Analysis of CO_2 Reduction Cost for Passenger Cars through the Introduction of Next-Generation Fuels and Vehicles

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Abstract

An analysis was conducted on the cost of CO_2 reduction associated with substituting internal combustion engine (ICE) gasoline vehicles with next-generation fuels and vehicles. The CO_2 reduction cost was calculated by dividing the differential driving cost (JPY/km) between ICE gasoline and next-generation vehicles by the corresponding CO_2 reduction (kg-CO_2/km) achieved through the adoption of the latter. The results indicate that, in future scenarios, next-generation vehicles combining e-fuel and hybrid electric vehicle (HEV) technologies exhibit the lowest CO_2 reduction cost, approximately 60,000 JPY per ton of CO_2, followed by battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The analysis revealed that fuel cost is the main driver of CO_2 reduction cost in HEVs (using e-fuel), whereas vehicle cost is the dominant driver in BEVs and FCEVs. A sensitivity analysis was conducted to examine how variations in both fuel and vehicle costs affect the CO_2 reduction cost. Furthermore, the relative cost competitiveness between HEVs (using e-fuel) and BEVs was analyzed by delineating the regions where each technology achieves a lower CO_2 reduction cost.

Keywords *:* CO_2 reduction cost, next-generation vehicles, e-fuel, hybrid electric vehicle, battery electric vehicle

1. Introduction

In Japan, the transport sector accounts for approximately 20% of total CO_2 emissions, of which about 44% are attributable to passenger vehicles. Consequently, reducing CO_2 emissions from passenger cars has become an urgent policy challenge. To address this issue, a variety of technological options have been discussed, including the deployment of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), as well as the substitution of conventional gasoline with alternative fuels such as biofuels and hydrogen-derived synthetic fuels (hereafter referred to as e-fuels).

At this stage, it is not necessary to commit to a specific technology or pathway. However, from the perspective of achieving substantial CO_2 emission reductions in the future, it is essential to identify economically rational options and to articulate strategic deployment pathways based on cost-effectiveness. Given the long lifetimes of vehicles and energy infrastructure, together with uncertainties in future costs and technologies, a forward-looking evaluation of alternative technological pathways is particularly important for informed policy and investment decisions.

This study focuses on passenger vehicles in Japan and evaluates the cost of CO_2 reduction associated with replacing conventional internal combustion engine vehicles using gasoline (hereafter referred to as ICE vehicles) with various combinations of next-generation fuels and vehicle technologies. Taking ICE gasoline vehicles as the reference case, the analysis examines how differences in fuel type and vehicle technology influence the total cost to society required to achieve CO_2 emission reductions, hereafter referred to as the CO_2 reduction cost.

In order to reflect the time required for the development and social implementation of new technologies, two cases are considered in this study. The first case considers options that can be implemented in the near term using existing technologies. The second case focuses on options that require longer lead times but are expected to play an essential role in achieving carbon neutrality in the future. This distinction allows for a comparative assessment of CO_2 reduction costs under different stages of technological and supply-chain development.

The estimation of CO_2 reduction costs relies on several assumptions regarding fuel prices, vehicle costs, and energy efficiency, many of which are subject to significant uncertainty for future scenarios. To examine how such uncertainties influence the results, this study conducts a sensitivity analysis focusing on variations in key cost parameters.

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2. Methodology and Assumptions

2.1 Calculation Method

Taking conventional internal combustion engine vehicles using gasoline (ICE vehicles) as the reference case, the CO_2 reduction cost for each case is calculated using the following equation:

$$C_{CO2} = \frac{\Delta C_{total}}{\Delta E_{CO2}} = \frac{C_{total} - C_{total\_0}}{E_{CO2\_0} - E_{CO2}} \quad (1)$$

where C_{CO2} denotes the CO_2 reduction cost [JPY/t-CO_2], C_{total} is the total cost per kilometer traveled [JPY/km], and E_{CO2} is the CO_2 emissions per kilometer traveled [t-CO_2/km]. The subscript 0 indicates the corresponding values for the reference ICE vehicle.

