Position of Hydrogen Energy and Prospect of Its Introduction Toward a Low-Carbon Society in 2050 in Japan

(Summary)♦

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Abstract

This study estimates the potential of hydrogen introduction by using the MARKAL (MARKet ALlocation) model based on the assumption that Japan will use imported hydrogen by 2050. It also analyzes the roles hydrogen could play in Japan's energy supply and demand structure, if an ambitious CO_2 reduction target is imposed.

The large-scale introduction of hydrogen is financially difficult if an ambitious long-term CO_2 reduction target is not set. On the other hand, tens of billions of Nm^3/year of hydrogen will be introduced if a target of reducing CO_2 by 65% or more from the 1990 level is assumed and the introduction of carbon capture and storage (CCS) is restricted. Hydrogen will be introduced mainly to the power sector (power generation by direct combustion of hydrogen).

Whether hydrogen-fired power generation or CCS will be used to achieve the CO_2 reduction target will be determined depending on their cost. Under the standard conditions in this study, CCS will be used. However, the use of hydrogen is likely to be cost competitive given the high prices of fossil fuels or the high cost of transporting CO_2 for CCS. In addition, the use of hydrogen is cost competitive over the use of some types of renewable energy, such as solar photovoltaics.

The introduction of hydrogen is regarded as an important future energy option, both as an alternative means to be applied if there is a restriction on the amount of CCS that can be introduced, and as a means of reducing the risk of rising energy costs. The benefits of hydrogen introduction are to be positioned appropriately with a long-term view extending to 2050. In relation to this, we need to proceed with research and development consistently in the overall aspects of energy supply, transportation, and demand.

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1. Introduction

The Great East Japan Earthquake and the subsequent accident at the Fukushima Daiichi Nuclear Power Plant that occurred in March 2011 had a significant influence on Japan's energy policy. In the Basic Energy Plan1) that was announced in 2010, the government aimed to advance the construction of new nuclear power plants and increase the ratio of nuclear power generation to approximately 50% by 2030. However, given the accident at the Fukushima Daiichi Nuclear Power Plant, the government decided to reconsider this plan fundamentally.

Meanwhile, the problem of climate change has remained a critical international issue. How to control greenhouse gases -- CO_2 that derives from energy, in particular -- is an issue that the world will have to face over a long period. Under these circumstances, hydrogen that does not emit CO_2 during combustion has been attracting attention as the ultimate energy carrier for reducing greenhouse gases. The focus has so far been on how to increase its use for fuel cells (for automotive use or stationary use). However, there is another way of utilizing hydrogen: by using it as a direct fuel for combined cycle power generation (hydrogen-fired power generation). It can be regarded as a zero emission power source, as long as CO_2 is not emitted during hydrogen production. What is attracting attention as a method of supplying "CO_2-free" hydrogen is to produce hydrogen from low-grade coal, etc. in an overseas energy-producing country, capture and store the CO_2 generated in the hydrogen production process (Carbon Capture and Storage: CCS2)), and then transport it to Japan.

This study estimates the potential of hydrogen introduction by using the MARKAL (MARKet ALlocation) model based on the assumption that Japan will use imported hydrogen by 2050. It also analyzes the roles hydrogen could play in Japan's energy supply and demand structure, if an ambitious CO_2 reduction target is imposed. The method of supplying hydrogen is assumed to be by importing it from overseas. As for forms of utilization of hydrogen, three kinds of use are assumed, i.e. for fuel-cell vehicles, stationary fuel cells, and power generation by direct combustion. This is different from the conventional view of "hydrogen society" in that it assumes imported hydrogen on the supply side and hydrogen-fired power generation on the utilization side.

2. Preconditions for the Estimate

2-1 Assumption of macro-economic indicators

In terms of macro-economic indicators such as population, real GDP, and international energy prices, those shown in Tables 2-1 and 2-2 were assumed for the estimate based on an existing study3).

The population will decrease from 128 million in 2010 to 97 million in 2050. As the population decreases, the average annual growth rate of real GDP will decline gradually, from 0.8% in 2010 - 2020 to 0.5% in 2040 - 2050. The crude oil price was assumed to continue rising over a long period of time, given the fact that the decline rates of existing oil fields will increase and development conditions will gradually grow tougher while demand for oil will remain strong, mainly in Asia. With regard to LNG, its import prices for Asian countries including Japan are currently set by linking with the crude oil price, and have remained higher than in other regions. It was assumed, however, that the ratio of the LNG price to the crude oil price will decline in the future, partly reflecting the assumption that LNG from shale gas produced in North America will be imported. The coal price was assumed to increase gradually, along with rise in the crude oil price. With regard to the price of imported hydrogen, the CIF price including the CCS cost was set at 30 yen/Nm^3 (0.33 dollars/Nm^3)2). The exchange rate was fixed at 90 yen/dollar going forward, and the discount rate was assumed to be 3%.

