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Energy modeling on cleaner vehicles for reducing CO_2 emissions in Japan

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Abstract

This study is to evaluate the impact of cleaner vehicles on energy systems and CO_2 emissions in the transportation sector in Japan. The transportation sector has the characteristic of spending petroleum. Even when the cost of petroleum rises, conventional vehicles cannot switch fuels to alternative energy right away. Cleaner vehicles, such as fuel cell vehicles, would be one of the alternative technologies in the transportation sector. It is supposed to have excellent performance in fuel efficiency and has strong possibility to reduce CO_2 drastically. This paper uses a multi-period market equilibrium model to explore the impacts of cleaner vehicles on the passenger transportation sector in Japanese energy system out to the year 2040. A Btu tax is tentatively imposed to evaluate the effect of fuel cost on energy consumption in the transportation sector. Financial parameters such as capital cost and operating cost are considered to summarize the profit in taxation case. The result of this study shows that fuel cell vehicles have a great effect on reducing CO_2 emissions especially when Btu taxes are imposed, which in turn has the advantage of encouraging a more diverse set of technologies and fuels. The analysis that petroleum consumption can be reduced using fuel cell vehicles will have effects on perspectives on energy systems in Japan.

Keywords: Energy model; Hybrid vehicles; Fuel cell vehicles; Carbon emissions; Energy taxes

1. Introduction

The fact that vehicles emit 90% of carbon emissions in the transportation sector suggests that additional changes in transportation are needed to meet the Kyoto Protocol. Albeit the Kyoto Protocol has called for substantial reductions in the emissions of carbon from the world's energy systems, it is ambiguous how these reductions should be achieved. Each country has its own unique considerations of energy resources, economic demand patterns, and energy security concerns. Thus, the best strategy in energy policy for each country will be different based on the situation of energy security and economic potential.

In this paper possible policy approaches for Japan are examined. There are two questions that must be addressed for Japan: First, how can the energy system be configured to meet future CO_2 constraints, Second: what sort of policies could be used to encourage the system into new configurations? The possible policies must be evaluated in light of their potential cost, emissions of the greenhouse gasses, and implications for strengthening Japan's energy security.

The CO_2 emission in the transportation sector occupies 23% of the total CO_2 emission in Japan. Ninety percent of CO_2 emission in the transportation sector comes from motor vehicles. The government contemplates that CO_2 emission in the transportation sector will increase every year, showing the highest increase rate in energy sectors in Japan. For this reason, we need to reduce CO_2 emission in the transportation sector to meet the Kyoto protocol. An improvement in fuel efficiency is one of the effective measures to control CO_2 emissions.

The transportation sector has the characteristics of mostly using petroleum. Electric trains are powered indirectly from a variety of energy sources; however, their share of energy consumption in the transportation sector was no more than 2.3% in Japan in 1998. Even

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when the cost of petroleum rises, conventional vehicles cannot switch immediately to alternative energy sources. Hybrid vehicles, though still using gasoline as a fuel, could be one alternative technology in the transportation sector. Such vehicles have excellent fuel efficiency and a strong likelihood of drastically reducing CO_2 emissions [1–4]. We studied the impact of hybrid vehicles on energy systems in Japan and showed their positive effect on reducing CO_2 emission [5].

Fuel cell vehicles could be another alternative technology in the transportation sector. Fuel cell technologies is enabling automobile, electrical equipment and portable power production manufactures to develop environmentally clean products. The fundamental component of these end-use products is fuel cell that combines hydrogen (which can be obtained from methanol, natural gas, petroleum or renewable sources) and oxygen (from air) without combustion to generate power. Motor companies were plunged into a hard struggle to develop fuel cell vehicles promptly [6–12].

Fuel cell vehicles use hydrogen as an energy carrier and hydrogen can be directly made from gas or indirectly reformed via methanol. A market penetration scenario is studied for both hydrogen-fueled vehicles and methanol-fueled vehicles by using cost analysis [13]. Fuel options for fuel cell vehicles are examined [14–19]. Gasoline-fueled fuel cell vehicles are also under development [20]. Alternative fuels and changes in fuel consumption are examined [21–24]. However, it is unclear how fuel cell vehicles will impact on the total reduction of CO_2 emissions. The first point that requires clarification is a switch in energy from petroleum to gas in the transportation sector. The second point in this study is an economic aspect of future energy systems with or without fuel cell vehicles.

