The Potential of Alternative Fuel Vehicles: A Cost-Benefit Analysis

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Abstract

This study investigates the economic validity of the diffusion of fuel cell vehicles (FCVs) and all-electric vehicles (EVs), employing a cost-benefit analysis from the social point of view. This research assumes the amount of NOx and tank-to-wheel CO_2 emissions and gasoline use reduction as the benefits and the purchase costs, infrastructure expenses, and maintenance costs of alternative vehicles as the costs of switching internal combustion engine (ICE) vehicles to alternative energy vehicles. In addition, this study conducts a sensitivity analysis considering cost reductions in FCV and EV production and increasing costs for CO_2 abatement as well as increasing gasoline prices. In summary, the results show that the diffusion of FCVs is not economically beneficial until 2110, even if the FCV purchase cost decreases to that of an ICE vehicle. EV diffusion might be beneficial by 2060 depending on increases in gasoline prices and CO_2 abatement costs.

Key words: Fuel cell vehicle; Electric vehicle; Cost benefit analysis; Sensitivity analysis

1. Introduction

Climate change is one of the most serious challenges of the 21st century. To avoid dangerous climate change, a variety of greenhouse gas (GHG) mitigation actions must be taken in all sectors of the global energy system. The International Energy Agency (IEA) indicated that the road transport sector accounted for approximately 17% of energy-related CO_2 emissions in 2007 and is likely to have a higher share in the future unless strong action is taken (IEA, 2009). Furthermore, if a 50% decrease in 2005 energy-related CO_2 emissions is to be achieved by 2050, the transport sector will be required to make a significant contribution. However, we should acknowledge that transport's large economic role and its significant influence on daily life will make the required rapid changes more difficult to achieve (IEA, 2000, 2008).

It is therefore critically important to develop a long-term, cost-effective strategy for reducing CO_2 emissions from the transport sector. In the past, the Japanese government implemented a number of environmental policies to move from gasoline-fueled to more efficient vehicles, such as hybrid and plug-in hybrid vehicles. As a result, the number of these alternative, efficient vehicles is increasing. In addition, the Japanese government currently claims that 2 million all-electric vehicles (EVs) and 5 million hydrogen fuel cell vehicles (FCVs) will be on the road in Japan before 2020 (METI, 2001, Ministry of the Environment, 2009). These two types of alternative vehicles do not have tailpipe greenhouse gas emissions[1]; therefore, EVs and FCVs, alternatives to conventional vehicles based on the internal combustion engine (ICE), have the potential to greatly reduce the emissions generated by the transport sector.[2] In addition, the Japanese government has been offering subsidies to purchasers of EVs for years to boost the sales of EVs, and a number of local governments are offering additional subsidies that could reduce the purchase price of EVs (see also Ito et al., 2013; Kagawa et al., 2013). The main objectives of these policies are to provide incentives to early adopters and to speed the implementation of pilot programs for verifying EV and FCV technology developments.

However, no previous study has determined when these new technologies will become economically and technologically beneficial for society by considering future energy prices, carbon prices and technological progress. The targets for the numbers of EVs and FCVs were not provided by previous studies because of their characteristics, such as short mileage per battery charge, high production costs and high purchase prices. Although car sharing services and rent-a-car businesses were introduced to resolve these issues, the targeted user's lifestyle and transport patterns were not matched with those services[3]. Thus, this study analyze whether the large-scale use of FCVs and EVs

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[1] EV vehicles are accounted for in Corporate Average Fleet Emissions in Europe. So including extra EV's in the fleet allows for more emissions by normal vehicles. (Massiani & Radeke, 2013)

[2] Clearly, for comparing CO_2 emissions from each type of vehicle, well-to-wheel (WTW) analysis should be used. This analysis is combined with well-to-tank (WTT) life cycle analysis and tank-to-wheel (TTW) analysis. The WTT of a petroleum-based fuel pathway includes all steps from crude oil recovery to final finished fuel. TTW analysis includes the actual combustion of fuel in a motor vehicle for motive power.

[3] Benefits from car sharing are based partly on the conversion of auto ownership from fixed to variable costs. Because drivers pay for shared cars by the hour or day, the economic efficiency of auto use can be improved by reducing the costs of maintenance, parking for drivers. Thus, EV sharing programs could contribute to reducing users' costs.

in Japan is justified from a socially economic perspective employing cost-benefit analysis, and, if so, under what conditions.

This paper first present an overview of earlier studies regarding EVs and FCVs diffusions. The following section outlines the structure of the cost-benefit and sensitivity analyses and the key assumptions in our scenarios[4]. The results of the scenarios are discussed in Section 4. Lastly, we conclude this study in Section 5.

2. Previous contributions

There is large body of literature calculating social net benefits costs (Hahn, 1995; Kazimi, 1997a, b; Funk and Rabl, 1999; Lave and MacLean, 2002; Managi, 2012; Massiani and Radeke, 2013; Somanathan et al., 2014). For example, Hahn (1995) discussed the cost-effectiveness of several measures to improve environmental quality in the transport sector. This results show that improved fuel qualities and tighter air pollution standards are more cost-efficient than an introduction of battery-driven electric cars. Kazimi (1997a, b) estimated the environmental benefits of introducing EVs in U.S. by using a micro-simulation model and his results show that large price reduction of alternative-fuel vehicles would not be socially beneficial. Massiani and Radeke (2013) also assess the EV policies considering the various technological, behavioral and economical mechanisms that govern the

[4] The data used in this paper are represented in the Appendix.

possible diffusion of EV in Germany by using a simulation tool. This study conclude that most of EV supporting policies have a negative outcome.

Although most of them find negative social benefits, Paolo (2007) noted that much more analysis examining the comprehensive components that affect the diffusion of alternative vehicles is needed. Therefore this study conducts a sensitivity analysis considering three components related to the benefit and cost for FCV and EV diffusion. First component is cost reduction in FCV and EV production. Second component is increasing CO_2 abatement costs. Last component is increasing gasoline prices.

Regarding the infrastructure setting, this paper use the data obtained from national reports on the two alternative vehicle types and interviews with car manufactures in Japan (New Energy and Industrial Technology Development Organization; NEDO, 2007). As well as the earlier studies, this studies determine the hydrogen or electric demand after assuming the number of FCVs or EVs on the road, the distance travelled and the vehicles' fuel efficiency (McKinsey, 2010, Jonathan et al., 2011). By examining alternative vehicle diffusion, this study contributes to environmental research, development and the definition of adequate transport policies.

3. Method

3-1. Cost-benefit analysis

This paper employs a Cost-Benefit Analysis (CBA) to evaluate the validity of FCV and EV diffusion from the social point of view. CBA is useful for determining the benefits of a project from an economic standpoint. In our study, the differences between net present value between benefit and cost is used as a welfare measures. In addition, this study conducts a sensitivity analysis considering cost reduction in FCV and EV production and increasing CO_2 abatement costs and gasoline prices.

3-1-1. Benefits

The reductions in NOx and CO_2 emissions and reduced gasoline use are considered as benefits that result from replacing ICE vehicles with alternative vehicles. For comparing CO_2 emissions from each type of vehicle, well-to-wheel (WTW) analysis should be used.[5] However, WTW analysis requires the total amount of CO_2 emissions in each step of the fuel and electricity production pathways. In our analysis, considering all the necessary information appears difficult owing to data unavailability. Thus, our research employs tank-to-wheel CO2 emissions in order to simplify our scenarios.