Based on these conditions, the energy service demand that will be the input data to the MARKAL model was estimated using an econometric-type energy supply-demand model4). The energy service demand thus estimated is shown in Fig.2-1.

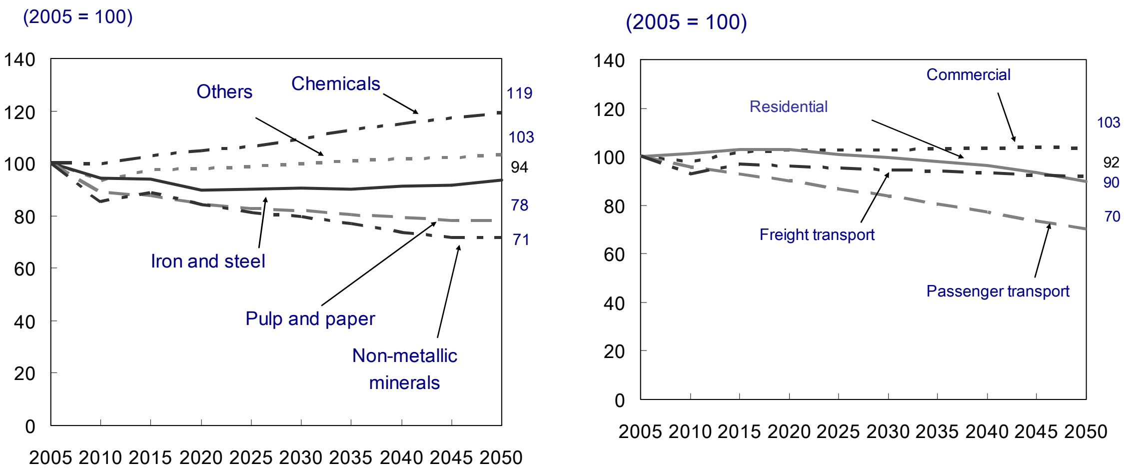
Table 2-1. Assumed macro-economic indicators

Real numbers	Historical			Projection			
	1990	2000	2010	2020	2030	2040	2050
Real GDP (2000 prices, trillion yen)	453.6	505.6	538.5	581.6	623.2	664.9	697.6
Population (in millions)	123.6	126.9	128.1	124.1	116.6	107.3	97.1
GDP per capita (2000 prices, 10,000 yen/ person)	367	398	420	469	534	620	719
Number of motor vehicles owned (in millions)	57.8	72.5	75.2	73.9	69.1	63.4	57.1
Floor area in the commercial sector (million m2)	1,285	1,656	1,834	1,964	1,966	1,938	1,881

Table 2-2. Assumed international energy prices (prices in 2011, import CIF prices)

		2011	2030	2050
Crude oil	(USD/bbl)	109	122	130
LNG	(USD/t)	762	739	721
Steam coal	(USD/t)	138	139	148
Hydrogen	(USD/Nm^3)	-	0.33	0.33

Fig.2-1. Assumed energy service demands



2-2 Assumptions regarding power generation technologies

Concerning power generation technologies, the costs and efficiencies were assumed as shown in Table 2-3 in accordance with the Costs Verification Committee5). The power generation costs of renewable energy, estimated by the Committee, feature a wide gap between the upper and lower limits. This study applies the average values between both limits. As for thermal power generation, the unit construction cost, operating and maintenance costs, and other costs shown in the report were adopted, and then the projections in Table 2-2 were adopted concerning the costs of purchasing fossil fuels.

With regard to nuclear power, it was assumed that reactors that conform to the regulatory standards will begin operating one by one and will each be closed down after an average service life of around 45 years. It was also assumed that a power plant capacity of around 25 GW will be maintained from 2035 onward as a result of the commencement of the operation of nuclear reactors that will be newly constructed in the future.

