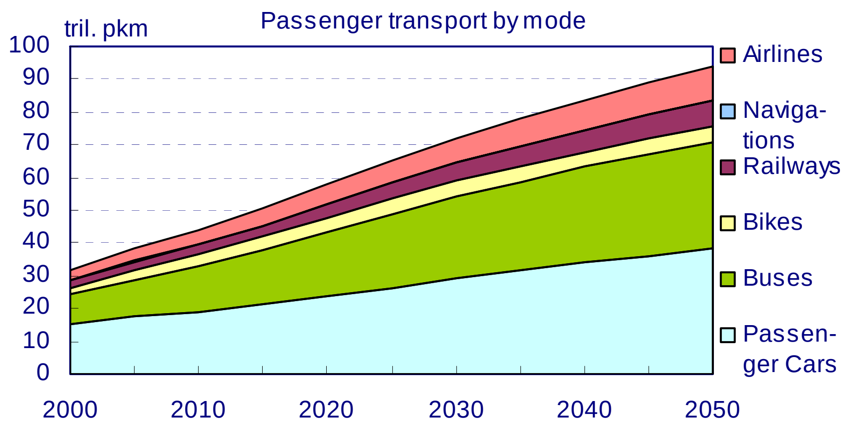

Figure 4-1 Future prospect for passenger transport demand

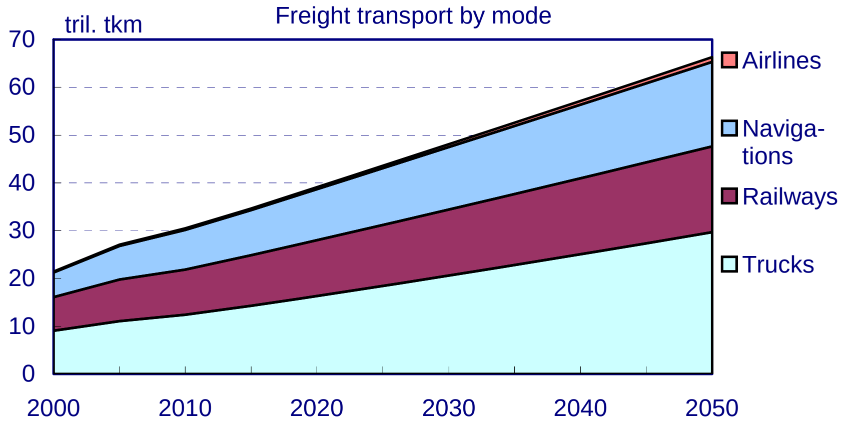

Figure 4-2 Future prospect for freight transport demand

4.2 Future prospect for vehicle stocks

With the expansion of transport demand, vehicle stocks (except for motorcycles) will be increased from 900 million units of present level to 2,300 million units in 2050 (i.e., 2.7 times). More than 80% of the increment would be contributed by developing countries. Passenger cars would feature a 2.8-times increase (2,000 million units in 2050), buses would feature a 2.5-times increase (40 million units in 2050), and trucks would feature a 2.2-time increase (300 million units in 2050). Motorcycle stocks will be increased from 300 million units to 500 million units (i.e., 1.9 times).

The ownership rate (vehicle stocks per thousand persons) will be increased from the current 586 units to 727units in 2050 in advanced countries, but vehicle stocks may saturate in some countries. In developing countries, this rate will be considerably increased from 47 to 189 units, but the level in 2050 would still be about one-fourth of the ownership rate in advanced countries and thus there is a room for increase even after 2050.

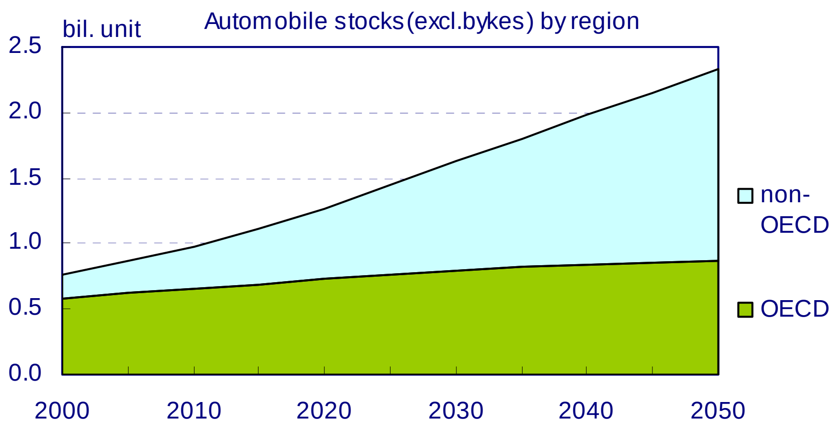

Figure 4-3 Future prospect for vehicle stocks

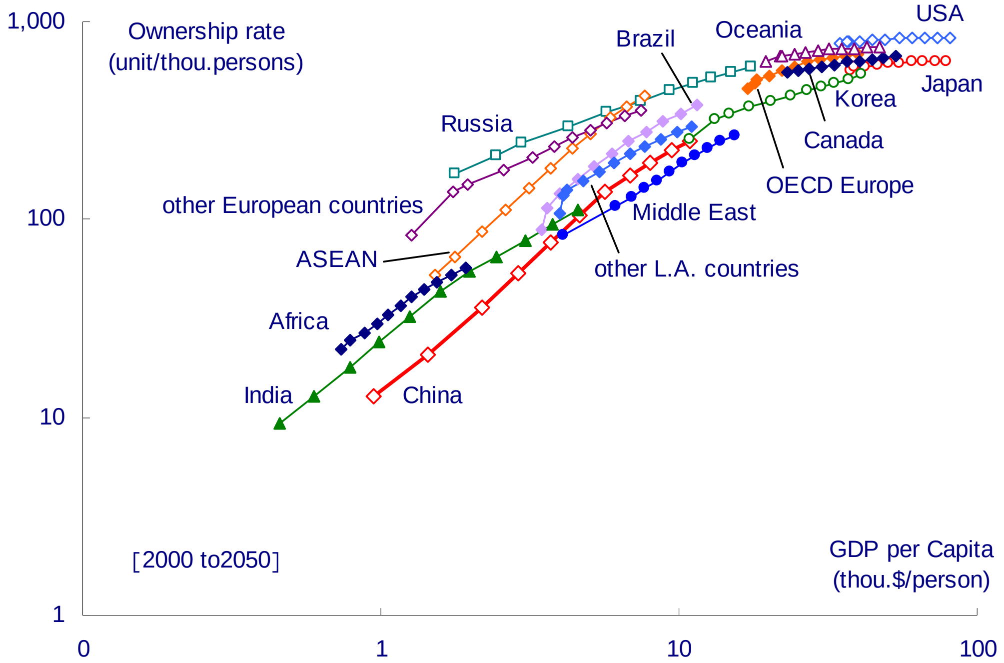

Figure 4-4 Future prospect for vehicle ownership rate

4.3 Future prospect for passenger car technology development

4.3.1 Improvement of ICEV fuel efficiency

Recently, strict regulations relating to fuel efficiency have been introduced in Japan, USA and Europe. In the USA, the act called “the Energy Independence and Security Act of 2007” was established in December 2007. This act ordered that the fuel efficiency standard (CAFE) from 2020 be improved from current 27.5 miles per gallon (11.7 km/L-gasoline; this definition is applied to the subsequent figures as well) to 35 miles per gallon (14.9 km/L). The Obama Government has proposed to strengthen this standard and move up its application timing (i.e., a fuel efficiency of 35.5 miles per gallon would be achieved by 2016). In the EU, the draft regulation on CO_2 emissions proposed by the European Commission was adopted in April 2009, and the CO_2 emission per 1-km run must be reduced to 120 g on average (equivalent to fuel efficiency of about 20 km/L) in the period between 2012 and 2015[4]. In Japan, the new fuel efficiency standard was enacted in July 2007 and the average fuel efficiency of passenger cars must be improved to 16.8 km/L by fiscal 2015.