The benefits of replacing an ICE vehicle with an alternative vehicle *m* (i.e., an FCV or EV) in year *t* is calculated as follows:

$$B_{t,m} = \sum_{p} ER_{t,p,m} \times price_{t,p} \quad (1)$$

[5] This analysis is combined with well-to-tank (WTT) life cycle analysis and tank-to-wheel (TTW) analysis. The WTT of a petroleum-based fuel pathway includes all steps from crude oil recovery to final finished fuel. TTW analysis includes the actual combustion of fuel in a motor vehicle for motive power.

ER indicates the amount of reduction in CO_2 and NOx emissions and in gasoline use. In the case of CO_2 and NOx, *price* represents the marginal abatement cost. In the case of gasoline, *price* indicates the price of gasoline per liter. Therefore, the benefit $B_{t,m}$ is represented as the sum of each *ER* multiplied by the reducing cost for each material *p* (i.e., CO_2, NOx and gasoline).

The amount of reduction of each pollutant *p* and each type of vehicle *m* in year *t* is determined in Eq.(2):

$$ER_{t,p,m} = AV_{t,m} \times \left(E_{p,ice} - E_{p,m}\right) \times TD \qquad (2)$$

The number of alternative vehicles (*AV*) indicates the number of ICE vehicles replaced by alternative vehicles from 2011 until *t*, i.e., the number of alternative vehicles used in year *t*. $E_{p,ice}$ and $E_{p,m}$ represent the emission per kilometer for pollutant *p*, for ICE vehicle *ice* and alternative vehicle *m*, respectively. *TD* represents the annual distance traveled per year.

Therefore, the total benefit (*TB*) is calculated by the sum of these components, i.e., reduced CO_2 and NOx emissions and gasoline use. The discounted present value of the benefit is then calculated and evaluated at 2011 prices. *TB* of type *m* alternative vehicle is defined as follows:

$$TB_m = \sum_{t=2011}^{T} \exp\left\{-i \times (t-2011)\right\} \times B_{t,m} \qquad (3)$$

In Eq.(3), *T* shows the target year for the diffusion of 5 million alternative vehicles, and *i* indicates a discount rate of 4%. The reason that 5 million is the diffusion target is explained in key assumption section.

3-1-2. Cost

The cost of replacing an ICE vehicle with alternative vehicle *m* (i.e., FCV or EV) in year *t* is calculated as follows:

$$C_{t,m} = C_{t,m,infrastructure} + C_{t,m,vehicle} \quad (4)$$

Costs, $C_{t,m}$, is divided into two components. $C_{t,m,infrastructure}$ consists of the construction and operating costs for the infrastructure needed for alternative vehicle diffusion. $C_{t,m,vehicle}$ indicates the difference between the sum of the purchase and operating costs of an alternative vehicle m compared with an ICE vehicle and is estimated in Eq.(5):

$$C_{t,m,vehicle} = (C_{t,m,prodution} - C_{t,ice,prodution}) + (C_{t,m,running} - C_{t,ice,running}) \quad (5)$$

Therefore, the total cost (*TC*) is calculated based on the sum of each cost and is discounted to arrive at a present cost evaluated at 2011 prices. The *TC* of alternative vehicle type *m* is defined as follows:

$$TC_m = \sum_{t=2011}^{T} \exp\{-i \times (t-2011)\} \times C_{t,m} \quad (6)$$

From Eq.(3) and Eq.(6), the net present value (*NPV*) can be estimated as follows:

$$NPV_m = TB_m - TC_m \quad (7)$$

3-1-3. Key Assumptions

This study assumes that the total cost, i.e., *TC* in Eq.(6), is the sum of the differences between the purchase and operating costs for alternative vehicles versus those for ICE vehicles and the construction and operating costs of the needed infrastructure. On the other hand, the total benefit, i.e., TB in Eq.(3), is the sum of the expected reductions of CO_2 and NOx emissions and gasoline consumption from replacing an ICE vehicle with an alternative vehicle. This study estimates the NPV for each case of alternative vehicle diffusion (FCV or EV).

We assume that the target years for the diffusion of 5 million FCVs (EVs) are set from 2011 to 2020, 2060, or 2110, and those target years are referred as the *Short, Middle*, and *Long targets*. In our calculation, we assume that the number of ICE vehicles replaced with FCVs (or EVs) is constant over time. Therefore, the numbers of vehicles replaced per year are different for each target year. This implies that if the target year is 2060, the number of replacement vehicles is 100,000 per year. The replacement number per year is 500,000 for the 2020 case and 50,000 per year in the case of a 2110 target date. The closer the target year, the more alternative vehicles are produced per year.

In the FCV distribution scenario, we assume that hydrogen is made in a hydrogen purification plant (HPP) where hydrogen is made by the electrolysis of water using the electricity generated by a nuclear plant. Nuclear-generated electricity does not pollute the atmosphere with greenhouse gas emissions as does a thermal electric power plant. Renewable energy-generated electricity, such as wind or solar power, cannot generate sufficient electricity to provide the amount of hydrogen needed to refuel FCVs. The hydrogen produced in HPPs is transported by hydrogen transport truck from the HPP to a hydrogen refueling station (HST) where users can refuel their FCVs. The number of trucks is calculated using the number of HSTs and the distance from the nearest HPP.

The FCVs are assumed to be distributed in each prefecture according to the number of gas stations in each prefecture and the number of HSTs. The capacity of the HPPs is determined by the demand for hydrogen in the last usable year of the HPP, i.e., if the number of usable years is t, the capacity is defined based on the hydrogen demand after t-1 years.

In the case of EVs, the driver can recharge the battery at a recharging station (RST) using a fast charger.[6] The number of fast chargers is one per charging station. The number of fast chargers needed is estimated by calculating the battery recharging time, mileage per charge, annual vehicle mileage, and number of distributed EVs in each year. We assume that the annual mileage of alternative vehicles is the same as that for ICE vehicles based on interview results[7]. The ICE infrastructure cost is not included in the cost calculations because this study assumes the additional cost from switching to an alternative vehicle from an ICE vehicle as the infrastructure cost.

3-2. Sensitivity analysis

3-2-1. Sensitivity to technology

In this study, three sensitivity factors are considered. The first factor is technological progress. We consider the reduced costs for EV batteries and FCV production using the exogenous

[6] This research does not consider the battery damage by using the fast charger.
[7] As we explain later, the data used in this paper are based on a survey of one of the largest automobile companies in Japan. The characteristics of each type of vehicle listed in Table A-1 were obtained from the same company, and the assumptions we set are also based on that survey.

technical progress ratio by learning curve. The learning curve (or experimental curve) is a model that describes the human activity of accumulating knowledge or experience by cumulative production and is typically adapted to industrial production processes. The typical learning curve is described as follows:

$$Y_i = AX_i^{-r} \tag{8}$$

where X_i is the cumulative number of products at ith production, Y_i is the product cost at ith production, and A is constant[8].