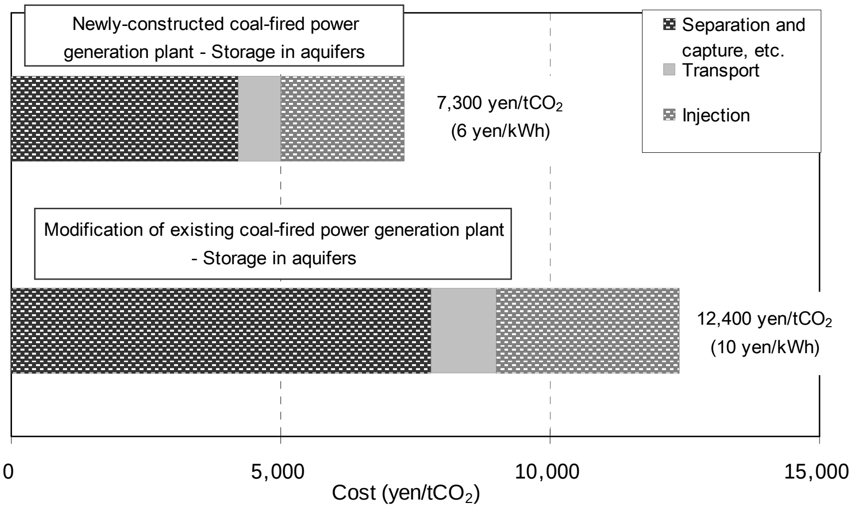
Concerning the prospects for the introduction of renewable energy, assumptions were made in accordance with the Energy and Environment Council6), which assumes that the amount of power generated from renewable energy will constitute 25% of the total power generation in 2030. It was also assumed that the introduction of renewable energy will continue to expand steadily from 2030 and onwards until 2050. Of the stationary fuel cells, the amount of hydrogen introduced and supplied by modifying the properties of fossil fuels (hereafter referred to as “deemed hydrogen”) was set in accordance with the Medium Introduction Case shown in a reference work7).

The CCS cost was set based on the estimate by the Research Institute of Innovative Technology for the Earth (RITE) 8), which assumes coal-fired power generation (Fig.2-2). Concerning LNG thermal power generation, the cost per amount of captured carbon was set to be the same as in the RITE estimate. With regard to hydrogen power generation, the year when its introduction can be commenced was set to be 2030, the construction cost was assumed to be equivalent to that of LNG thermal power generation (120,000 yen/kW), and the power generation efficiency was set at 57% (equivalent to the assumed efficiency of LNG thermal power generation (HHV) in 2030).

Table 2-3. Assumptions regarding power generation technologies

	Capacity factor (%)	Power generation efficiency (HHV, %)	Initial investment cost (dollar/kW)	Fixed operation and management cost (dollar/kW/year)
Coal-fired	70	42 - 48	2,556 - 3,194	94 - 116
LNG-fired	70	51 - 57	1,333	51
Oil-fired	50	39	2,111	74
Nuclear	80	-	3,889	206
Hydrogen power generation	45	-	9,444	97
Solar PV	12	-	2,261 - 5,000	73 - 123
Wind	20	-	2,928 - 3,056	113 - 118
Geothermal	80	-	8,889	361
Hydrogen	70	57	1,333	51
Gas reformed fuel cell	70	37	5,556 - 88,889	27 - 828

Fig.2-2. CCS cost estimation by RITE



2-3 Assumptions regarding vehicles and hydrogen transport infrastructure

The costs of vehicles were set as shown in Table 2-4 in accordance with Suehiro et al.[9] It was assumed that the price of a fuel cell vehicle (price as of 2005) will decline to 33,200 dollars/vehicle in 2050.

The introduction of hydrogen requires a new energy system. From the viewpoint of cost, it is expressed as infrastructure costs concerning the supply, transport, and distribution, etc. of hydrogen. When hydrogen is imported, the cost of landing is generated first of all. In addition, the costs of constructing hydrogen stations and transporting and distributing hydrogen by tank trucks etc. are required for the use of fuel cell vehicles. These costs were assumed by referring to the values shown in reference works2), 10). Further, the costs of constructing pipelines leading to points of demand such as households and for transporting and distributing hydrogen are required for the use of stationary fuel cells. These costs were set based on the financial statements, etc. of major gas companies11).

Table 2-4. Assumed costs of vehicles (2005 prices)

Type	Vehicle price in 2005 (in dollars)	Vehicle price in 2050 (in dollars)
Gasoline vehicle	13,600	14,800
Gasoline hybrid vehicle	17,600	15,800
Diesel vehicle	16,600	17,700
LP gas vehicle	16,400	17,600
Natural gas vehicle	16,300	17,300
Electric vehicle	44,000	25,200
Fuel cell vehicle	136,200	33,200
Plug-in hybrid vehicle	37,000	18,200

2-4 Setting of restrictions on CO_2 emissions

For cases where upper limit restrictions on CO_2 emissions are set, reductions of 50% to 80% from the 1990 level were assumed as the reduction targets for 2050. For the standard cases, a reduction of 65% was assumed.