With regard to the fuel efficiency for conventional engine vehicles (ICEV), advanced countries have designed the vehicles to meet the regulations on the fuel efficiency in 2010s. It is forecast that the

[4] Car manufacturers are planning to improve the fuel efficiency to 130 g/km through refinement of engines etc. The reduction of remaining 10 g/km will be achieved by other technological developments: for example, enhancement of performance of tires, improvement of efficiency of air conditioners, and positive utilization of bio fuels that contain less carbon compared to gasoline.

improvement of the fuel efficiency will continue at a slow pace and the fuel efficiency will be enhanced by 41% (in km/L base) by 2050 when compared to the level in 2005. For developing countries, drastic regulatory strengthening movement is not expected and, therefore, it is forecast that the fuel efficiency will be gradually improved by 37% in 2050 when compared to the level in 2005.

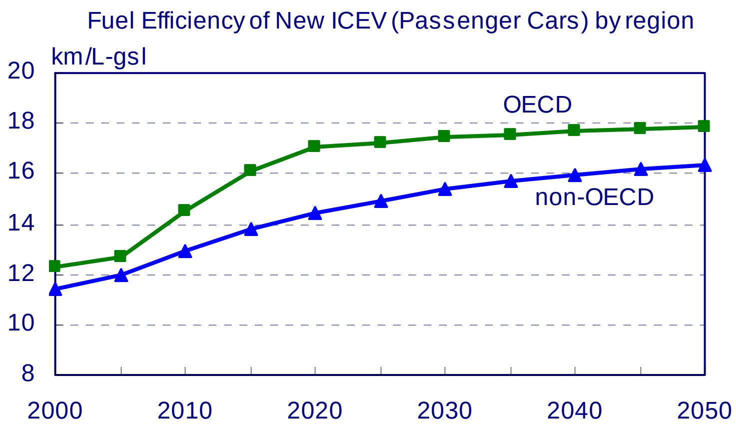

Figure 4-5 Estimated fuel efficiency of new passenger cars (ICEV)

4.3.2 Formulation of diffusion model

The present mainstream is internal combustion engine vehicles (ICEVs). Recently, the motor-driven vehicles have been positively developed. Although zero-emission vehicles (ZEVs) such as electric vehicles offer the energy efficiency of about 3 to 4 times as high as ICEVs, the present technology level limits the performance of batteries and, therefore, their running distance is short. Hybrid electric vehicles (HEVs) are equipped with an internal engine and a motor to take advantage of the merits of both power sources. HEVs have been popularized because of environmental problems and the steep rise in gasoline prices. However, HEVs and ZEVs suffer various technical problems, and, inter alia; the vehicle’s prices are a major bottleneck against dissemination. Other problems pointed out include provision of fuel supply infrastructures and limited supply of resources such as rare metals.

In determination of future vehicle types (engine technology), it is necessary to study the selection of vehicle types by consumers. The probabilistic selection model can estimate the most reasonable selection probability (selection distribution) based on the vehicle utilization intensity in consumers’ selection process.

It is assumed that consumers select and purchase most utility vehicles by taking into consideration three factors: economy, environmental conservation performance, and convenience. The economy is evaluated by combining the initial cost (vehicle price) and running cost (fuel cost) to calculate the running distance per dollar (km/$). The economy will change every year depending on the reduction in the vehicle price resulting from the mass production effect and the improvement of fuel efficiency. The environmental conservation performance is measured with the Well-to-Wheel CO_2 emission from the fuel and evaluated by means of the running distance per kilogram of CO_2 (km/kg-CO_2). The evaluation of the environmental conservation performance will change every year depending on the improvement of fuel efficiency and the generation mix (if electric vehicles). The convenience is comprehensively evaluated by taking into consideration fuel supply infrastructures, running distance per fuel charge, and present market share.

Each factor is evaluated using a point system with the gasoline vehicles (GICEVs) defined as 10 points. The following Cobb-Douglas utility function is used.

$$U_i = \text{Economy}_i^{\ \alpha} \times \text{Environmental conservation performance}_i^{\ \beta} \times \text{Convenience}_i^{\ \gamma}$$

(Note that $\alpha + \beta + \gamma = 1$; $\alpha, \beta, \gamma \geq 0$; and "i" shows vehicle type.)

As for weights (α,β and γ), this reference case assumes that consumers select only economy and convenience and do not evaluate the environmental conservation performance and, therefore, the weight for the economy α is defined as 2/3 and the weight of the convenience γ is defined as 1/3. If the environmental conservation performance is more weighted, more environment-friendly vehicles will be introduced at higher costs. This way of thinking will be discussed in the technology development case of the next section.

Once the utility (U_i) is calculated, the multivariate Logit-model-type selection probability (P_i) can be obtained from the following equation. The resultant selection probability corresponds to the sales share in each year.

$$P_i = \frac{\exp(U_i)}{\sum_i \exp(U_i)}$$

4.3.3 Future prospect for dissemination of engine technology

The future prospect for dissemination of engine technologies obtained from the probabilistic selection model discussed above shows that HEVs will be considerably disseminated since they have sufficient cost competitiveness against ICEVs and less limitations on infrastructures. When the world share of passenger car sales in 2050 is broken down, ICEVs would account for 56%, HEVs would account for 42%, and ZEVs would account for only 2%. It is forecast that the share of HEVs will be 46% comparing with 51% of ICEVs in advanced countries while in developing countries, it will be 39% since the introduction of these vehicles would be slightly delayed.

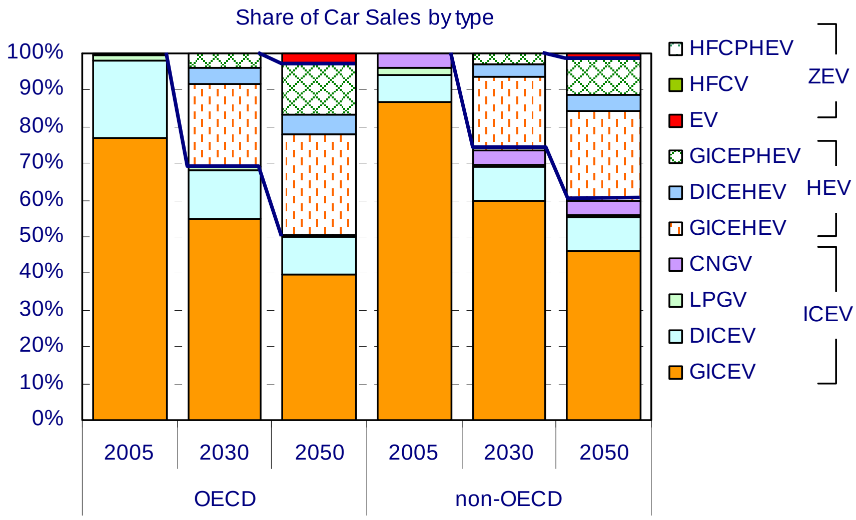

Figure 4-6　Share of new passenger car sales

The share of vehicle stocks will be changed with slight delays in their sales. In 2050, the share of HEVs in total passenger car stocks is estimated to be 41% for advance countries and 34% for developing countries.