Because the number r in the exponent is difficult to understand, a simpler expression is introduced as a progress ratio: ($F=2^{-r}$). F shows how the production cost could be reduced each time cumulative production is doubled. F=90% implies that the cost is reduced to 90% each time the cumulative production volume is doubled. Development of FCVs and EVs is needed to apply advanced technology as well as to adapt existing ICE technology. Therefore this paper applied the progress ratio exogenously to calculate the production costs for FCV and EV batteries in order to consider the cost reductions attributable to the cumulative production[9]. In our research, the EV and FCV purchase costs are assumed to be twice the production costs.

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[8] In earlier studies, learning curve models are used to forecast the unit prices of many kind of goods. For example, Shinoda et al. (2011) show that the historical track record of price and cumulative production volumes of the small Li-ion batteries used for cellular phones or PCs fits well with function based on a learning curve. The initial costs of SO_2 and NOx control systems in thermal power plants also follow this function (Rubin et al., 2004).

[9] If historical cost data was available, we could estimate the progress ratio F by regression analysis. However, there is no previous research that estimates the F of FCV production costs and EV battery costs.

Fig. 1 and Fig. 2 show the relationship between FCV and EV cumulative production and purchase costs, respectively, where three types of progress ratios are considered. The *Lower progress* scenario implies that the cost reduction attributable to cumulative production is the smallest in all scenarios. The purchase costs of the 5 millionth FCV and EV are approximately $90,000 and $39,000, respectively. The costs decrease by approximately $132,000 and $12,000 from the initial FCV and EV purchase costs, respectively. The *Realistic progress* scenario indicates that the purchase costs of the 5 millionth FCV and EV converge to the target value of the automobile company we interviewed, which is approximately $56,000 and $30,000 per unit, respectively. The last scenario is the *Higher progress* scenario, in which the purchase costs of the 5 millionth FCV and EV decrease to $21,000 per unit.

The progress ratio we applied in the *Lower*, *Realistic*, and *Higher progress* scenarios are 0.96, 0.94, and 0.90, respectively, for the FCV diffusion scenario and 0.98, 0.96, and 0.92, respectively, in the EV diffusion scenario.

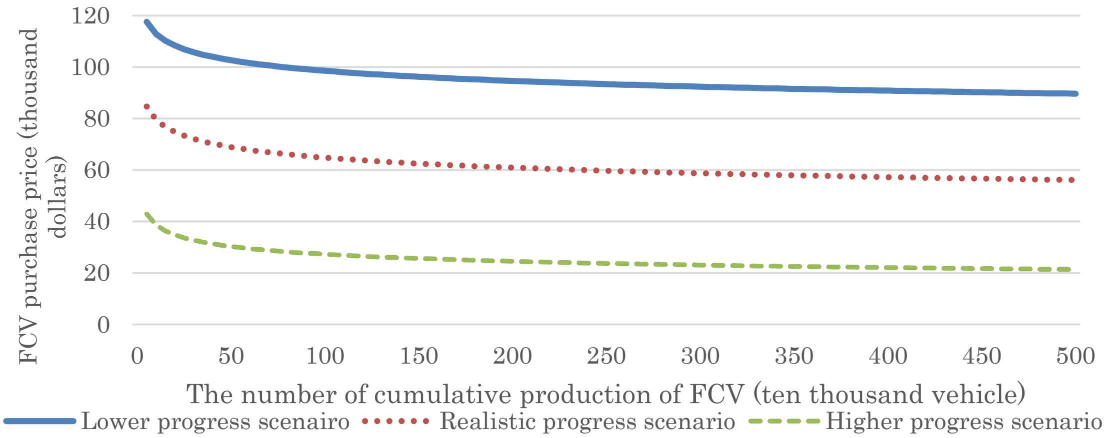


Fig. 1 FCV purchase prices considering progress ratios

The progress ratios in the *Lower*, *Realistic*, and *Higher progress* scenarios are 0.96, 0.94 and 0.90, respectively. That is, in the *Lower progress* scenario, the FCV purchase price decreases 4% when the production doubles.

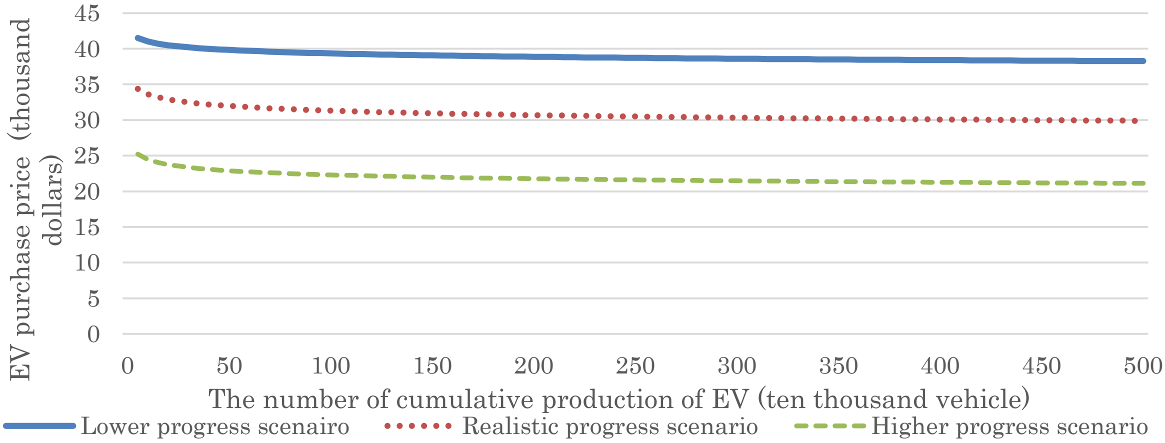


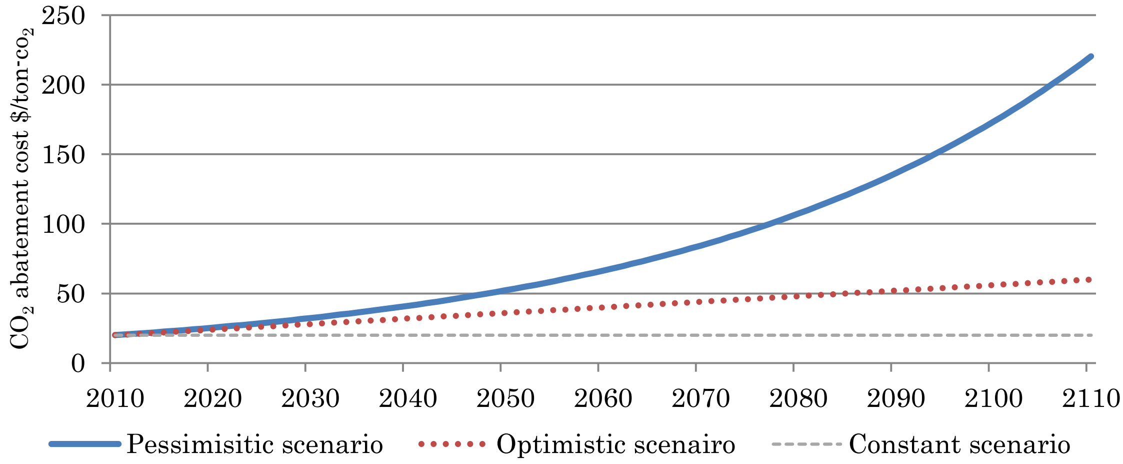
Fig. 2 EV purchase price considering progress ratios

The *Lower*, *Realistic*, and *Higher progress* ratios are 0.98, 0.96 and 0.92, respectively.