3. Results of the Analysis

3-1 Energy supply-demand structure

In this section, the potential of hydrogen introduction in Japan by 2050 is assessed quantitatively on the basis of the following three cases.

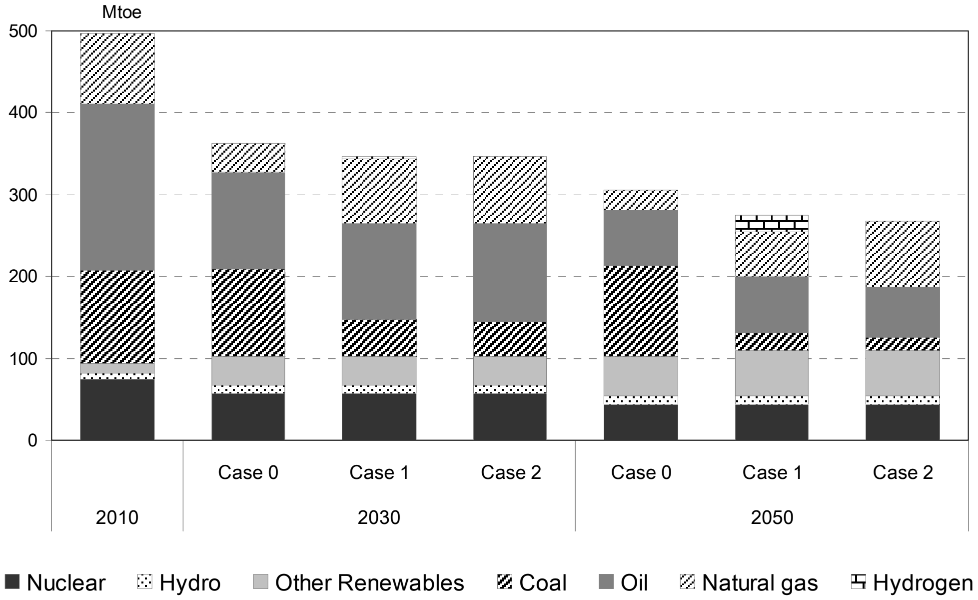
Case 0: A case in which hydrogen introduction is allowed and CO_2 constraints are not set
Case 1: A case in which hydrogen introduction is allowed and a target of reducing CO_2 by 65% from the 1990 level by 2050 is set as a CO_2 constraint
Case 2: A case in which hydrogen introduction is not allowed but a target of reducing CO_2 by 65% from the 1990 level by 2050 is set as a CO_2 constraint

3-1-1 Primary energy supply

The primary energy supply in each case is as shown in Fig.3-1. Even in Case 0, where CO_2 constraints are not set, the primary energy consumption will be reduced from 497 Mtoe in 2010 to 306 Mtoe in 2050, down 38%. In this case, cheap coal will be the major energy source. It should be noted that the dependence on coal will continue to increase from 2010, reaching 36% in 2050, which is much higher compared with Case 1 and Case 2 with CO_2 constraints (8% and 6% in 2050, respectively). On the other hand, the shares of oil and natural gas will decline from the 2010 levels, reflecting the rise in crude oil and LNG prices. In Case 0, the introduced amount of nuclear will be 44 Mtoe in 2050, and that of renewables (excluding hydro) will be 48 Mtoe in the same year. Hydrogen is not introduced in this case.

In Case 1 and Case 2, where CO_2 constraints are set, the amount of primary energy consumption in 2050 will be 275 Mtoe (down 45% from 2010) and 267 Mtoe (down 46% from 2010), that is, 10% and 13% below the level in Case 0, respectively. In these cases, energy conservation will be promoted extremely strongly to ensure compliance with the tough restrictions on CO_2 emissions. In addition, while the share of natural gas will rise to 19% and 30% respectively from 17% in 2010, the shares of oil and coal will decline significantly. This reveals that fuel switching will take place to meet the CO_2 constraints. In Case 1, hydrogen will start to be introduced gradually in 2030, and 21 Mtoe (81.6 billion Nm^3) of hydrogen will be introduced in 2050. Almost all of this will be introduced to the power sector.