This paper is intended as a study of analyzing the future passenger transportation in Japanese energy systems. An energy-economic model is introduced to find the impacts of practical use of fuel cell vehicles on energy consumption and CO_2 emission in the transportation sector. First, the impact of fuel cell vehicles in reducing CO_2 emission is examined. It would be helpful not only for decision-makers but also for engineers to realize the economic and environmental impact of the taxes which are proposed. Then, a Btu tax is hypothetically imposed to evaluate the effect of fuel cost on energy consumption in the transportation sector and on CO_2 emission emissions. Financial parameters such as capital costs and operating costs are considered to estimate the profits for taxation purposes. The effect of factors such as capital investments, resource depletion, and the market penetration of advanced technologies were included, in addition to a multi-period modeling of the price-quantity equilibrium in various markets. The impact of regulatory policies involving devices such as taxes on emissions or constraints on quantities and prices has been modeled.

2. An energy model and input conditions

An energy economic model for evaluating CO_2 emissions policies should incorporate energy technologies, economics, and environmental impacts. Technology innovation and its efficiency improvement are factors that should be included for this model as well.

There are several modeling approaches available in energy economics based on either optimization or equilibrium approaches shown in Table 1. The METANet economic modeling system developed at the Lawrence Livermore National Laboratory [27] has been used for this study.

METANet is a partial equilibrium modeling system that allows for explicit price competition between technologies, and can constrain or tax emissions. It allows a user to construct an energy model as a network of processes such as end-uses (price sensitive demand), markets (allocating market shares based on relative prices), conversion processes (computing inputs required to meet output requirements based on efficiencies, and computing prices based on capital and operating costs), and resources (which can be exhaustible, or can follow a set price track). The system takes the model descriptions and computes the multi-period price-quantity equilibrium. Various policy actions such as subsidies and taxes can be represented in the model. It accounts for resource exhaustion over time and for the addition and eventual retirement of increments of capacity in the conversion nodes.

Fig. 1 shows the outline of the Japan model. It has 74 processes; includes eight demand nodes in the industrial, commercial, residential and transportation sectors; and contains nine resource nodes modeling purchases of coal, natural gas, petroleum and nuclear fuel on the world markets, along with domestic hydropower and other renewables. Additional processes model electrical services, transportation services, and the conversion of fuels to heat. Necessary operating parameters such as capital costs and operating costs are used based on the current references [30–32].

There are a variety of fuel supply systems for possible use in fuel cell vehicles. The main point in fuel is how to supply hydrogen fuel from fossil fuels or H_2O through electrolysis reaction. In this study, gas is chosen as a source of hydrogen fuel to evaluate the impacts of fuel switch from petroleum to gas in the transportation sector. Accordingly, the node of fuel cell vehicles is designed in the transportation sector directly connected from a gas market node.

There are several key assumptions that drive any analysis of this type. These include growth rates, govern-

Table 1
Comparison of METANet to existing modeling approaches

Modeling technologies	Tools	Developer	Feature
Fixed coefficient model	LEAP[a]	Tellus Institute	All impacts and inputs are set in a fixed ration to the out put required
Technology based market model	MARKAL[b]	BNL	Rigid structure of linear programming
Technology based market model	METANet[c]	LLNL	Solves the economic equilibrium problem directly
General equilibrium model	Second generation model[d]	PNL	World scale modeling
General equilibrium model	GREEN[e]	OECD	World scale modeling

[a] Based on Lazarus et al. [25].
[b] Based on Lydick et al. [26].
[c] Based on Lamont [27].
[d] Based on Edmonds et al. [28].
[e] Based on Lee et al. [29].