3-2-2. Sensitivity to the marginal cost of CO_2 abatement

The second sensitivity analysis focused on the marginal cost of CO_2 abatement. There is no certainty about future CO_2 prices. Therefore, we assume three CO_2 price scenarios for simplicity (see Fig. 3). The first scenario maintains the 2010 European Union Emission Trading Scheme (EU-ETS) CO_2 emission price. The EU-ETS is the largest cap-and-trade scheme in the world, regulating roughly half of EUs CO_2 emissions. The caps for 2020 are set at 21% below 2005 emissions. The first and second ETS trading periods have already passed, and the third trading period is from 2013 to 2020. Covered entities receive European emission allowances (EUAs). For each allowance, they can emit 1 ton of CO_2. If their CO_2 emissions exceed their number of allowances, a factory can purchase EUAs from other installations or countries. Conversely, if an installation has performed well at reducing its carbon emissions, it can sell its leftover EUAs. Thus, we assume EUA prices as marginal costs for

CO_2 abatement. The price of an EUA in 2010 was approximately twenty dollars per ton of CO_2 (Talberg and Swoboda, 2013). The second scenario is Optimistic, and the third is Pessimistic. In the Optimistic scenario, the cost of CO_2 abatement increases approximately linearly (see Cline, 2004).



The Pessimistic scenario assumes that the cost of CO_2 abatement increases exponentially (see Manne, 2004).

Fig. 3 CO_2 abatement cost in each scenario

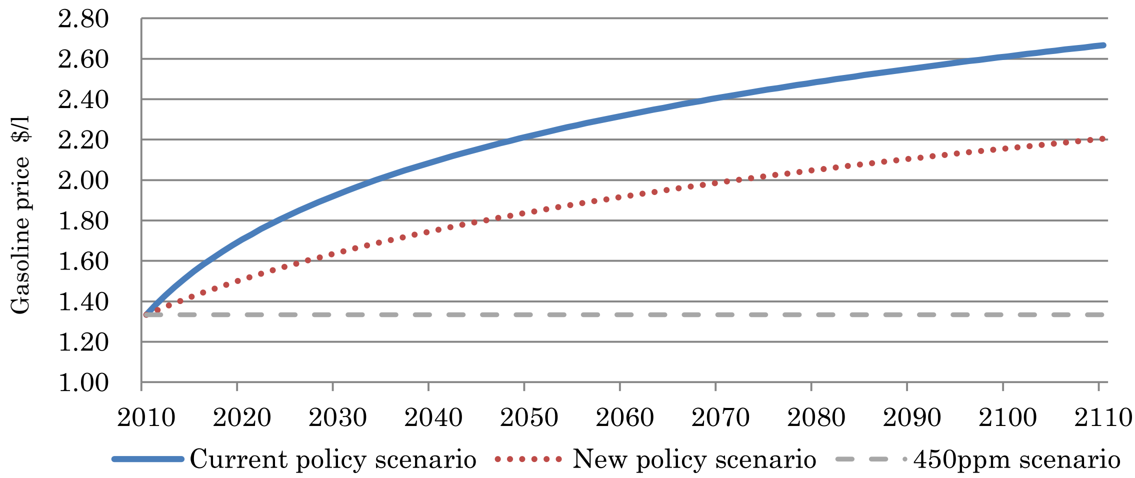


Fig. 4 Gasoline price in each scenario

3-2-3. Sensitivity to gasoline prices

The third sensitivity factor is gasoline prices. In our model, gasoline price is an important factor[10]. Similar to the CO_2 abatement price, we do not model the gasoline price using past data. Instead, the gasoline price trends are the same than in the three oil price scenarios provided by the IEA(2010). These gasoline prices are assumed as their real value after tax in Japan. The three scenarios are displayed in Fig. 4. The first is the *450ppm* scenario, which sets an energy pathway that is consistent with the goal of limiting the increase in average temperature to 2 degrees. This scenario shows the first price remaining steady at 1.35 dollars per liter. Note that this is the gasoline price scenario and it is independent from the carbon price scenario. The second scenario is the *Current* policy scenario. *Current* policy takes into consideration only those policies that had been formally adopted by mid-2010. In this case, the price of gasoline increases to approximately 2 dollars per liter by 2035. The last scenario is the *New* policy scenario. This scenario assumes the cautious implementation of recently announced commitments and plans, even if they are not yet formally adopted. The gasoline price in this scenario increases to approximately 1.7 dollars per barrel by 2035.

[10] Regarding diesel prices, the number of passengers using diesel vehicles was approximately 1.05 million in Japan, and their proportion of total passenger vehicles was only 1.8% in 2010. Thus, this paper did not consider diesel prices in this research.

4. Results and discussion

4-1. FCV diffusion scenario

4-1-1. A negative Cost Benefit Analysis outcome

Tables 2 show the NPV results for the 5 million FCV vehicle diffusion scenarios[11]. We do not find economic benefits for FCV diffusion under any scenario. The highest NPV is −19 billion dollar for the *Long target* with the *Current* policy gasoline price and *Higher progress* scenarios. In contrast, the lowest NPV is −416 billion dollar for the *Short target* under the *New* policy and *450ppm* gasoline price scenarios. Based on the CO_2 abatement cost scenario, the *Pessimistic* scenario has the highest NPV and the *Optimistic* scenario has the second highest. In the case of the gasoline price scenario, the *Current* policy scenario NPV is the highest, and the second highest is the *New* policy scenario.

4-1-2 Sensitivity analysis:

Fig. 5 shows the proportion of the cost components under the *450ppm* oil price scenario. This proportion is the amount that each single components accounts for the total cost after discounting in each scenario. The total cost was divided into seven components[12]. Our results indicate that the FCV purchase cost is the highest cost in all scenarios. The proportion of FCV in the *Lower progress* scenario for the *Short target* is approximately 80% and approximately 75% for the *Middle* and *Long targets*.

[11] The results for each FCV cost and benefit are displayed in Tables A-5 and A-6 in the Appendix.

[12] Because the CO_2 abatement cost does not influence the cost factors in the applied methodology, this figure does not describe the CO_2 abatement cost scenarios.

The *Lower progress* ratio is approximately 50% for the *Short target* and 40% for the *Middle* and *Long targets* in the *Higher progress* scenario.

Fig. 6 shows the proportion of the benefit components of FCV diffusion in the *450ppm* and *Current* policy gasoline price scenarios. In the *Constant* CO_2 abatement cost scenario under the *450ppm* scenario, the proportions of CO_2 emission and gasoline use reduction are approximately 2.2% and 97.5% in the *Long* and *Short target*s. In the *Current* policy scenario, the proportion of these components is approximately 1.8% and 98% in both the *Long* and *Short target* cases. Therefore, the contributions to the benefits of each of these two components do not differ greatly between the two gasoline price scenarios. In contrast, in the *Pessimistic* scenario under the *450ppm* scenario for the *Long target* case, the proportion of CO_2 emission reduction increases to 52% and gasoline use reduction decreases to 48%. Therefore the CO_2 emission reduction cost is the more important components for FCV diffusion, especially in the long term. Lastly, the amount of the benefit of NOx reduction effect is under 1% in all of the benefit components under all scenarios.