Fig.3-1. Primary energy supply

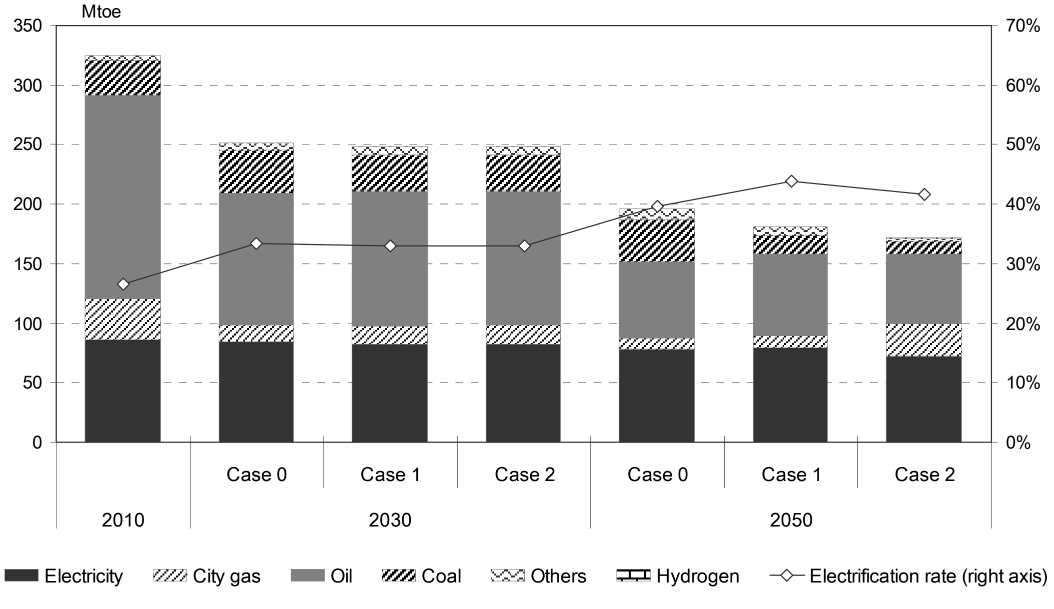


3-1-2 Final energy consumption

The final energy consumption in each case is as shown in Figure 3-2. Compared with the final energy consumption of 325 Mtoe in 2010, the consumption in 2050 will decline to 197 Mtoe in Case 0 (down 39%), 180 Mtoe in Case 1 (down 45%), and 173 Mtoe in Case 2 (down 47%). While the consumption of fossil fuel including petroleum products and city gas will decrease significantly from 2010 to 2050, electricity will not decrease substantially because low-carbon electricity will be utilized to reduce CO_2 emissions. As a result, the electrification rate in the final energy consumption in 2050 will increase from 27% in 2010 to 40% in Case 0, 44% in Case 1, and 42% in Case 2. It should also be noted that the electrification rate will be higher in Case 1 and Case 2 than in Case 0 without CO_2 constraints.

The introduced hydrogen amount in the final consumption sector is ignorably small, and fuel cell vehicles will barely be introduced in Case 1. This is attributed mainly to the high prices of fuel cell vehicles. As Table 2-4 shows, the price of a fuel cell vehicle is assumed to be 33,200 dollars in 2050 in this estimate. It was found in an additional analysis that if this price drops to 70% by 2050, 6.7 billion Nm^3 of hydrogen will be introduced to the transport sector.