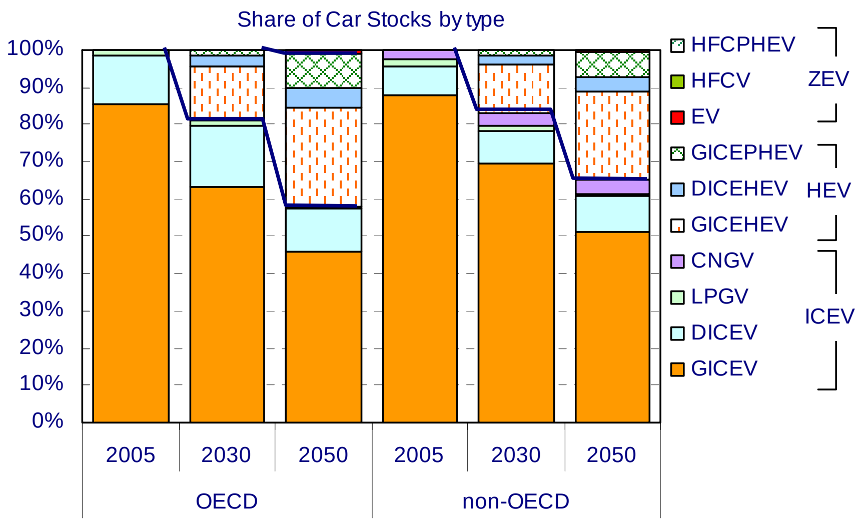

Figure 4-7　Share of passenger car stocks

4.4　User cost

Since hybrid electric vehicles (HEVs) and zero-emission vehicles (ZEVs) use advanced technologies, they cost higher when compared to the vehicles equipped with conventional engines (ICEVs). With further introduction of these advanced-techonology vehicles, users will have to bear higher costs. The money paid by users for these vehicles can be calculated as additional costs to the present vehicle prices (under the assumption that the present technology level is maintained, i.e., no improvement of fuel efficiency and no dissemination of HEVs and ZEVs)[5]. In this estimation, presently expensive HEVs and ZEVs will become cheaper in the future because of mass production effect induced by expanded dissemination. ICEVs that have already enjoyed the benefit of the mass production effect are estimated to cost high because of the introduction of more advanced fuel efficiency improvement technologies.

Table 4-1 Car price estimate per vehicle type (for small vehicles)

Vehicle type	Price in 2005	Price estimate in 2050
Gasoline-engine Vehicle [GICEV]	$13,600	$14,000 - 15,600
Gasoline-powered Hybrid Vehicle [GICEHEV]	$17,600	$15,000 - 16,500
Diesel-engine Vehicle [DICEV]	$16,600	$17,000 - 18,400
Diesel-powered Hybrid Vehicle [DICEHEV]	$19,600	$18,600 - 20,000
LPG-powered Vehicle [LPGV]	$16,400	$16,800 - 18,400
CNG-powered Vehicle [CNGV] Note 1	$15,600 - 16,900	$16,000 - 18,600
Electric Vehicle [EV]	$44,000 Note 2	$24,900 - 25,500
Fuel Cell Vehicle [HFCV]	$136,200	$32,400 - 33,900
Plug-in Gasoline-powered Hybrid Vehicle [GICEPHEV]	$37,000	$17,400 - 18,900
Plug-in Fuel Cell Vehicle [HFCPHEV]	$154,300	$41,700 - 43,200

Note 1: Retrofit to gasoline vehicles is a mainstream in Latin America.
Note 2: This figure is the vehicle price in 2010. It does not include battery replacement expenses.

Since advanced-techonology vehicles feature high fuel efficiency, their running costs (fuel expenses) are lesser than those of conventional vehicles. The reduction in fuel expenses under the assumption that the present technology level is maintained is counted as a merit of energy conservation. Although the running cost is generated over the life of each vehicle, the period within which consumers expect to recover the initial cost (investment return period) is generally several years[6]. In this estimation, the number of years used to calculate the merit of energy conservation is defined as about 3 to 5 years; however, the exact figure differs according to the region.

The cost actually borne by users is calculated by deducting the merit of energy conservation from the

[5] The investment on the supply infrastructure is not counted.

[6] The legal durable years in Japan generally range from 3 to 5 years; however, they depend on the use (passenger or freight transport) or vehicle size (small or large).

initial additional cost. In this reference case, the introduction of expensive advanced-techonology vehicles is promoted as well and, therefore, the accumulated initial additional cost in the world by 2050 will be 4.7 trillion dollars. The fuel cost saved by the advanced technologies will be 4.6 trillion dollars. The difference of 0.1 trillion dollars will be the net user cost. This figure corresponds to 0.002% of the global GDP (the level for both advanced countries and developing countries are similar) and, therefore, it can be said that users will be almost free from cost bearing. When this user cost estimation is broken down on a year-by-year basis, the initial cost is higher than the merit of energy conservation at the initial stage of introduction where the mass production effect is small but the merit of energy conservation will overcome the initial cost, that means so-called “negative cost,” with a gradual decrease in vehicle prices and the improvement of fuel efficiency.

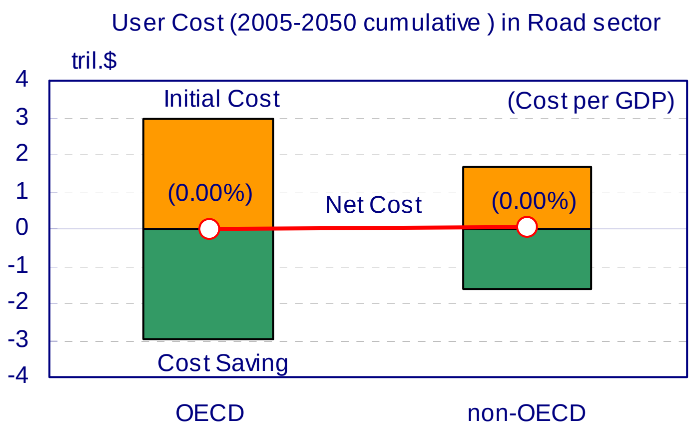

Figure 4-8 User cost in the road sector (2005–2050 cumulative)

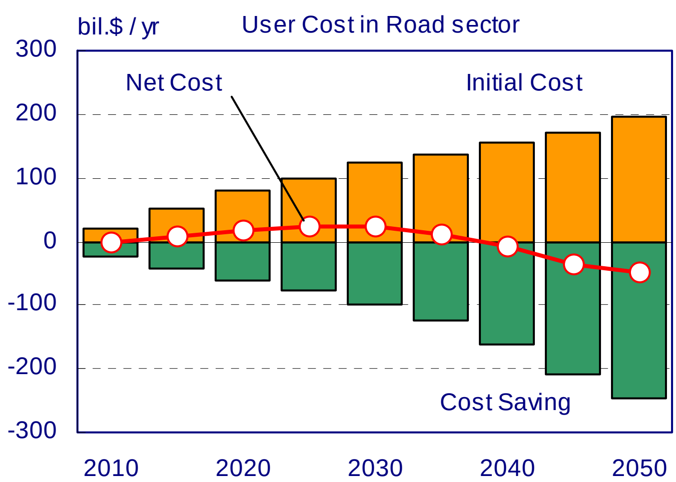

Figure 4-9 User cost in road the sector

4.5 Energy demand and CO_2 emission

In 2050, the energy demand in the transportation sector is estimated to rise to 2.0 times the present level, and as a result, the Well-to-Wheel CO_2 emission is expected to be 1.9 times higher than the present level. The increase in CO_2 emission is slightly lower than that of energy demand due mainly to efforts toward lower-carbon generation mix. The CO_2 emission in advanced countries will be reduced by 4% while that in developing countries will rise to 3.0 times the present level.