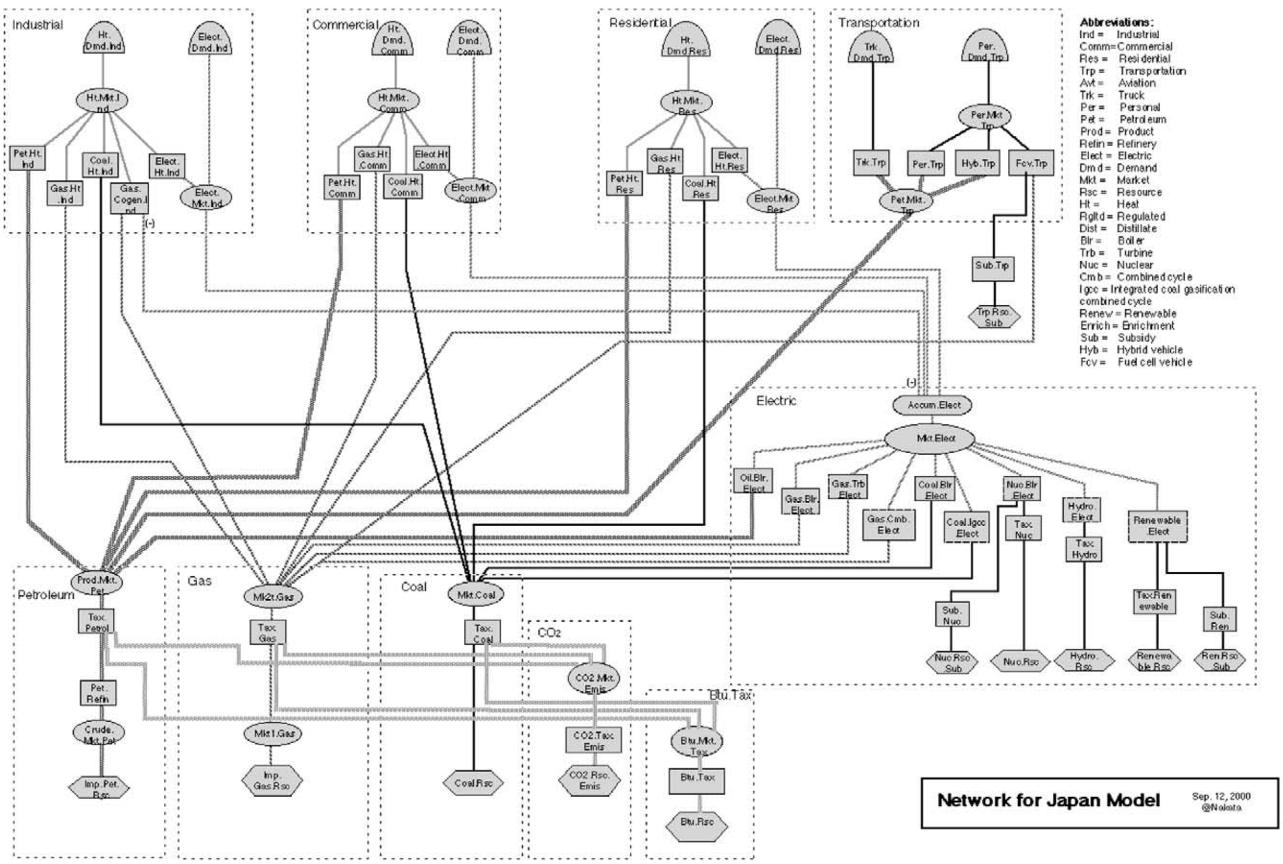

Fig. 1. Network for Japan model.

ment policies to encourage particular technologies, and demand responses to changes in price. A moderate rate of growth over the model horizon is assumed. Assumptions about the growth and demand elasticities in each sector are shown in Table 2. Because the energy share of aviation is less than five percent, aviation energy is not included in the transportation sector in this study.

Technology assumptions for the electricity sector are set as follows: Hydropower is set at a constant generation quantity because of physical constraints. Oil-burning power plants are subject to maximum quantity constraints according to the IEA agreement just after the first oil embargo. It is assumed that nuclear power plants will maintain the generating capacity of 1995 constantly until 2040, contemplating government concerns. Coal gasification combined cycle will become available in 2005 and are assumed to be put to maximum generating capacity, augmenting by eight percent every year com-