From these results, the diffusion of FCVs require a technological breakthrough in production because of the high production costs. Therefore, government support for R&D and fundamental research to reduce the costs of the main FCV parts are essential.

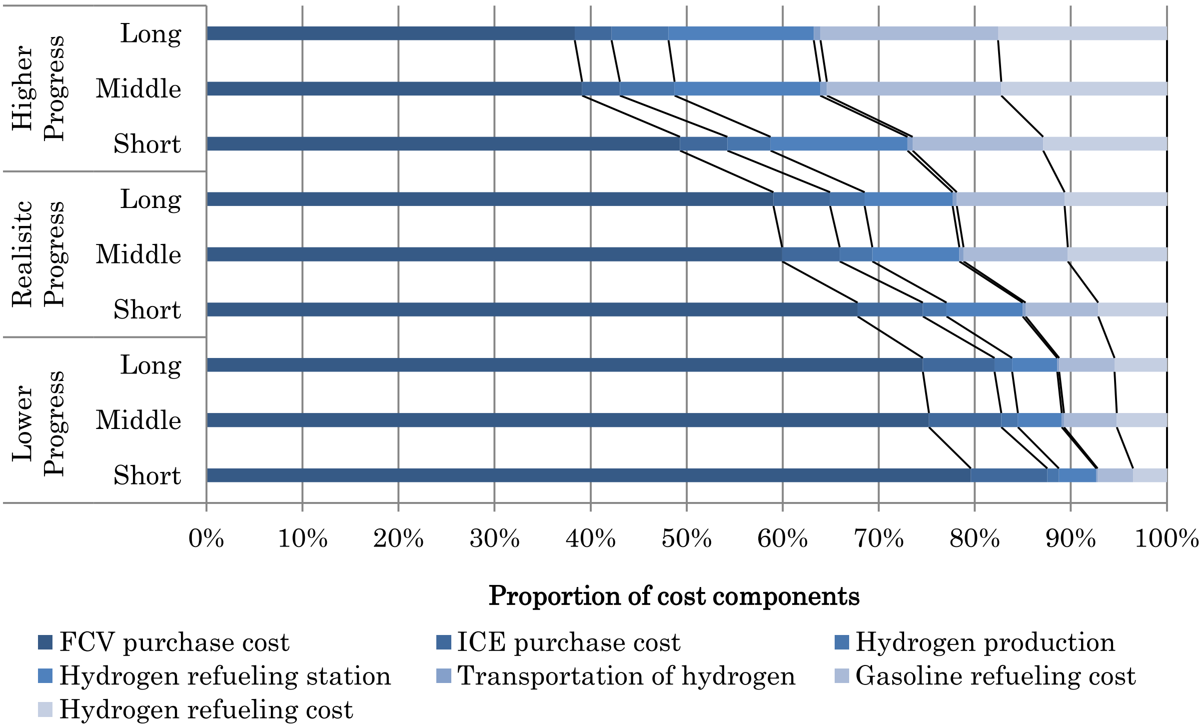


Fig. 5 The proportion of cost components for the FCV diffusion scenarios

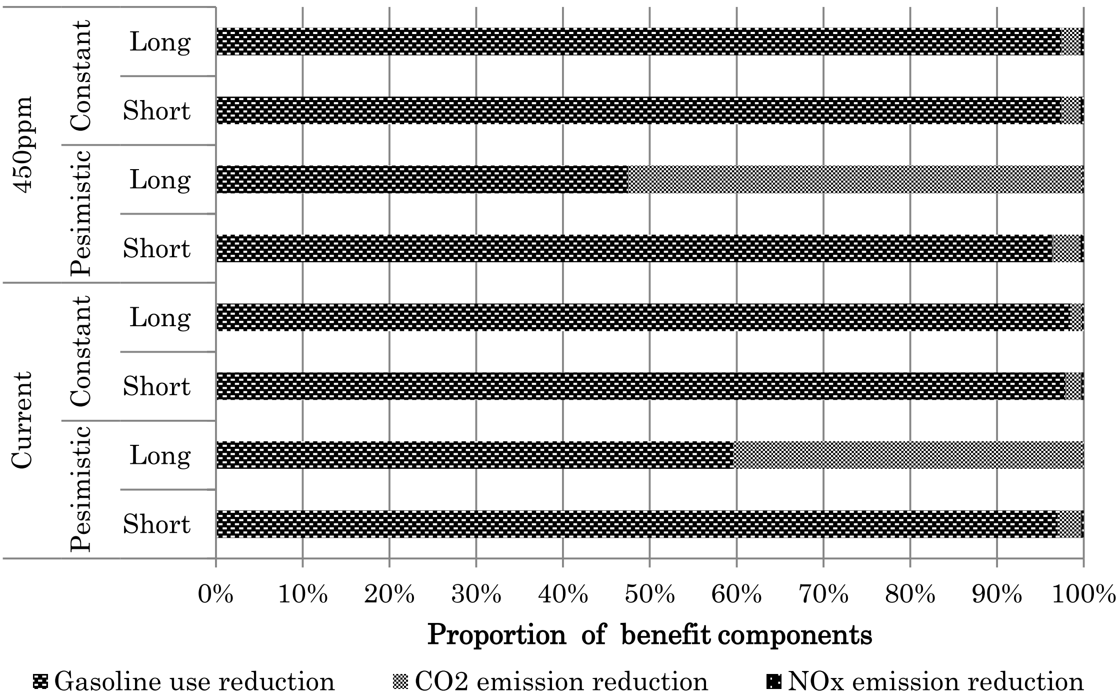


Fig. 6 The proportion of benefit components for the FCV diffusion scenarios

4-2. EV diffusion scenario

4-2-1.A positive Cost Benefit Analysis outcome in the *Long target*.

Tables 3 shows the NPV results for the 5 million EV vehicle diffusion scenarios[13]. In the EV diffusion scenarios, we find economic benefits, especially for the *Long target*. For the *Short target*, EV diffusion would be difficult under all scenarios. In the case of the *Middle target*, diffusion may be possible if both the gasoline price and CO_2 abatement cost increase and the purchase cost of an EV decreases to that of an ICE vehicle. For the *Long target*, if the gasoline price and CO_2 abatement cost increase, EV diffusion would be economically beneficial even if the EV purchase cost is higher than the target price of the automobile maker we interviewed.

4-2-2 Sensitivity analysis:

Fig. 7 shows the proportions of the cost components. The EV purchase cost share is the highest proportion in all scenarios and is 71.7% on average of total costs. In addition, there is little change in this share among scenarios; for example, 76.9% and 68.6% are the highest and lowest shares, respectively. The contribution to the total cost of ICE vehicle production is higher in the *Lower progress* compared with the *Higher progress* scenario, approximately 17% and 5% on average, respectively. The proportions of the EV charging station are approximately 0.4% and 0.8% in the *Lower* and *Higher progress* scenarios. Gasoline refueling cost accounts for 15.2% on average in all

[13] The results for EV cost and benefit are displayed in Tables A-7 and A-8 in the Appendix.

scenarios, 7.5 times more than the EV recharging cost on average. According to these results, EV purchase cost reduction has the most significant effect on EV diffusion.