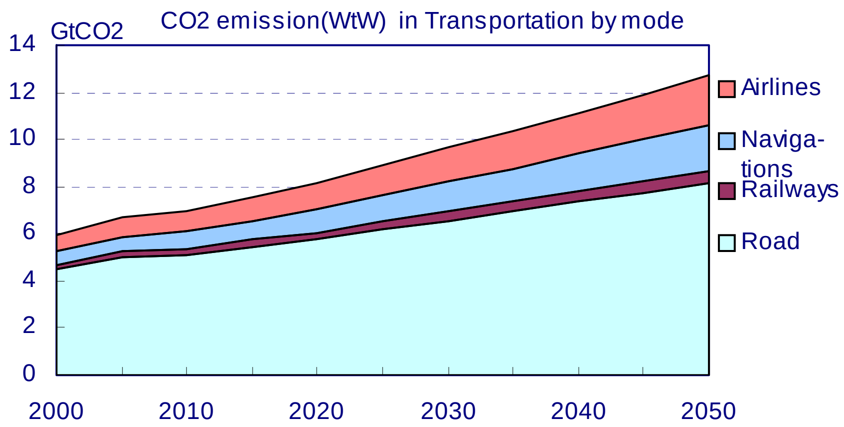

Figure 4-10 Future prospect for energy-related CO_2 emission (in the transportation sector)

The energy demand in the road sector (automobiles and motorcycles) that accounts for more than 70% of the transport sector will rise to 1.7 times the present level and the CO_2 emissions will be 1.6 times higher than the present level. When discussing developing countries, CO_2 emissions will be 3.0 times higher than the present level. The CO_2 emissions from passenger cars whose share is 50% in the road sector will be 1.4 times higher than the present level and 3.8 times higher in developing countries.

With the increasing need for transport, the demand for oil that is the major fuel for transportation will remarkably increase. Oil demand in the world will be increased from the present 80 million b/d to 129 million b/d in 2050. About 70% of the increment is brought by the transportation sector. Moreover, the road sector accounts for more than 40%.

Table 4-2 Future prospect for oil demand (unit: Mb/d)

		2005	2050	Change
Oil demand		80	129	+49
in the Transportation sector		41	76	+34
	OECD	24	23	-2
	Non-OECD	14	41	+27

in the Road sector		31	53	+22
	OECD	19	18	-1
	Non-OECD	11	35	+24

Note: International marine bunkers are included.

5. Future Prospect for Technology Development in the Automotive Sector

5.1 Basic philosophy of technology development

Energy conservation and CO_2 abatement measures include modification of vehicles (e.g., improvement of fuel efficiency and application of alternative fuels), control of transport demand (e.g., restriction of demand and modal shift to public transportation), and dissemination of ITS-based traffic control and green driving. This article only covers the technology development on vehicle (promotion of dissemination of HEVs and ZEVs). However, it is very difficult to accurately foresee the extent of the technology development since it is influenced by various parameters such as future technology development strategies, technological renovation, practical application timing, and introduction procedures.

For this reason, in the technology development case, multiple scenarios are assumed with regard to the extent of introduction of each engine technology into market. Several scenarios are defined depending on the additional cost level (the additional cost is obtained by deducting the merit of energy conservation from the initial cost). As for the additional cost level[7], three scenarios are defined: 0.1%, 0.2%, and 0.3% of GDP. Under the assumption that these additional costs will be completely used for the road sector, the probabilistic selection model is used to promote the introduction of HEVs and ZEVs until the cost in each scenario reaches the predetermined level.

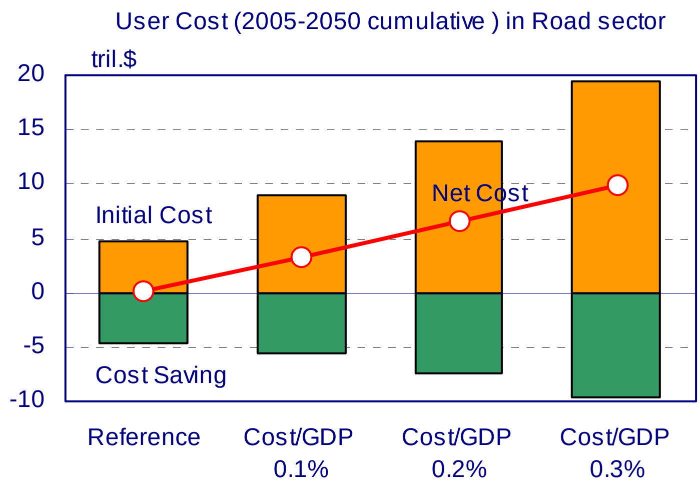

Figure 5-1 User cost in the road sector (2005–2050 cumulative)

This probabilistic selection model increases the weight of the environmental conservation

[7] "Energy Technology Perspectives (2008)" of the IEA (International Energy Agency) states that the additional investment equivalent to 0.4% of GDP will be required in the ACT MAP scenario that aims at returning the CO_2 emission to the present level by 2050 and the additional investment equivalent to 1.1% of GDP will be required in the BLUE MAP scenario that aims at halving the CO_2 emission by 2050. However, the cost reduction brought by the energy conservation is not counted. Since the cost equivalent to 0.3% of GDP, which is defined in the study of this article, is the figure in which the merit of energy conservation has been deducted and is limited to the road sector, it can be said that the cost to be borne by users is considerable.

performance, which was ignored in the reference case, until it reaches the predetermined level. We think this concept is equivalent to the effect that the introduction of advanced-techonology vehicles that are not selected only based on the economy will be stimulated by means of the government's subsidy. While the additional cost is paid by the government in this subsidy system, it will be finally borne by the nation since the source of revenue of the subsidy is taxes collected from the nation.

As for shares of the advanced-techonology vehicles in the new passenger car sales (in 2050), HEVs and ZEVs account for 42% and 2%, respectively, in the reference case. In the "0.1% of GDP" scenario that requires the additional cost of 3.2 trillion dollars in total, shares of HEVs and ZEVs are 71% and 8%, respectively. Most of the ZEVs are EVs. In the "0.2% of GDP" scenario that requires the additional cost of 6.5 trillion dollars in total, shares of HEVs and ZEVs are 73% and 13%, respectively. In the "0.3% of GDP" scenario that requires the additional cost of 9.8 trillion dollars in total, shares of HEVs and ZEVs are 73% and 21%, respectively. The share of ICEVs in the "0.3% of GDP" scenario is 2% in advanced countries and about 6% over the world. It can be said that advanced-techonology vehicles are dominantly sold in this scenario.