Table 2
Growth rate end elasticity assumptions for end-use sector

Process	Abbreviated name	Annual demand in starting period	Annual rate of demand growth (at a constant price)[a]	Demand elasticity[b]
Industrial heat demand (mmBtu/yr)	Ht.Dmd.Ind	5.10E+09	0.002	−0.34
Industrial electricity demand (mmBtu/yr)	Elect.Dmd.Ind	1.24E+09	0.007	−0.34
Commercial heat demand (mmBtu/yr)	Ht.Dmd.Comm	9.00E+08	0.012	−0.24
Commercial electricity demand (mmBtu/yr)	Elect.Dmd.Comm	6.64E+08	0.014	−0.24
Residential heat demand (mmBtu/yr)	Ht.Dmd.Res	1.10E+09	0.006	−0.30
Residential electricity demand (mmBtu/yr)	Elect.Dmd.Res	7.37E+08	0.017	−0.30
Truck transportation demand (Ton-km/yr)	Trk.Dmd.Trp	2.14E+08	0.003	−0.17
Personal transportation demand (passenger-km/yr)	Per.Dmd.Trp	6.43E+08	0.010	−0.23

[a] Based on Energy Data and Modeling Center [34].
[b] Based on data supplied by Nagata [35].

mencing in 2005. It is assumed that the maximum electric power generation by renewable energy will reach 2.24E+7 mm Btu in the year 2010 (MITI [33]), which will increase fifteen percent every year.

3. Analyzed energy scenarios

First in this study, a reference case analysis was developed to model the expected resource use, emissions, and investments in energy technologies in the absence of policy actions. In this case, it is assumed that a maximum capacity of hybrid vehicles increases by 15% every year commencing in 2000. Fuel cell vehicles will become available in 2005 and are assumed to be put to maximum capacity, increasing by 15% every year commencing in 2005. Based on the reference the performance factors of vehicles are shown in Table 3. It is assumed that the fuel of fuel cell vehicles is produced from gas directly or indirectly. We use the averaged data for fuel costs, capital costs and fuel efficiency in this study.

The next step was to model the effect of Btu taxation with a goal of a reduction of CO_2 by the year 2040. A variety of approaches to reduce energy-related emissions of CO_2 and other greenhouse gases are possible. A Btu tax is expected to be one of the most efficient approaches to reduce carbon emissions [36]. Under the term of The Kyoto Protocol, Japan would agree to reduce their carbon emissions by 6% below 1990 levels, corresponding to a 22–25% reduction from projections for 2010 [34]. This study focuses on a target rate of reductions of around 20% of CO_2 emissions by the year 2040 since reaching the target in 2010 appears to be difficult and might not be realistic for Japan. We then determined the level of tax needed to reach the required level of carbon emissions in the year 2040. In the taxation case, the Btu tax was assumed to be imposed in increments, starting at zero in the first period and then rising by a fixed amount in each subsequent period until reaching the target amount of the tax. This approach avoids the sudden shock to the system and the stranded assets that can result from rapid market changes.

This study evaluated several different tax rates to determine the rate that would achieve the target reduction in the year 2040. Both cases—with and without Btu tax—were extrapolated to explore the difference in fuel prices. Since the share of energy consumption in

Table 3
Performance of vehicles

Type of passenger vehicles	Fuel cell[a]	Hybrid[b]	Conventional[c]	Fuel cell/conventional	Hybrid/conventional
Specific capital cost \$/(mmBtu/Yr)	1031	824	687	1.5	1.2
Ancillary operating cost \$/mmBtu	34.33	27.46	34.33	1.0	0.8
I-O coefficient (mmBtu/k passenger mile)	1.1927	1.431	3.578	0.33	0.4

[a] Based on Thomas et al. [13].
[b] Based on Hybrid Car PRIUS [38].
[c] Based on Energy Data and Modeling Center [34].

the transportation sector is 25.2% in Japan, one-quarter of total tax revenue is assumed to be returned to the node of fuel cell vehicles to deprecate its price. A sensitivity analysis was conducted to confirm the reliability of this model [37].

4. Results of the analysis

The first result concerns the composition of passenger vehicles up to the year 2040 for the different scenarios. The graph in Fig. 2 shows the changes in kilo-miles in passenger vehicles in the transportation sector for the reference case. The long tail of increase is easily expressed in the figure showing the total passenger miles. Only the conventional vehicles show a decline in output commencing the year 2005 until 2020. A sharp increase in hybrid vehicles and fuel cell vehicles are made clear. The share of conventional vehicles, hybrid vehicles and fuel cell vehicles in the year 2040 reach 44.2%, 45.7% and 10.1%, respectively.