Fig.3-2. Final energy consumption

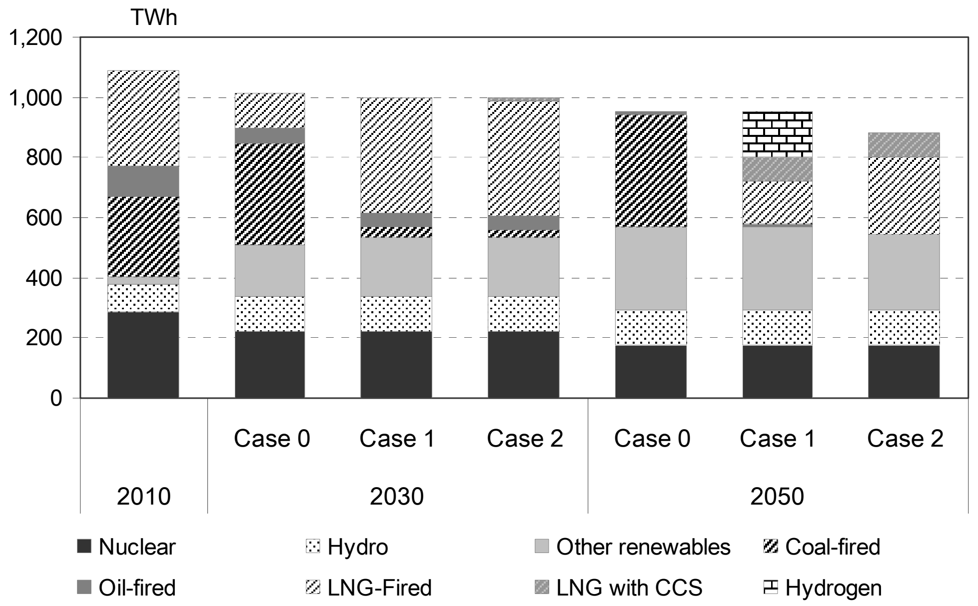


3-1-3 Amount of power generation

Fig.3-3 shows the breakdown of power generation in each case. The amount of power generated from nuclear and renewables is almost equal for all the cases because their assumed introduced amount is fixed, while the breakdown of the others, all of which are thermal power generation, differs among the cases. In Case 0, in which there are no CO_2 constraints, the amount of coal-fired power generation will increase, and its share will increase from 24% in 2010 to 39% in 2050. Meanwhile, in Case 1 and Case 2 with CO_2 constraints, the amount of coal-fired power generation will be zero in 2050, and LNG-fired power generation (with/without CCS) will be introduced instead. Coal CCS will not be introduced from the viewpoint of minimizing the cost.

The amount of hydrogen power generation in Case 1 will be 151 TWh, which will account for 16% of the total power generation in 2050. On the other hand, stationary fuel cells (to which hydrogen is supplied directly as fuel; hereafter referred to as “direct hydrogen”) will not be introduced. This reflects the difference in the price per power plant capacity between hydrogen power generation and stationary fuel cells (direct hydrogen). However, as stationary fuel cells (deemed hydrogen), which are inferior to large-scale natural gas thermal power generation in terms of economies of scale, have actually begun to become more widespread with policy support, stationary fuel cells (direct hydrogen) are likely to become common in the future depending on the conditions from the viewpoints of the overall energy use efficiency and value of the fuel cells as a distributed power system. In this study, the amount of power generated from stationary fuel cells (deemed hydrogen) is 51 TWh, which will constitute 5% of the total power generation in 2050.