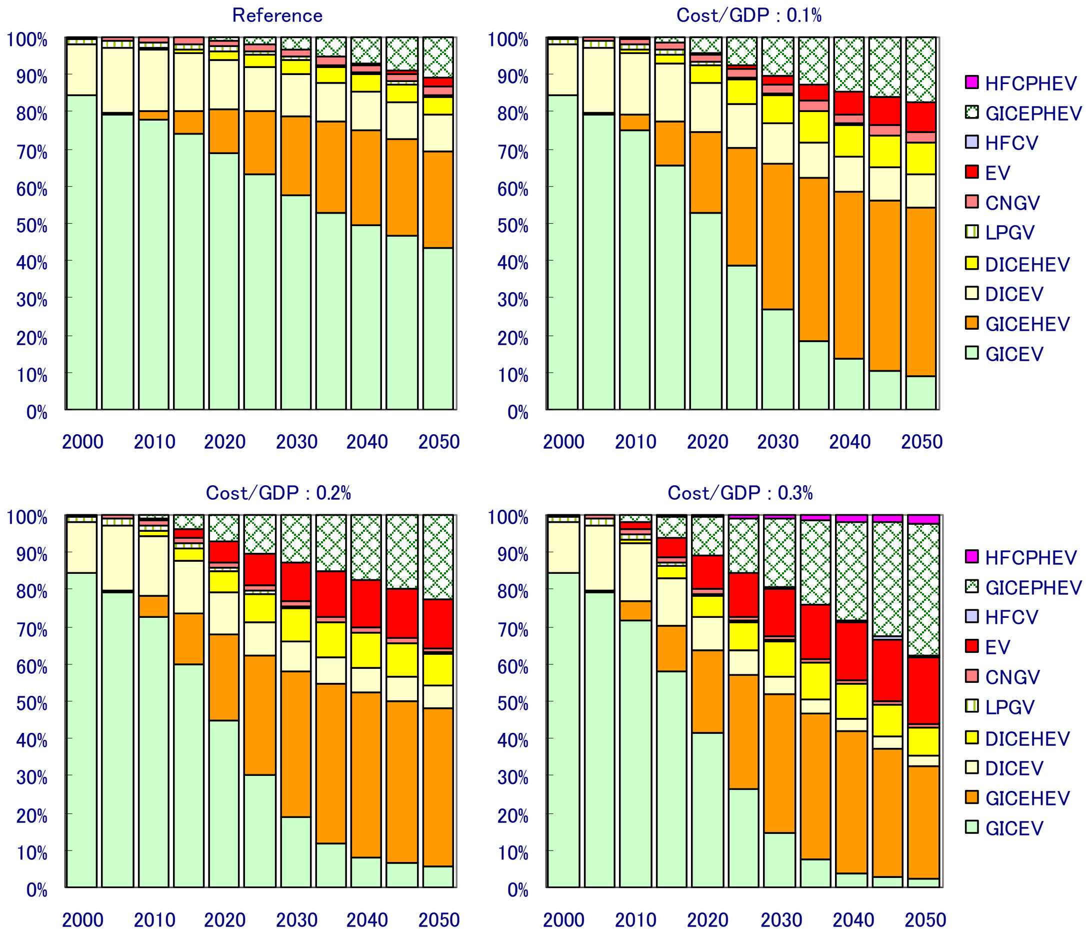

Figure 5-2 Share of passenger car sales

From the viewpoint of dissemination of advanced-techonology vehicles, the tendency for gasoline hybrid vehicles (GICEHEVs) featuring relatively low prices are introduced first and plug-in hybrid vehicles (GICEPHEVs) and electric vehicles (EVs) follow them in this order is observed. EVs have several bottlenecks such as short running distance and insufficient infrastructure and, therefore, the introduction potential is limited.

From the viewpoint of share of vehicles stocks (passenger cars and trucks), HEVs and ZEVs account for 35% and 1%, respectively, in the reference case while the former is increased to 71% and the latter is increased to 18% in the "0.3% of GDP" scenario. The share of HEVs is 71% in advanced and developing countries. However, these two regions represent different breakdowns: plug-in hybrid vehicles (GICEPHEV) are widely introduced in advanced countries (37% for advanced countries and 19% for developing countries). ZEVs are also introduced earlier in advanced countries and the share is 22% (15% for developing countries).

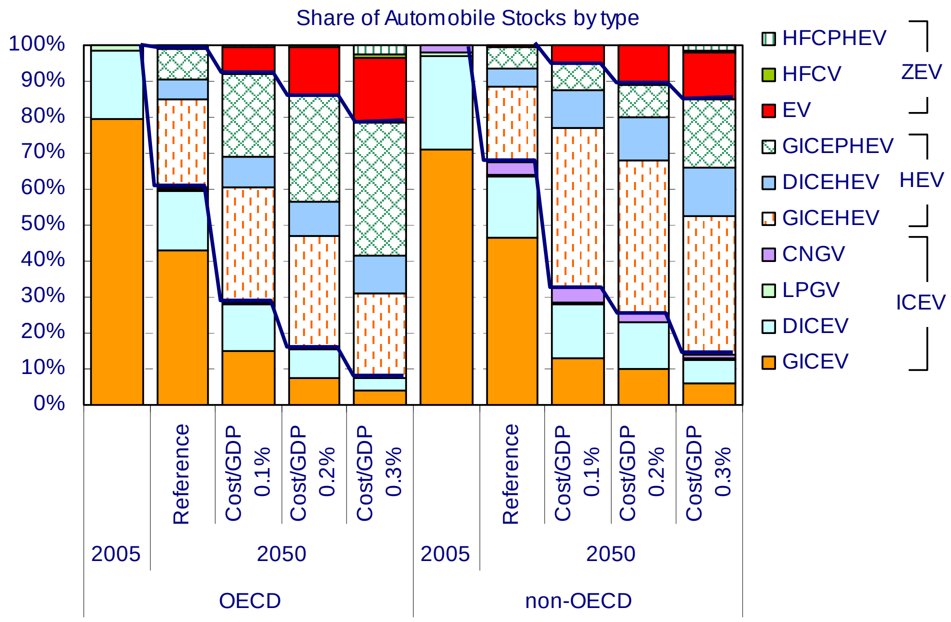

Figure 5-3 Share of vehicle stocks

The fuel efficiency improvement rate of the new passenger cars (liter per 100 km) in the "0.3% of GDP" scenario is 45% (in comparison with 2005; this definition is applied to the subsequent figures as well) in 2030 and 51% in 2050. The FIA (Federation Internationale de I'Automobile) and other organizations state in the fuel efficiency improvement initiative "50 by 50"[8] that the improvement

[8] FIA Foundation, International Energy Agency (IEA), International Transport Forum (ITF), and United Nations Environment Programme (UNEP), "50 by 50 Global Fuel Economy Initiative," 2009

up to 50% is possible by 2030 (50% plus α in 2050). The study of this article concludes that the fuel efficiency improvement rate for the vehicle stocks is 41% in 2050. The 50% improvement potential stated in "50 by 50" is based on not only the technology improvement of new vehicles but also improved efficiency of aftermarket products such as replacement tires, green driving, and other available measures. We judge that results of our study are reasonable when these measures are considered.

Table 5-1 Summary of technology development (as of 2050)

	Share of vehicle stocks		Fuel efficiency in stock base	
	Passenger cars (HEV, ZEV)	Trucks (HEV, ZEV)	Passenger cars (vs.2005)	Trucks (vs.2005)
in 2005	0%, 0%	0%, 0%	-	-
Reference	37%, 1%	20%, 0%	21%	18%
0.1% case	67%, 6%	37%, 5%	30%	26%
0.2% case	69%, 13%	46%, 8%	37%	31%
0.3% case	72%, 18%	62%, 15%	41%	37%

5.2 Cost performance of CO_2 abatement

We have measured the abatement effects against energy-related CO_2 emissions and oil demand in the world when the additional costs discussed above are used in technology development activities.