The total driving cost per kilometer is expressed as:

$$C_{total} = C_v + C_f + C_I \quad (2)$$

where C_v, C_f, and C_I represent the vehicle cost, fuel cost, and infrastructure cost per kilometer traveled [JPY/km], respectively.

The vehicle cost per kilometer is calculated as:

$$C_v = \frac{P_v + P_m}{D \times L} \quad (3)$$

where P_v is the vehicle purchase price [JPY/vehicle], P_m is the maintenance cost over the vehicle lifetime [JPY/vehicle], D is the vehicle lifetime [years], and L is the annual driving distance [km/year/vehicle].

The fuel cost per kilometer is given by:

$$C_f = \frac{P_f}{\eta} \quad (4)$$

where P_f is the fuel price [JPY/L] and η denotes fuel efficiency [km/L].

The infrastructure cost per kilometer is calculated as:

$$C_I = \frac{(C_e/D_e) \times n}{L} \quad (5)$$

where C_e is the capital cost of refueling or charging facilities [JPY/unit], D_e is the lifetime of the infrastructure [years], and n is the number of facilities required per vehicle [units/vehicle].

CO_2 emissions per kilometer traveled are calculated as:

$$E_{CO2} = \frac{\varepsilon_{CO2}}{\eta} \quad (6)$$

where $\varepsilon_{\mathrm{CO2}}$ is the CO_2 emission factor of the fuel [t-CO_2/L] and η is the fuel efficiency [km/L].

2.2 Scope of Analysis

The next-generation fuels considered in this study include biofuels represented by E10 (a gasoline blend containing 10% bioethanol), electricity, hydrogen, and hydrogen-derived synthetic fuels (e-fuels). The vehicle technologies examined are conventional internal combustion engine vehicles (ICE), hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs).

Because the costs and carbon intensities of next-generation fuels are expected to differ substantially between the present and the future, the analysis distinguishes between two cases: a "current" case, in which next-generation fuels and vehicles are assumed to be introduced in the near term, and a "future" case, in which they are assumed to be deployed after supply chains consistent with carbon neutrality have been established. The current case is assumed to correspond to the period around 2025–2030, while the future case corresponds to the period around 2040–2050.

Given constraints on biomass supply, the evaluation of biofuels is limited to E10 and confined to the current case. In the future case, the technologies evaluated are HEVs using e-fuels, BEVs, and FCEVs. Plug-in hybrid electric vehicles (PHEVs) are examined by combining the analytical results for HEVs and BEVs.

2.3 Parameter Settings and Assumptions

The main assumptions and parameter values used in the analysis are summarized in Tables 1 and 2. The parameter values are primarily drawn from publicly available statistics and reports published by the Ministry of Land, Infrastructure, Transport and Tourism, the Ministry of Economy, Trade and Industry, as well as reports by industry organizations and international institutions such as the International Energy Agency (IEA). For the future case, target values presented in official policy documents and reports are used wherever possible

For parameters that are difficult to predict reliably over the long term, such as vehicle purchase prices, electricity prices, and fuel efficiency, the same values are used in the current case and the future case. Among these parameters, the vehicle cost of BEVs is considered to have a particularly large influence on the CO_2 reduction cost; therefore, a sensitivity analysis is conducted for this parameter.

Synthetic fuels (e-fuels) and hydrogen are assumed to be supplied from overseas and treated as CO_2-free fuels for use in Japan. In addition, electricity supplied from the power grid in the future case is assumed to be fully decarbonized, reflecting a power generation mix dominated by renewable energy, and its carbon intensity is therefore set to zero.

Vehicle purchase prices and fuel prices in the current case are generally based on market prices. Policy-related price adjustments, such as subsidies and taxes, are excluded from the analysis to clarify the inherent cost structures.

The purchase prices of ICE vehicles and HEVs are set based on average domestic sales prices[2)], as well as observed market price differentials and sales shares between ICE vehicles and HEVs.

The purchase price of BEVs is derived from price ratios relative to ICE vehicles[3], referencing observed market price ratios in regions where electric vehicles are more widely deployed, such as Europe and North America. For BEVs, battery replacement during the vehicle lifetime is assumed, and the associated cost is included as part of maintenance costs. Other maintenance costs are assumed to be identical across vehicle types and fuel types.