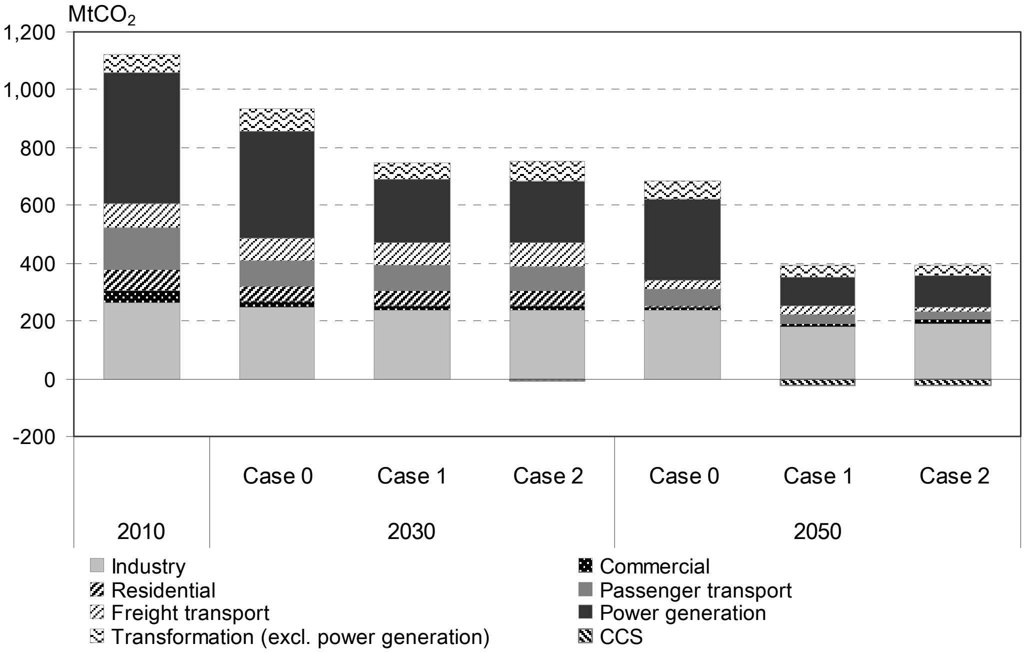
Fig.3-3. Power generation mix



3-1-4 Amount of CO_2 emissions

Fig.3-4 shows the prospects of energy-related CO_2 emissions. In Case 0, where there are no CO_2 constraints, the amount of CO_2 emissions will decline significantly from the 2010 level, down 39% to 683 Mt in 2050. Factors behind this trend include the reduction of energy consumption and the mass introduction of renewable energy power generation, which are also assumed in Case 0. In Case 1 and Case 2, CO_2 emissions will be reduced significantly in the power sector to achieve the tough CO_2 reduction targets. In Case 1, the reduction target is achieved by using hydrogen-fired power generation. In Case 2, hydrogen cannot be used, so the reduction target is achieved by saving power, without increasing thermal power generation. Accordingly, the difference between these cases in CO_2 emissions in the power sector is as small as 10 Mt.

Fig.3-4. Energy-derived CO_2 emissions



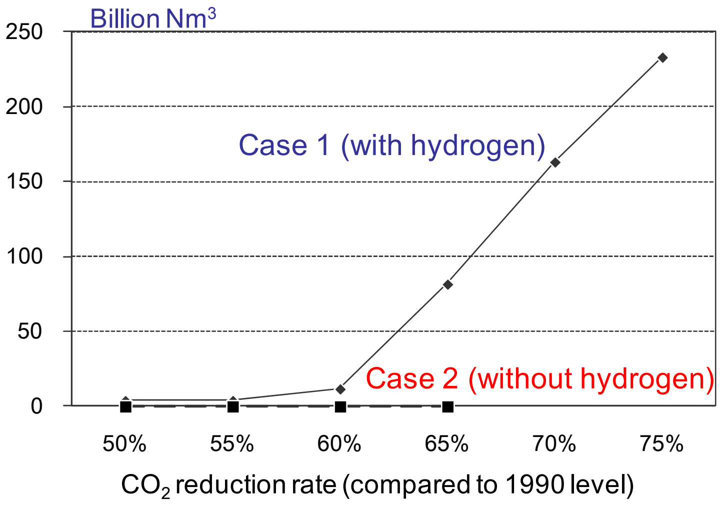
3-2 Sensitivity analysis based on CO_2 reduction targets

In this section, cases with CO_2 constraints that were analyzed in the previous section 3-1 (Case 1 and Case 2) are analyzed to see how the introduced hydrogen amount, carbon price, and amount of energy-related investments in 2050 will change when the values of the constraints (reduction target based on 1990 level) are changed.

3-2-1 Introduced hydrogen amount

Fig.3-5 shows the introduced hydrogen amount in 2050 in cases with CO_2 reduction targets. The tougher the reduction targets, the more hydrogen will be introduced. While the introduced hydrogen amount is 81.6 billion Nm^3 in the case of a 65% reduction, the amount increases to 233 billion Nm^3 with a 75% reduction. In this calculation, the problem could not be solved in the case of an 80% reduction for either Case 1 or Case 2.

Fig.3-5. Introduced hydrogen amount in 2050

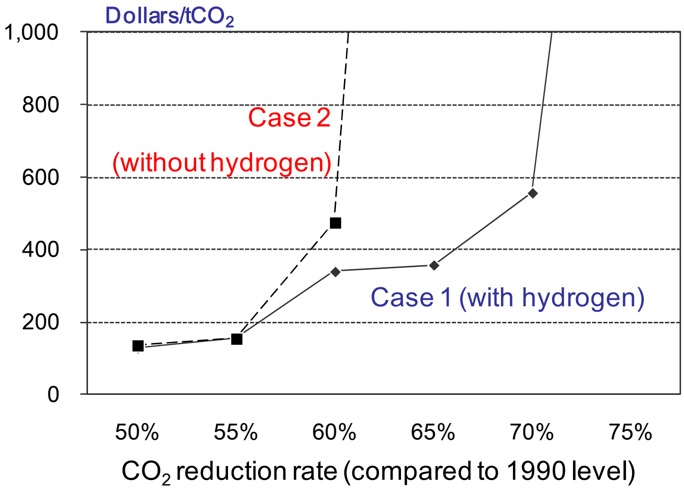


3-2-2 Carbon price

Fig.3-6 shows carbon prices in 2050 (2000 prices) in the cases with CO_2 reduction targets. In Case 2, where the introduction of hydrogen is not assumed, a higher carbon price will be necessary than in Case 1, where the introduction of hydrogen is assumed, and the difference in the price between the two cases grows greater as the reduction targets become tougher. Where a 65% reduction is targeted, the price is 359 dollars/tCO_2 in Case 1, while it is 4,107 dollars/tCO_2 in Case 2. In the case of a 75% reduction, the carbon price in Case 1 amounts to 2,713 dollars/tCO_2.