When the accumulated cost of 9.8 trillion dollars, which is equivalent to 3% of the global GDP, is used, the direct Tank-to-Wheel CO_2 emissions from the road sector will be cut by about 2,600 million tons (35%) in 2050 when compared to the reference case and the emission level in 2005 can be almost achieved. The share of the advanced-techonology vehicles in vehicle stocks will be about 90% (HEVs: 71%, ZEVs: 18%), but it will offset the increment of energy demand in the transportation sector. To reduce CO_2 emissions below the present level, it is necessary to develop more energy-efficient motor-driven vehicles (i.e., further electrification of engine). To this end, it is indispensable to develop innovative batteries that feature lower price and higher density.

On a Well-to-Wheel basis, CO_2 emissions will be cut by about 1,400 million tons in 2050 when compared to the reference case (i.e., the emissions are 18% less than the reference case). This level is 1.3 times higher than that in 2005. The reason is that the development of vehicle electrification leads to increased CO_2 emissions in the power generation sector. In other words, although vehicles are furthermore electrified by investing a lot of money, the CO_2 abatement potential will be limited when CO_2 emitted from the power generation sector is counted.

In 2050, oil demand in the road sector can be reduced by 18 million b/d when compared to the reference case. Our scenario can restrict the increase in demand to 4 million b/d in comparison with that in 2005, while the demand will be increased by 22 million b/d in the reference case.

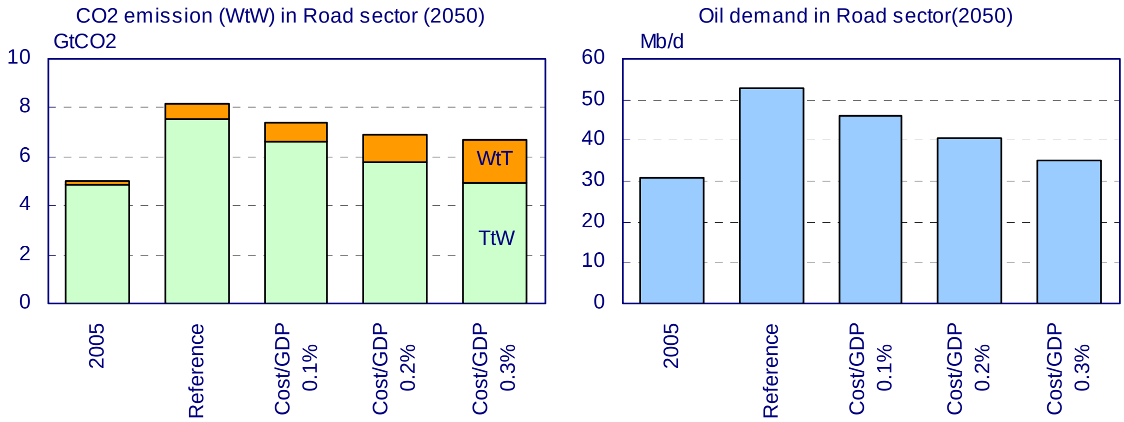

Figure 5-4 Future prospect for abatement of energy-related CO_2 emissions and oil demand (in the road sector)

When the total expense used for the technology development is divided on the basis of the accumulated CO_2 emissions, the average cost required for CO_2 abatement is obtained. This average cost is 243 dollars per ton-CO_2 in the "0.1% of GDP" scenario while it is elevated to 322 dollars per ton-CO_2 in the "0.3% of GDP" scenario. Further CO_2 abatement effort leads to increased average cost. The reason is that further abatement of CO_2 will need earlier introduction of advanced-techonology vehicles. In other words, the CO_2 abatement cost is very high at the initial stage of introduction during which the cost of vehicles is high. However, when the vehicle costs are decreased on the basis of the mass production effect, the CO_2 abatement cost will gradually drop. In any of these scenarios, the CO_2 abatement cost will stay at the same level from 2025 to 2030 and decrease to 100 dollars per ton-CO_2 in 2050.

Since the transaction prices in the present carbon markets range from 20 to 40 dollars per ton-CO_2, it can be said that the CO_2 abatement costs described above are very high. Since the IEA states the marginal abatement costs ranges from 200–500 dollars per ton-CO_2 (38 to 117 dollars per ton-CO_2 for the average cost in the entire technology field) in the scenario that aims at halving the CO_2 emission by 2050[9], the CO_2 abatement cost in the road sector is at the highest level.

[9] BLUE MAP scenario in "Energy Technology Perspectives (2008)"

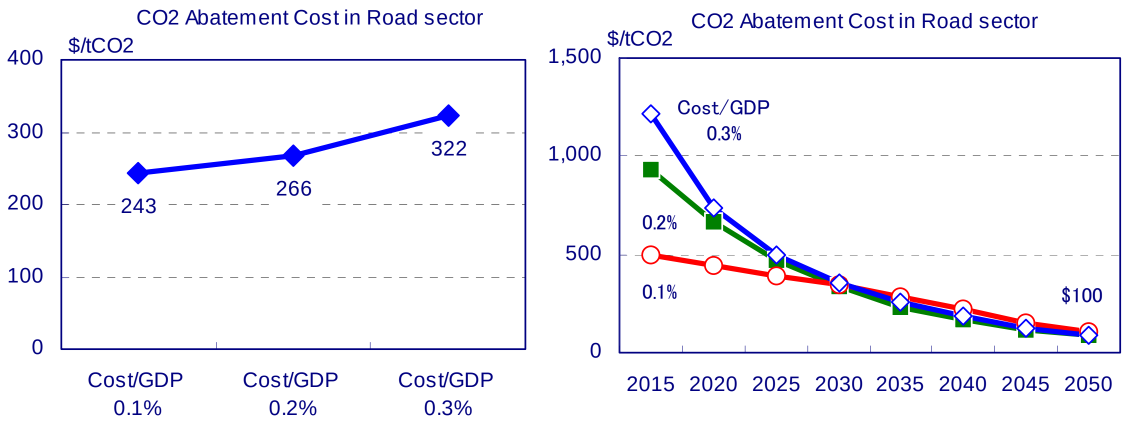

Figure 5-5 CO_2 abatement cost in the road sector

5.3 Effects of low-carbon technologies in the power generation sector

The study results described above prove that the advanced vehicle technologies effectively reduce CO_2 emissions (Tank-to-Wheel basis) and oil demand, but have less CO_2 abatement potential in the road sector on a Well-to-Wheel basis and also need high abatement cost. Even when the vehicle engines are more electrified to enhance the energy efficiency, global CO_2 abatement potential generated by this electrification effort is insufficient if the CO_2 emissions in the power generation sector are counted. This means drastic improvement of CO_2 emissions intensity (CO_2 emission per unit generated power) in the power generation sector will play a key role. Therefore, it is necessary to verify the extent to which the low-carbon technologies in the power generation sector will contribute to the CO_2 abatement in the road sector.

5.3.1 Low-carbon technologies in the power generation sector

This section examines the following technologies that contribute to the low-carbon power generation sector: (1) improvement of thermal power generation efficiency, (2) introduction of more renewable-energy-based power generation, (3) further introduction of nuclear power generation, and (4) introduction of CCS (carbon capture and storage technologies). The paragraphs below discuss CO_2 abatement effects and additional costs in the low-carbon power generation scenario.