Fig. 8 shows the proportion of benefit components for EV diffusion under the *450ppm* and *Current* gasoline price scenarios. These results are similar to the FCV results. Except for the *Long target* date under the pessimistic scenario, the proportion of gasoline use reduction is approximately 97.1% on average, and that of CO_2 emission reduction is approximately 2.6% on average in both scenarios. In contrast, the proportions of these two components under the *Pessimistic* scenario are 73.3% and 26.4% on average for the *Long* and *Short target* scenarios. For the *Long target* case under the *Pessimistic* scenario, the proportions of gasoline use reduction are 44.3% and 56.5% in the *450ppm* and *Current* policy scenarios, respectively. The proportions of CO_2 emission reduction are 55.5% and 43%, respectively. Therefore the effect of CO_2 emission reduction on NPV is significantly higher in the case of a CO_2 abatement cost increase. In addition, compared with the FCV case, the effect of a CO_2 emission reduction is higher than that of a gasoline use reduction because the amount of an EV's CO_2 emission in annual mileage is relatively lower than that for an FCV, i.e., 559 kg- CO_2 per year for an FCV and 425 kg- CO_2 per year for an EV. As in the FCV case, the amount of the benefit of NOx reduction is under 1% in all of the benefit components under all scenarios.

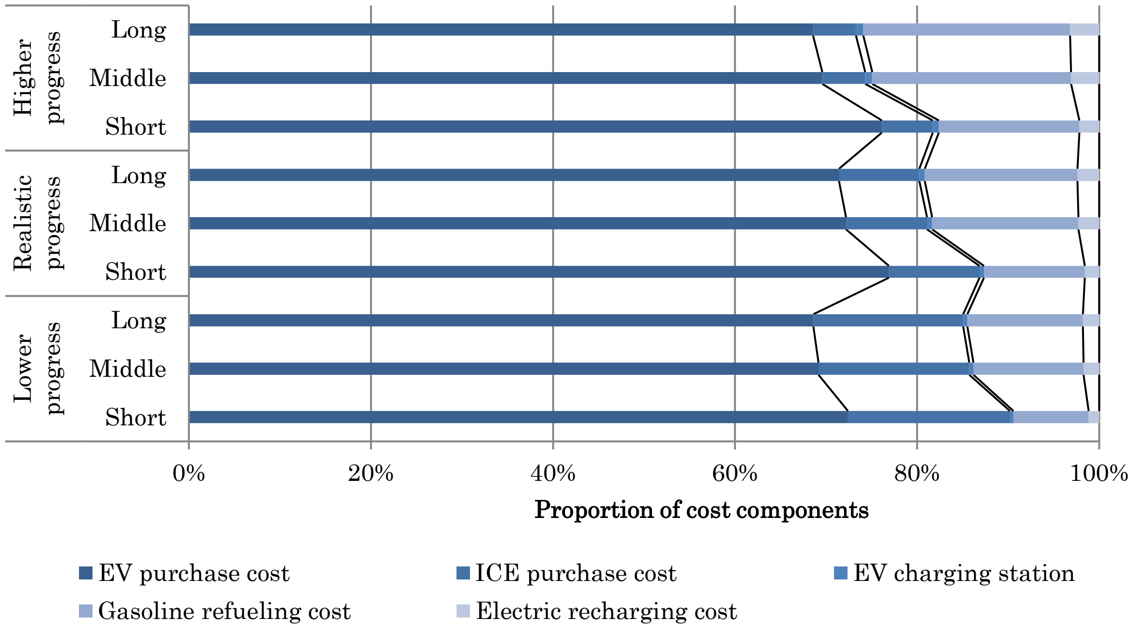


Fig. 7 The proportion of cost components for the EV diffusion scenarios

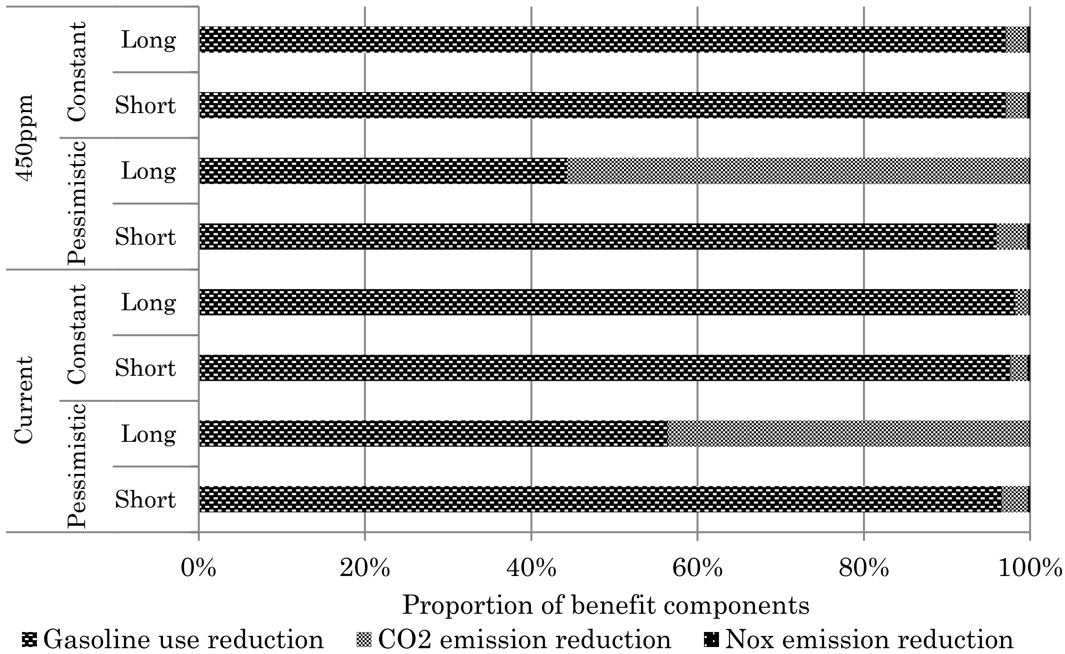


Fig. 8 The proportion of benefit components for EV diffusion scenarios

5. Conclusion and future work

The futures of both the automobile and the transportation system are of significant interest to a large audience. In this study, we investigate the economic benefits for FCV and EV diffusion by employing cost-benefit analysis from the social point of view. We obtained the data on two alternative fuel vehicles from an interview with an automobile maker in Japan. Considering uncertainties, we applied a sensitivity analysis to the NPV. These scenarios consist of the following: progress in the speed of alternative vehicle production, increased CO_2 abatement costs, gasoline price increases, and the target year for the alternative vehicle diffusion.

In summary, the results show that FCV diffusion is not economically beneficial in either the short or the long term, even if the FCV purchase cost decreases to that of ICE vehicle. In contrast, EV diffusion might be beneficial as soon as 2060, considering the increase in gasoline prices. The major obstacle to the widespread use of FCV is their high purchase (or production) costs. Therefore, innovation is needed to produce a significant cost reduction in FCV production. In addition, the government must promote the development of such fundamental technological progression. As in FCVs, the electric battery is one of the major obstacles to EV diffusion. Major technological progress is required to reduce the production costs and improve EV performance.