The fuel efficiency of ICE vehicles is calculated based on average fuel efficiency data excluding HEVs for gasoline passenger vehicles in Japan in 2024[4]. The fuel efficiency of HEVs is assumed to meet the fuel efficiency standards for fiscal year 2030[5]. The fuel efficiency of HEVs using E10 is calculated by assuming the same driving distance per unit of energy as that of gasoline-fueled HEVs. The calorific value of e-fuels is assumed to be identical to that of gasoline, and fuel efficiency is therefore assumed to be unchanged.

The future price of e-fuels is set at 300 JPY/L, assuming production in overseas regions with high resource potential and subsequent import to Japan. While previous governmental working group reports[6] indicate that the e-fuel cost has a wide range from 200 to 700 JPY/L, this study adopts 300 JPY/L as a representative value based on hydrogen price of 32.9 JPY/Nm³ under this supply assumption.

An annual driving distance of 7,950 km per vehicle[7] and a vehicle lifetime of 13.32 years[8] are assumed to be common across all vehicle types. Resale values and CO_2 emissions associated with vehicle manufacturing are excluded from the scope of the analysis.

3. Results and Discussion

3.1 Driving Cost

Figure 1 shows the cost per kilometer traveled (hereafter referred to as the driving cost). The driving cost is calculated as the sum of vehicle cost, fuel cost, and infrastructure cost per kilometer.

For ICE vehicles using gasoline, the vehicle cost is 23.1 JPY/km and the fuel cost is 6.3 JPY/km. For gasoline HEVs, although the vehicle cost increases to 26.4 JPY/km compared with ICE vehicles, the fuel cost decreases to 3.8 JPY/km. As a result, the total driving cost of gasoline HEVs increases only marginally by 0.9 JPY/km—relative to gasoline ICE vehicles. When E10 is applied to HEVs, both fuel cost and infrastructure cost increase; however, the total driving cost remains only 1.2 JPY/km higher than that of gasoline ICE vehicles, indicating a limited overall impact.

Table 1 Assumptions for Calculating CO2 Reduction Costs

Vehicle type	Fuel	Parameter	Unit	Current	Future
ICE	Gaso-line	Purchase price	million JPY	2.45	
		Fuel efficiency	km/L	15.5	
		Fuel price	JPY/L	98	
		Carbon Intensity	gCO_2/MJ	73.08	
HEV	Gaso-line	Purchase price	million JPY	2.80	
		Fuel efficiency	km/L	25.4	
		Fuel price	JPY/L	98	
		Carbon Intensity	kgCO2/L	2.29	
HEV	E10	Purchase price	million JPY	2.80	
		Fuel efficiency	km/L	24.6	
		Fuel price	JPY/L	100	
		Carbon Intensity	$kgCO_2/L$	2.06	
HEV	e-fuel 100%	Purchase price	million JPY		2.80
		Fuel efficiency	km/L		25.4
		Fuel price	JPY/L		300
		Carbon Intensity	$kgCO_2/L$		0
BEV	Elec-tricity	Purchase price	million JPY	3.62	3.62
		Maintenance cost	million JPY	0.60*	0.60*
		Electricity consumption	km/kWh	5.56 [9]	5.56
		Electricity price	JPY/kWh	23.9 [10]	23.9
		Carbon Intensity	$kgCO_2/kWh$	0.456	0
FCEV	Hy-dro-gen	Purchase price	million JPY	7.40	7.40
		Fuel efficiency	km/kg	148	148
		Fuel price	JPY/kg (JPY/Nm^3)	2,200 (198)	333 (30)
		Carbon Intensity	$kgCO_2/kg$	10	0

*Maintenance costs for BEVs include battery replacement during the vehicle lifetime.