Fig. 3 shows the changes in energy consumption in the passenger transportation sector for the reference case. Since the fuel efficiency of hybrid vehicles and fuel cell vehicles is higher than that of conventional vehicles, total energy consumption by these advanced vehicles is smaller than that of conventional vehicles. Trucks, which don't have any alternative technologies, show a constant increase in energy consumption up to the year 2040.

The impacts of Btu tax rates on the reduction of CO_2 emission are plotted in Fig. 4 with or without tax returns to fuel cell vehicles. The tax was introduced gradually over time, increasing the tax rate in uniform steps in each period until the maximum rate was reached in 2040. It was found that a tax rate of \$2.0/mm Btu case produced an emission rate of 324 mm TC in the year 2040, achieving a reduction of 23% in the emission rate, since our previous study shows that CO_2 emission in 2040 would be 420 mm TC without having any fuel cell vehicles [39]. Without tax return in this case, CO_2 emission rises to 332 mm TC, producing an 8 mm TC production compared with the tax return case.

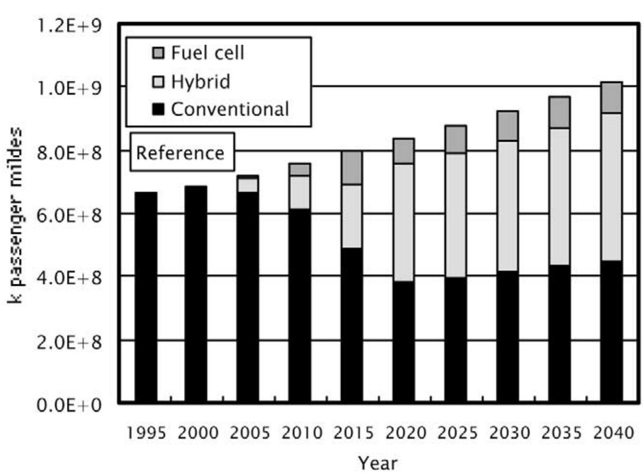

Fig. 2. Changes in passenger miles in the transportation sector (Reference case).

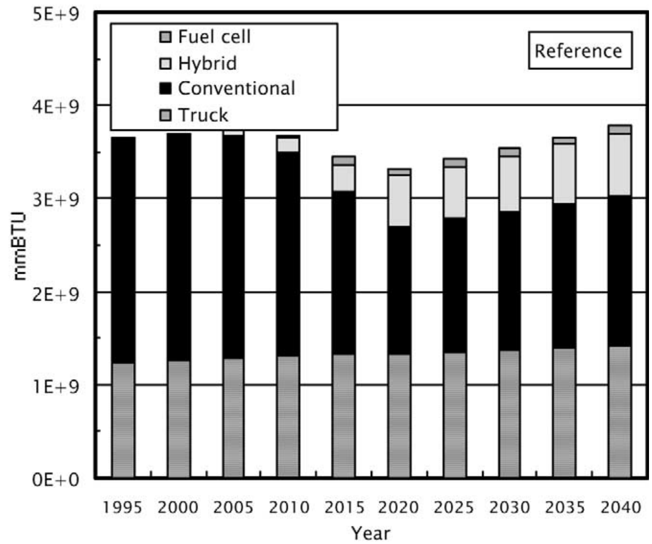

Fig. 3. Changes in energy consumption in the transportation sector (Reference case).

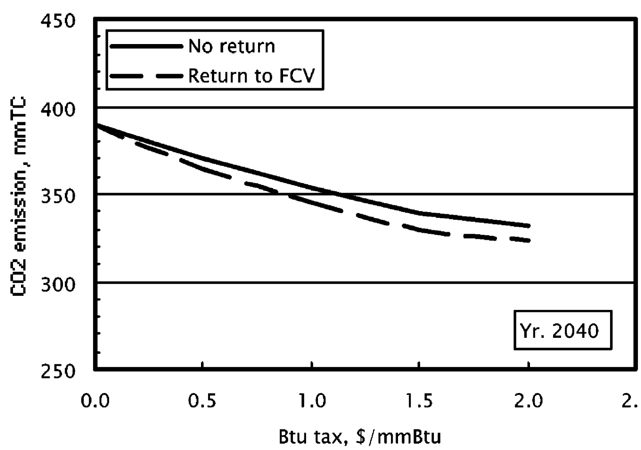

Fig. 4. Impact of Btu taxation on the reduction of CO_2 emissions with or without returns.