Finally, we consider the limitations of our study. First, this research is based on tank-to-wheel rather than well-to-wheel analysis. All of the CO_2 emissions considered in this research are the emissions associated with electricity generation for EVs and hydrogen production for FCVs in addition to fuel consumption for ICE vehicles. However, the fuel production process and its transportation for generating electricity, infrastructure construction and many other steps also emit CO_2. Therefore, in future work, well-to-wheel CO_2 emissions rather than tank-to-wheel should be examined in order to evaluate alternative vehicle options more comprehensively. The NPV of EVs and FCVs might decrease if the proportion of electricity generated by coal-fired or oil-fired plant increases. However, increasing the proportion of electricity generated by renewable energy such as wind, solar, and geothermal power might improve the NPV of EV and FCV. In Japan, huge losses in nuclear power capacity and increasing awareness of nuclear safety after the large earthquake have begun to cause changes in the power system structure and energy policy. Thus, WTW analysis could have useful implications for policy making.

Second, this research set strong assumptions, such as the assumption that the characteristics of all passengers are homogeneous and constant and there is no rebound effect of fuel efficiency changes. Needless to say, these are unrealistic assumptions. Additionally, the interaction between marginal CO_2 abatement cost and oil price should have been considered in our model, and other externalities associated with vehicle use such as PM2.5 and/or sound pollution should have been included in the benefit components.

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Table 2 The results of NPV for the 5 million FCV diffusion scenarios (Billion dollars)

Gasoline				*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
CO2				*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*
Progress ratio	*Lower progress*	Target year	Short	-361	-361	-361	-365	-365	-365	-369	-369	-369
			Middle	-377	-379	-382	-393	-394	-398	-411	-413	-416
			Long	-240	-257	-268	-254	-270	-281	-272	-289	-300
	Realistic Progress	Target year	Short	-234	-234	-234	-238	-238	-238	-241	-241	-242
			Middle	-228	-229	-232	-243	-245	-248	-262	-263	-267
			Long	-133	-150	-160	-146	-163	-174	-165	-182	-193
	Higher progress	Target year	Short	-95	-95	-96	-99	-99	-100	-103	-103	-103
			Middle	-69	-70	-74	-84	-86	-89	-103	-105	-108
			Long	-19	-36	-46	-32	-49	-60	-51	-68	-78

The first row indicates sensitivity to gasoline price, and it increases in order from the *Current* policy (i.e., high oil price) to the *New* policy (i.e., moderate oil price) and the *450ppm* (low oil price) scenarios. The second row displays the sensitivity to the marginal cost of CO_2 abatement, and it increases in order from the *Pessimistic* (i.e., high carbon price) to the *Optimistic* (i.e., moderate carbon price) and the *Constant* (i.e., low carbon price) scenarios.

Table 3 The results of NPV for the 5 million EV diffusion scenarios (Billion dollars)

Gasoline			*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
CO2			*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*
Progress ratio	*Lower progress*	Target year: Short	-60	-60	-60	-64	-64	-64	-68	-68	-68
		Middle	-18	-20	-24	-33	-35	-39	-52	-54	-58
		Long	24	5	-7	11	-8	-20	-8	-27	-39
	Realistic Progress	Target year: Short	-47	-47	-48	-51	-51	-52	-55	-55	-55
		Middle	-3	-4	-8	-18	-20	-24	-37	-39	-43
		Long	35	16	4	22	3	-9	3	-16	-28
	Higher progress	Target year: Short	-33	-33	-33	-37	-37	-38	-41	-41	-41
		Middle	14	12	8	-2	-4	-7	-21	-22	-26
		Long	47	28	16	34	15	2	15	-4	-16

The first row indicates sensitivity to gasoline price, and it increases in order from the *Current* policy (i.e., high oil price) the *New* policy (i.e., moderate oil price), and the *450ppm* (low oil price) scenarios. The second row displays the sensitivity to the marginal cost of CO_2 abatement, and it increases in order from the *Pessimistic* (i.e., high carbon price) to the *Optimistic* (i.e., moderate carbon price) and the *Constant* (i.e., low carbon price) scenarios. The shaded numbers indicate that the benefit is greater than the cost.

Appendix

A-1) Data

The specifications for FCV, EV, and ICE vehicles and EV recharging stations were obtained from interviews with one of the largest automobile manufacturing companies in Japan. These data are described in Table 1. The FCV fuel consumption is modeled as 13.6 km/Nm^3.The EV battery is modeled as a 10 km/kWh battery system with a 160 km range. This study model standard ICE vehicles as 15.5 km/l. The specifications for the HPPs, HSTs and hydrogen transport trucks are obtained from NEDO (2007). For the NOx reduction benefit, this study uses estimates from the European Union (National Environmental Technology Centre, 2002), which reports the marginal external cost of NOx in 15 EU countries, because there is no equivalent study in Japan. The lifetime and mileage settings are 10 years and 100,000 km per year, respectively, and that information is also based on a survey administered at one of the largest automobile companies in Japan. A report by the Ministry of Land, Infrastructure, Transport and Tourism (2005) showed that the annual mileage of private vehicles was on average 10,575 km and the lifetime of private vehicles was on average 11.0 years in 2004. Thus, this paper assumed that these differences do not impact the results. A discount rate of 4% is used to calculate the present value of both the benefit and the cost[14].

Table A-1 Characteristics of each vehicle type.

	Hydrogen fuel cell vehicle	Electric battery vehicle	Internal combustion engine vehicle
Purchase price (Thousand dollars)	222	51	22
Initial production cost (Thousand dollars)	111	25.6	11
Battery production cost (Thousand dollars)	-	17.8	-
Fuel consumption per km	0.074Nm^3/km	0.1kWh/km	0.645 l/km
Refueling/Recharging cost	1.1 \$/Nm^3	0.12 \$/kWh	1.3\$/l
CO2 emissions per fuel consumption	0.76 kg-CO_2/m^3	0.425 kg-CO_2/kWh	2.36 kg-CO_2/l
NOx emissions per km	0.00 g/km	0.00 g/km	0.05 g/km
Marginal external cost of NOx		5880\$/ton	
Lifetime		10year	
Discount rate		4%	
Running distance		10000 km/year	

Note: These values are based on our interviews with the automobile company.

[14] Regarding the public policy evaluation for transportation sector in Japan, 4% is adopted as a social discount rate based on the Technological Guidelines to Cost-Benefit Analysis published by the Ministry of Land, Infrastructure, Transport and Tourism (2009).

A-2) Hydrogen supply station

The number of hydrogen supply stations (HSTs) is defined as follows:

$$HST_t = H_{t,production} / CHST \qquad (A-1)$$

where $H_{t,production}$ indicates the amount of hydrogen production for refueling FCVs in year *t* and $CHST$ is the annual supply capacity of one HST. $H_{t,production}$ is estimated as follows:

$$H_{t,production} = NAV_{t,FCV} \times TD / FC_{FCV} \qquad (A-2)$$

As we mentioned in Section.2, $NAV_{t,FCV}$ refers to the net number of alternative vehicles (number of FCVs) in year *t*, and TD indicates the vehicle travel distance. FC_{FCV} represents the FCV fuel consumption.