(1) Improvement of thermal power generation efficiency

It has been well known that the efficiency is improved by the combined cycle (CC) system where power generation by conventional steam turbines is combined with the power generation by gas turbines. When the combined cycle system that offers a higher gas temperature (1,500°C to 1,700°C) and the integrated coal gasification combined cycle (IGCC) are widely introduced, the power generation efficiency in 2050 is expected to become 5.7 percent point higher than that of the reference case on world average. The additional initial investment cost is 300 billion dollars in total. The improved efficiency will cut the fuel costs by 2 trillion dollars (this figure is calculated by assuming the investment return period as 10 years; this definition is applied to the following calculations as well). The net user cost will be minus 1.8 trillion dollars (negative cost) and, as a result, the average CO_2 abatement cost will be minus 78 dollars per ton-CO_2.

(2) Introduction of more renewable-energy-based power generation

Although non-fossil power generation mainly based on natural energies, has vast physical potential, bottlenecks such as unstable supply and high introduction costs exist. We assume that renewable-energy-based power generation, except for solar power generation, will sufficiently compete with the thermal power generation with respect to generation costs if the cost reduction will be steadily deployed with the help of technology development and mass production effect. Our scenario assumes that the introduction scale of the renewable energy power generation is twice as large as the reference case and the additional investment cost is 6.6 trillion dollars in total. When the reduction of fossil fuel costs are counted after the power generation by renewable energies substitutes for the thermal power generation, the average CO_2 abatement cost will be 49 dollars per ton-CO_2.

(3) Further introduction of nuclear power generation

Nuclear power generation, which is different from natural energies, is a non-fossil power generation method that allows stable supply of electric power. For this reason, lots of countries—inter alia; developing countries have large-scale introduction plans. Our scenario assumes that China and India will construct a large number of nuclear power plants that almost meet their national plans and Southeast Asia and Middle East countries will steadily introduce such plants. This scenario also assumes that in Europe and the USA, which have employed “non-nuclear policies,” the decommissioning of nuclear plants will be considerably delayed due to response to environmental problems. Although the additional investment cost is 300 billion dollars in total, the generation cost is relatively lower than that of the thermal power generation and, therefore, the average CO_2 abatement cost will be minus 40 dollars per ton-CO_2 (negative cost).

(4) Introduction of CCS (carbon capture and storage technologies)

In the power generation sector, highly expected low-carbon technologies, among others, are carbon capture and storage technologies (CCS). CO_2 exhausted from the thermal power generation plants is not released to the open air but will be stored underground. Presently, verification experiments are underway in various locations to examine whether CO_2 can be stably stored underground for a long period.

CCS technologies cost are high and it is said that the carbon capture and storage cost ranges from 40 to 90 dollars per ton-CO_2, depending on the system configuration. To widely commercialize these technologies, this cost must be reduced to 30 to 40 dollars per ton-CO_2. Our scenario assumes that about 3.4 trillion dollars, which corresponds to 0.1% of the global GDP, will be required as the initial investment cost. It corresponds that CCS will be introduced to about 50% of thermal power generation facilities in the reference case in 2050.

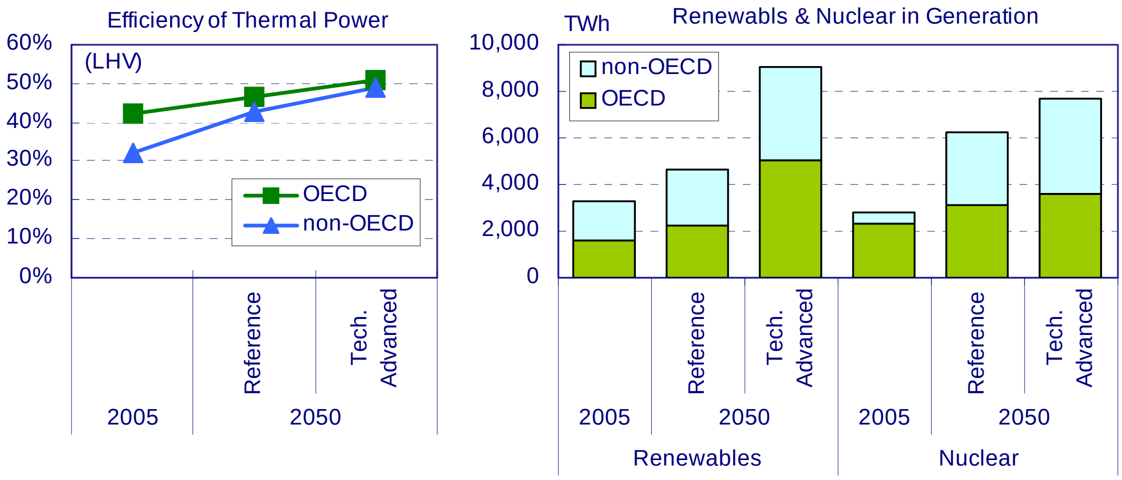

Figure 5-6 Introduction of low-carbon technologies in the power generation sector

5.3.2 Global CO_2 abatement effects of low-carbon power generation

When the low-carbon technologies discussed above are simultaneously introduced, the share of thermal power generation will drop to 54% from 73% of the reference case, but the fossil fuel power generation would still stay in the mainstream[10]. We assume that CCS will be used in more than 50% of thermal power generation facilities. CO_2 emissions intensity of the power generation sector will drop to 367 g/kWh from 556 g/kWh of the reference case as a result of introduction of low-carbon technologies into power generation facilities. Moreover, the introduction of CCS will reduce this value to 189 g/kWh.

In 2050, the energy-related CO_2 emissions in the world would be cut only by 2% of the 47,500 million tons of the reference case (1.8 times of the level in 2005) when the technology development is implemented only in the road sector ("0.3% of GDP" scenario). If the low-carbon technologies are used for power generation, the decrement will be 13%. If CCS is introduced, this decrement will be 26%. If the technology development is simultaneously implemented in the road and power

[10] Note that the energy conservation strategy better than the reference case is not considered in the industrial and the residential & commercial sectors.

generation sectors, CO_2 emissions will be cut by 29% from the reference case: i.e., emissions will be as low as 1.3 times of the level in 2005.

The additional initial investment cost necessary to reduce CO_2 emissions is 19.4 trillion dollars in total in the road sector. In the power generation sector, the figure is 10.6 trillion dollars, which is almost half of the road sector. The user cost obtained after deduction of saved fuel cost is 9.8 trillion dollars for the road sector while that for the power generation sector is 2.9 trillion dollars, which is almost one-third of the road sector. This comparison clearly shows that the cost performance in the power generation sector is higher than that in the road sector.

Although the power generation sector features large-scale facilities and thus requires vast investment, it substantially affects CO_2 abatement. For automobiles, the cost performance is distributed to individual vehicles and, therefore, it is estimated that scale merit will not sufficiently contribute to CO_2 abatement even when the price reduction by the mass production effect is counted. We think this formulation can also be used to explain why, in the power generation sector, the CO_2 abatement cost obtained from the introduction of nuclear and high-efficiency thermal power generation systems is a negative value, while the CO_2 abatement cost obtained from the introduction of renewable energy based power generation such as small-scale solar and wind power generation systems is a positive value.