The carbon price starts to increase rapidly at a 75% reduction or above in Case 1 and at a 65% reduction or above in Case 2. This means that the reduction measures set in the model almost reach their upper limits at these levels, and measures with extremely low economic efficiency, which can even be said to be unrealistic, will be required for further CO_2 reduction. However, the measures' upper limits depend partly on the various assumed potentials of the introduced amounts, including the introduced amount of renewables. Accordingly, it must be noted that a carbon price corresponding to a particular reduction rate is not absolute, but fluctuates significantly depending on changes in the preconditions.

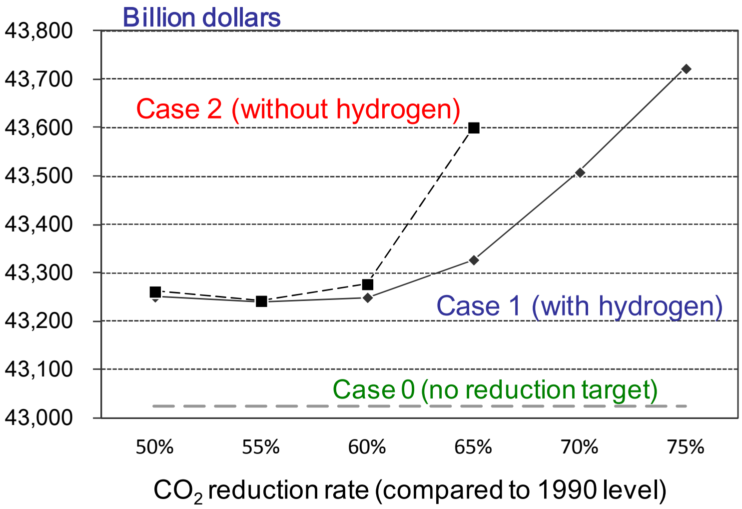
Fig.3-6 Carbon prices in 2050



3-2-3 Amount of energy-related investments

Fig.3-7 shows the accumulated amount of energy-related investments to be made by 2050 (2000 prices). The tougher the CO_2 reduction target is, the greater the accumulated amount of investments grows. The investment amount differs only slightly between the cases with and without hydrogen introduction if the target reduction rate is 60% or below. If the rate is 65%, however, the amount of investment in Case 2 is much greater than that in Case 1. This is because relatively expensive equipment with high energy-saving performance will be introduced to meet the given energy service demand and achieve the tough CO_2 reduction target without introducing hydrogen to the energy system.

Fig.3-7. Accumulated amount of energy-related investments to be made by 2050



4. Conclusion

This study assessed the possibility of hydrogen introduction in Japan in the period through 2050, by assuming the use of hydrogen imported from overseas ("CO_2-free" hydrogen). If an ambitious target is not set toward 2050, the introduction of hydrogen is difficult to expect from the viewpoint of cost minimization. On the other hand, if an ambitious target of a 65% reduction from the 1990 level is set, and if there is a restriction on the introduced amount of CCS, a mass introduction of hydrogen, which amounts to tens of billions of Nm^3/year, will be made mainly for hydrogen-fired power generation.

In this study, under the standard conditions, LNG with CCS is more cost-competitive than hydrogen-fired power generation, and therefore CCS is selected from the viewpoint of cost minimization in case where the introduction amount of the CCS is not restricted. Actually, however, the selection depends on the relationship between the import price of LNG and that of "CO_2-free" hydrogen, as well as the cost of CCS. Considering the risk of a price hike of fossil fuels resulting from soaring energy demand in developing countries and the uncertainty regarding the amount of CCS that can be introduced to thermal power plants in Japan, the use of hydrogen will be an important option, both for ensuring energy security and for securing means of achieving the CO_2 reduction targets.

The value of hydrogen as a future energy option should be defined properly with a long-term view extending to 2050. In relation to this, we need to proceed with research and development consistently in the all aspects of supply, transportation, and demand. As the future of the energy policy is difficult to forecast so far, future strategies need to be considered objectively and dispassionately with future uncertainty kept in mind at all times.

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