Figs. 5 and 6 shows the changes in energy consumption in the passenger transportation sector for the Btu tax cases, \$1.0/mm Btu and \$2.0/mm Btu, respectively. Higher Btu tax results in promoting fuel cell vehicles instead of conventional vehicles in passenger transportation. In particular, tax rate of \$2.0/mm Btu case implies drastic changes in passenger transportation toward fuel cell vehicles. The shares of fuel cell vehicles in the year 2040, then, reach 32.8% and 83.5%, respectively.

The CO_2 emissions in the year 2040 from the transportation sector for the three scenarios are represented schematically in Fig. 7. The differing volumes of carbon emissions are plotted in the bar graph. The reference case shows the maximum CO_2 emission emitted from

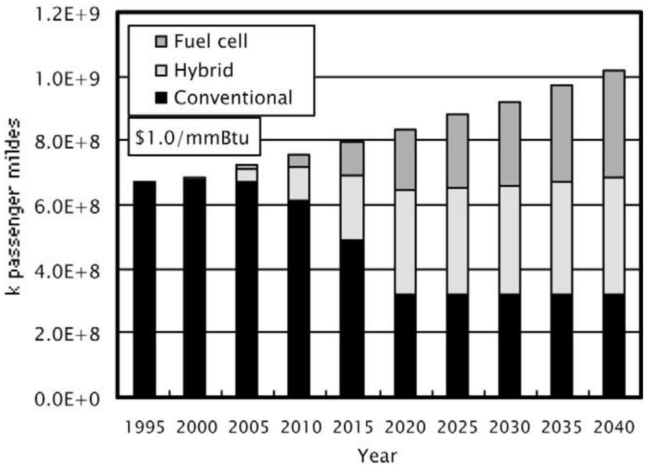

Fig. 5. Changes in passenger miles in the transportation sector ($1.0/mm Btu case).

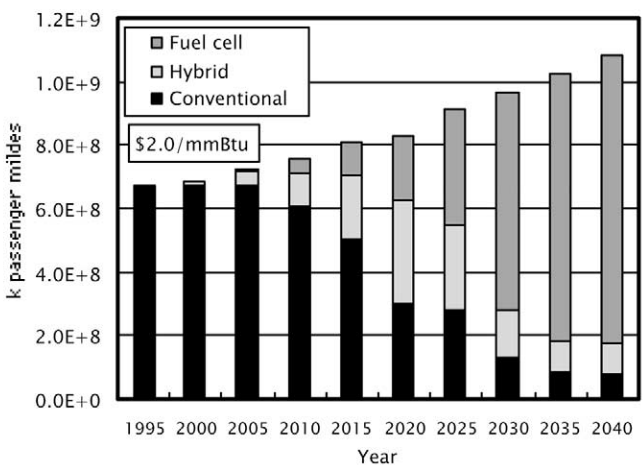

Fig. 6. Changes in passenger miles in the transportation sector ($2.0/mm Btu case).

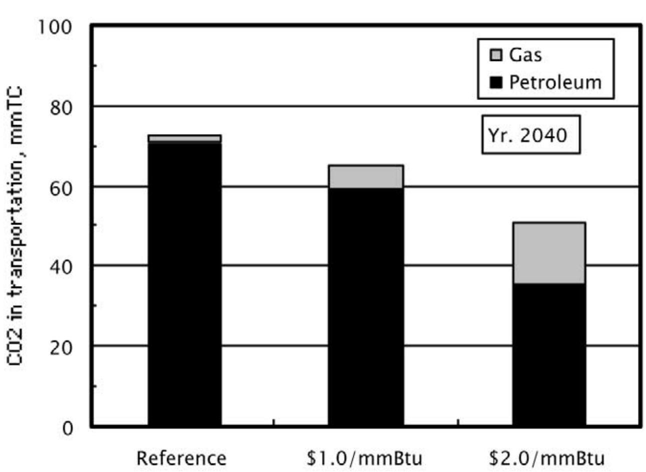

Fig. 7. Estimated CO_2 emission in the transportation sector in 2040 for the three scenarios.

petroleum consumption. In the Btu tax cases, it is clear that CO_2 emission from petroleum consumption decreases, leading the increases CO_2 emission from gas. If we contemplate the Btu tax of $2.0/mm Btu case in this figure, we will see that total CO_2 emission in the transportation sector decreases by 30%, leading possible approaches to meet the extended Kyoto Protocol after 2010.