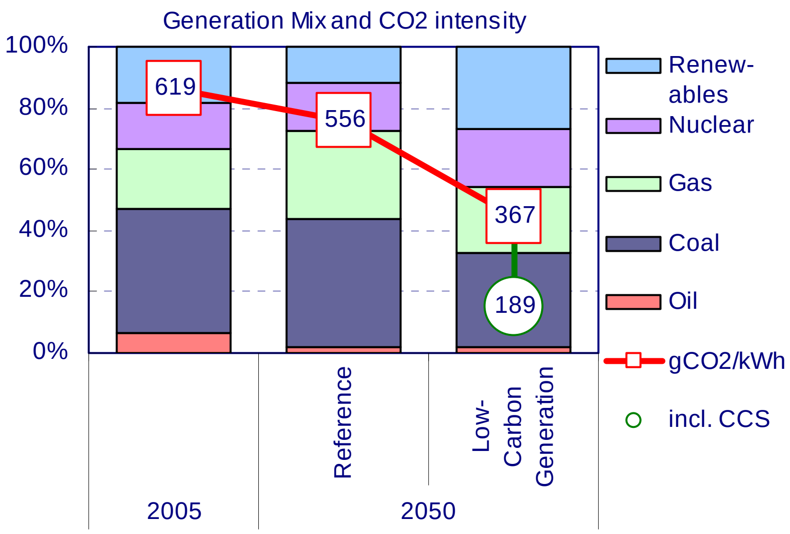

Figure 5-7 Generation mix and CO_2 emission intensity

5.3.3 Recalculation of CO_2 abatement effect and cost in the automotive sector

The influence on the road sector is discussed herein. The Well-to-Wheel CO_2 emissions are 8,100 million tons in the reference case (1.6 times higher than the level in 2005). These emissions will be cut by 18% (i.e., CO_2 emissions are 1.3 times higher than the level in 2005) when the technology development is implemented in the road sector ("0.3% of GDP" scenario). Emission levels will be reduced by 29% (i.e., CO_2 emissions will be 1.2 times higher than the level in 2005) when the low-carbon technologies are applied to the power generation sector. The extent of electrification is only 11% in the automotive sector (energy consumption base) and, therefore, there is small room for CO_2 abatement. When vehicles are more electrified, the effect of the low-carbon power generation will be intensified; however, the additional cost will increase accordingly.

CO_2 abatement cost in the road sector will drop to 246 dollars per ton-CO_2 from 322 dollars per ton-CO_2 ("0.3% of GDP" scenario) with the joint effect of technology development and low-carbon power generation. If invested in the low-carbon technologies for the power generation sector, CO_2 abatement cost will be cut by 76 dollars per ton-CO_2. In other words, this result shows that even if technology development is promoted in the road sector, vehicle users (or government) will bear the cost as long as the low-carbon technologies are not developed in the power generation sector.

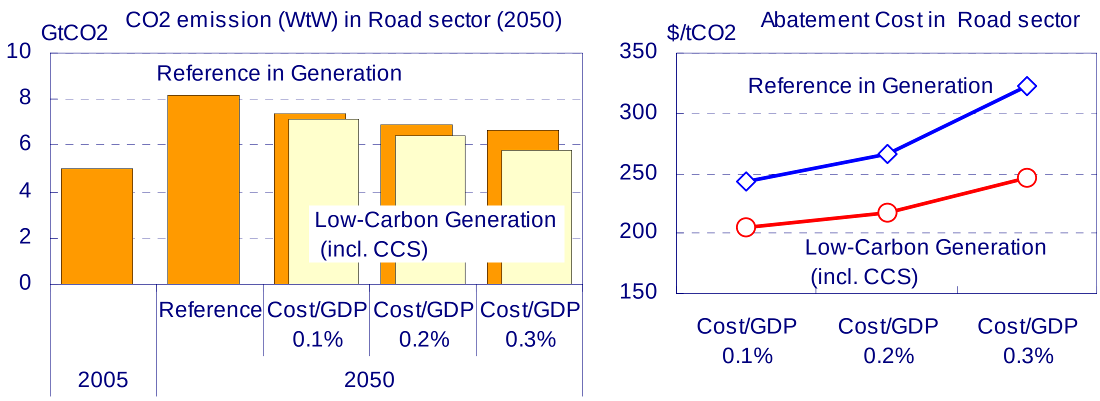

Figure 5-8 CO_2 emission and abatement cost in the road sector

6. Conclusion

By using the IEEJ2050 Model, we have forecast the economical situations and technology development based on the forecasts and then evaluated the energy demand and fossil-fuel-related CO_2 emissions for the future. Under the trend forecast based on the present technological systems and energy policies (reference case), it is foreseen that the world energy demand will be 1.8 times higher than the present level and CO_2 emissions will rise to 1.8 times of the present level in 2050. The demand for oil that is the most important energy source will rise to 1.6 times of the present level due to steep increase in demand in road sectors mainly in developing countries. This result indicates that the sustainable growth might be impossible due to a shortage of energy resources and global warming. Therefore, it is necessary to take some effective measures in advance.

This study has examined the CO_2 abatement potential by focusing on the vehicle transportation sector. When a total of 9.8 trillion dollars, which is 0.3% of the global GDP, is used, the direct Tank-to-Wheel CO_2 emissions from the road sector can be almost controlled to stay at the level in 2005. However, the Well-to-Wheel CO_2 emissions will be increased to 1.3 times as high as the figure in 2005 (18% less of the reference case). The reason is that the shift to electric motors from internal combustion engines will cause increased CO_2 emissions in the power generation sector. If the electrification of vehicles is a vital measure to drastically abate CO_2 emissions, the introduction of low-carbon technologies in the power generation sector will be very important.

When low-carbon technologies are established in the power generation sector as well (CO_2 emissions intensity will be reduced by 66% when compared to the reference case), it is estimated that the Well-to-Wheel CO_2 emissions in the road sector in 2050 will be decreased to 1.2 times higher than the figure in 2005 (29% less of the reference case). Even in the technology development scenario, the electrification of vehicles accounts for about 10% on an energy consumption basis. This means that the low-carbon generation system has limited effect on CO_2 abatement. When vehicles are more electrified, the effect of the low-carbon generation system will be further increased, but the additional cost will increase accordingly. The average CO_2 abatement cost in the road sector is as high as about 200 to 300 dollars per ton-CO_2, and thus, it is unavoidable to say that the cost performance is low. We think that the cost performance is distributed to individual vehicles and, therefore, the scale merit will not sufficiently contribute to CO_2 abatement.

In this study, we planned to achieve reduction of CO_2 emissions and oil demand by disseminating advanced-techonology vehicles even if they have low cost performance; however, the reduction only offsets the increased emission and demand brought by the increased transport demand mainly in developing countries. The development of automotive technologies is based on the present technological system. Although the cost reduction brought by the mass production effect is incorporated into the estimation, development and dissemination of low-cost technologies that are completely different from the present technologies may be progressed when viewing the long span until 2050. Particularly, the development of low-price and high-density innovative batteries is indispensable to promote further electrification of vehicles. In the road sector where the transport demand will be increased, we highly expect the development of innovative technologies to reduce CO_2 emissions below the present level in the future.

For the abatement of CO_2 emissions in the road sector, it is important to develop and promote comprehensive measures. These measures include the development and dissemination of fuel efficiency improvement technologies implemented by car manufacturers, introduction of bio fuels, improvement of traffic flow, and green driving, which are not discussed in this study. Of course, establishment of low-carbon technologies in the power generation sector is one of those measures. Using these measures simultaneously will permit further abatement of CO_2 emissions. Car manufacturers have to continue cost reduction efforts but financial supports by the government, including subsidy, will also be necessary. To achieve the cost reduction based on the mass production effect, it is vital to create the initial demand through the introduction of subsidies. When individual members of the society, including car manufacturers, fuel and power generation industries, government, and vehicle users play their roles and take actions comprehensively, global warming problems in the automotive transportation sector can be solved and great results can be expected.

The electrification of vehicles and low-carbon generation technology are mainly examined in this study. Bio fuels, fuel cell vehicles, and production of hydrogen, all of which are important global warming solutions in the road sector, will be the future subjects to be studied.

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