A-3) Recharging station

As with HSTs, the number of recharging stations (RSTs) is defined as follows:

$$RST_t = E_{t,production} / CRST \qquad (A-3)$$

$E_{t,production}$ indicates the amount of electricity production for recharging EVs in year *t*, and $CRST$ is the annual charging capacity of one RST. $E_{t,production}$ is estimated as follows:

$$E_{t,production} = NAV_{t,EV} \times TD / EM_{EV} \qquad (A-4)$$

where $NAV_{t,EV}$ is the net number of EVs in year t. EM_{EV} is the EV electric mileage.

Initial and maintenance costs for HSTs and RSTs are displayed in Tables A-2 and A-3

A-4) Hydrogen purification plants

The initial and maintenance costs for HPPs in year t are estimated by the engineering model in Eqs.(A-5) and (A-6).

$$HPP_{t,initial\cos t}\left[dollar\right]=4.3\times\left(\frac{CHPP_t\left[Nm^3/h\right]}{0.9}\right)^{0.68} \qquad (A-5)$$

CHPP refers to the hydrogen purification plant capacity in each prefecture where a nuclear plant is located.

$$\begin{aligned} HPP_{t,ma\text{int}enance}\left[dollar\right] &= HPP_{t,initial}\left[dollar\right]\times(0.075+0.075\times Unit\ capacity\ factor\left[\%\right]) \\ &+CHPP_t\left[Nm^3/h\right]\times 3.54/0.826\times 365\left[day/year\right] \\ &\times 24\left[hour/day\right]\times \text{Electric power consumption }\left[\text{dollar/kwh}\right] \qquad (A-6) \end{aligned}$$

Eqs.A-5 and A-6 are obtained from an industry survey of an automobile manufacturing company in Japan.

A-5) Transportation of hydrogen

The hydrogen transportation cost (HTC) is defined as follows:

$$HTC_t = H_{t,transport} + TR_t \qquad (A-7)$$

$H_{t,transport}$ refers to the hydrogen transportation cost by truck, and it is estimated below:

$$H_{t,transport} = CT\times 2D\times NT_t \qquad (A-8)$$

where *CT* indicates the truck transportation cost per kilometer and *D* shows the distance from the HPP to the HST. We assume that in prefectures where a nuclear plant is located, D is half the square root of its area, whereas in prefectures where there is no nuclear plant, D is the distance from a prefecture where there is a nuclear plant to a prefecture where there is not one. These data are obtained from the

Logistic Solution Net (1990). NT_t shows the hydrogen supply in year t from the HPP to the HST, and it is estimated below:

$$NT_t = H_{t,production} / CTR \qquad (A-9)$$

CTR is the capacity for hydrogen transportation by truck. $H_{t,trailer}$ is the truck production and maintenance costs in year *t*, and it is determined as follows:

$$TR_t = TR_{t,production} + TR_{t,mentenanec} \qquad (A-10)$$

where $TR_{t,production}$ is the truck production cost and $TR_{t,mentenanec}$ is the truck maintenance cost. $TR_{t,production}$ is estimated by multiplying the truck production number NTR in year *t* by the truck production cost. NTR_t is indicated in the following Eq.:

$$NTR_t = NT_t / NRT_t \qquad (A-11)$$

where NRT_t is the number of round trips by truck from the HPP to the HTS in year *t*, and it is determined in the following Eq:

$$NRT = OT / RT \qquad (A-12)$$

where OT is the truck operation time and RT is the time for a round trip by truck from the HPP to the HST. RT is the sum of transportation time (TT) and hydrogen supply time (ST), and TT is also estimated as follows:

$$TT = 2D/TS \qquad (A-13)$$

where TS is the truck speed per kilometer. We display the truck specifications in Table.A-3.

Table A-2.The construction and operating expenses of a hydrogen supply station (100 m^3/h).

Specification	Parts	Price of each parts (Thousand dollar)
Specific equipment that is expected to reduce costs following diffusion.	Dispenser unit	133
	Pressure accumulator	50
	Boosting transformer	211
	Progress ratio	11
The equipment cost is expected to reduce following mass production.	Valve	11
	Electrical instrumentation	69
	Progress ratio	11
The equipment cost is expected to reduce by improving learning levels and rationalization	Instrumentation and electrical construction	33
	Installation	127
	Design and application costs	62
	Progress ratio	11
The equipment costs are constant with or without diffusion	Foundation cost	373
	Utility system	29
	Other equipment	106
	Progress ratio	11
Annual management expenses	Land cost	39
	Employment cost	89
	Electricity expense	11
	Industrial water	1
Expense of refueling hydrogen		1.1 $/kWh

These data were obtained from NEDO (2007). NEDO (2007) describes the three types of HSTs, 100 m^3/h, 300 m^3/h, and 500 m^3/h. In this study, we consider the comprehensive diffusion of FCV in Japan. Therefore, it is better to locate HSTs in many areas, and thus, we chose the 100 m^3/h type of HST.

Table A-3.The construction and operating expenses of a recharging station.

Factor	Specification
Initial RST cost	11.1 (1000 $)
Annual RST maintenance cost	1.1 (1000 $)
Initial fast charger cost	4.4 (1000 $)
Annual fast charger maintenance cost	4.4 (1000 $)
Cost to recharge	0.12 $/kWh

These data were obtained from an interview with one of the largest automobile manufacturing companies in Japan.

Table A-4. The truck specifications.

Factor	Specification
Production cost	122 (1000$)
Truck hydrogen capacity	2740 Nm3
Pressure	20 Mpa
Annual maintenance cost	12.4 (1000$)
Speed per kilometer	20 km/hr/ 60 km/ hr
Hydrogen supply time	1 hr

As in Table A-2, these data were obtained from NEDO (2007). The speed per kilometer is 20 km/hr for hydrogen transported to an area where there is a nuclear plant, i.e., where there is an HPP; it is 60 km/hr when hydrogen is transported to an area where there is no nuclear plant.

Table A-5. Total cost for the FCV diffusion scenario. (Billion dollars)

Progress ratio	Target year	*Current* policy scenario	*New* policy scenario	*450ppm* scenario
Lower progress	Short	384	386	388
	Middle	434	441	451
	Long	310	317	326
Realistic progress	Short	257	259	261
	Middle	284	292	301
	Long	203	209	219
Higher progress	Short	118	121	122
	Middle	125	133	143
	Long	89	95	105

Table A-6. Total benefit of the FCV diffusion scenario. (Billion dollars)

Target year	*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant
Short	23	23	23	21	21	21	19	19	19
Middle	57	55	52	49	47	44	39	38	34
Long	70	53	42	63	46	35	54	37	26

Table A-7. Total cost for the EV diffusion scenario. (Billion dollars)

Progress ratio	Target year	*Current* policy scenario	*New* policy scenario	*450ppm* scenario
Lower progress	Short	83	85	87
	Middle	75	83	92
	Long	49	56	65
Realistic progress	Short	71	73	74
	Middle	60	68	77
	Long	38	45	54
Higher progress	Short	56	59	60
	Middle	44	51	61
	Long	26	33	43

Table A-8. Total benefit of the EV diffusion scenario. (Billion dollars)

Target year	*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant
Short	23	23	23	21	21	21	19	19	19
Middle	57	56	52	50	48	44	40	38	35
Long	74	55	42	67	48	36	57	39	26