Fig. 8 shows the comparison of estimated cost per kilo passenger miles for conventional, hybrid and fuel cell vehicles with or without returns from Btu tax in the year 2040. Without tax returns, the estimated price of fuel cell vehicles shows highest in passenger vehicles, resulting in weak competitiveness in the market of passenger transportation. With tax returns, on the contrast, the estimated price of fuel cell vehicles lowers to the level of the other vehicles, leading increases in the share of fuel cell vehicles in passenger transportation.

In any cases in our study, petroleum is still a main emission source in the transportation sector. The constraint of CO_2 emission with Btu taxes promotes the energy shift from petroleum to gas. Fuel cell vehicles hence contribute greatly toward the reduction in CO_2 emission in passenger transportation. Some of the uncertainties we must notice related to implement of fuel cell technology are (1) regional or nation wide infrastructure for supplying fuel for fuel cells, (2) incremental innovation in traditional technologies such as lean burn combustion engine and the other unexpected changes, and (3) the way of returning the Btu tax revenues to promote environmental sound technologies.

5. Conclusions

This study shows the impact of introducing fuel cell vehicles in the passenger transportation sector on energy systems in Japan using an energy-economy model. The analysis indicated (1) the changes in shares for passenger

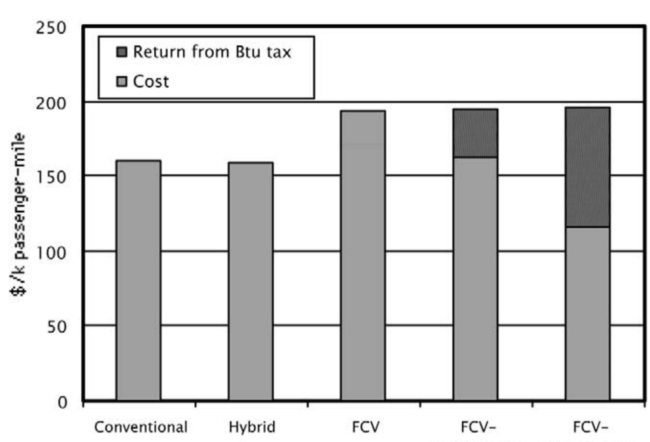

Fig. 8. Cost comparison for passenger vehicles

cars, (2) increase in the number of fuel cell vehicles, and (3) the reduction in CO_2 emission as a result. The Btu taxation is effective for accelerating the changes in the vehicles' market, leading a drastic reduction of CO_2 emission. We have outlined the way in which energy system is modified to suit each cases such as fuel cell vehicles and the Btu taxation.

To sum up the major characteristics of the transportation sector, a reduction in conventional vehicles and increases in hybrid and fuel cell vehicles are of most significance as follows:

- As fuel cell vehicles are introduced into the passenger transportation market, the share of conventional vehicles decreases proportionally, leading to a decrease in CO_2 emissions.
- Btu taxation has a positive impact on switching fuels from coal to gas, which results in reducing CO_2 emission. In the transportation sector, higher fuel prices will promote a shift by consumers from conventional vehicles to hybrid and fuel cell vehicles.
- Another consideration is the expected technology innovation of fuel cell vehicles. In this study, hybrid and fuel cell vehicles are only seen in the passenger transportation sector, as an advanced technology in the freight sector is not yet on the horizon. If future technology were to enable the use of fuel cell vehicles in the freight sector, decreased petroleum consumption could lead to drastic reductions in CO_2 emission.
- Although there is still some uncertainty about the development of fuel cell vehicles in the future, the results of this analysis implies possible options in the direction of energy security policies to meet the Kyoto protocol.

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