Table 2 Assumptions for Infrastructure Development

item		value
E10	Capital investment	895.9 billion JPY
	Lifetime	8 years
	Annual gasoline consumption	42.97 million kL/year
BEVs	Fast-charging equipment cost	6.2 million JPY per unit
	Lifetime	8 years
	Number of chargers	6.6 units per 1,000 vehicles
FCEVs	Hydrogen refueling station cost	200 million JPY per station
	Lifetime	10 years
	Number of stations	1.25 stations per 1,000 vehicles

In contrast, BEVs exhibit a very high vehicle cost of 39.9 JPY/km, which alone substantially exceeds the total driving cost of gasoline ICE vehicles (29.4 JPY/km). Although the fuel cost of BEVs is lower than that of ICE vehicles at 4.3 JPY/km, its impact on the total driving cost is relatively small compared with that of the vehicle cost. FCEVs are characterized by both vehicle cost and fuel cost that are considerably higher than those of the other cases. The infrastructure cost has a relatively minor impact on the driving cost when expressed on a per-kilometer basis.

In the future case, total driving costs differ substantially across vehicle technologies, reflecting differences in their dominant cost components. Although the fuel cost of HEVs using e-fuels becomes the highest among the cases, at 11.8 JPY/km, their total driving cost remains relatively low at 38.3 JPY/km, which is lower than that of BEVs. For FCEVs, the fuel cost decreases to 2.3 JPY/km under the assumption that the hydrogen price declines from 198 JPY/Nm³ to 30 JPY/Nm³. A comparison among the three future cases indicates that fuel cost is the dominant driver of the driving cost for HEVs using e-fuels, whereas vehicle cost is the dominant driver for BEVs and FCEVs.

3.2 CO_2 Emissions and CO_2 Reduction Cost

Figure 2 shows CO_2 emissions per kilometer traveled (hereafter referred to as CO_2 emissions). Compared with gasoline ICE vehicles, gasoline HEVs exhibit lower CO_2 emissions as a result of improved fuel efficiency. When E10 is applied to HEVs, CO_2 emissions are further reduced due to the blending of ethanol.

In the current case, CO_2 emissions from BEVs and FCEVs are influenced by the carbon intensity of grid electricity and gray hydrogen, respectively. As a result, although BEVs and FCEVs achieve lower CO_2 emissions than gasoline ICE vehicles owing to their high energy efficiency, their emissions do not reach zero and remain at approximately half the level of those of gasoline ICE vehicles. In the future case, by contrast, CO_2 emissions are assumed to be zero (0 kg-CO_2/km) for BEVs, FCEVs, and HEVs using e-fuels, reflecting the assumption of zero carbon intensity for electricity, hydrogen, and e-fuels, as discussed above.

Figure 3 presents the CO_2 reduction cost. As defined in Eq. (1), this cost is calculated by dividing the difference in driving cost relative to gasoline ICE vehicles, as shown in Fig. 1, by the corresponding CO_2 reduction per kilometer, as shown in Fig. 2.

Among the technologies considered in the current case, gasoline HEVs exhibit the lowest CO_2 reduction cost, at 15,000 JPY/t-CO_2. In other words, gasoline HEVs represent an effective option for reducing CO_2 emissions without requiring substantial changes to existing fuel infrastructure. HEVs using E10 also achieve a very low CO_2 reduction cost of 19,000 JPY/t-CO_2. In contrast, BEVs and FCEVs in the current case exhibit CO_2 reduction costs exceeding 200,000 JPY/t-CO_2, indicating that CO_2 reduction through these technologies requires substantially higher costs under current conditions.

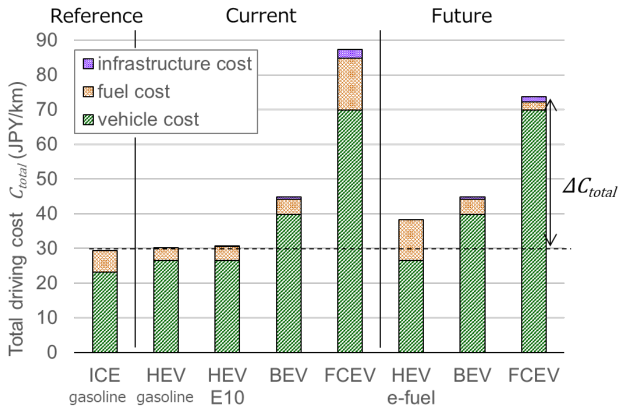

Fig. 1 Cost per kilometer traveled

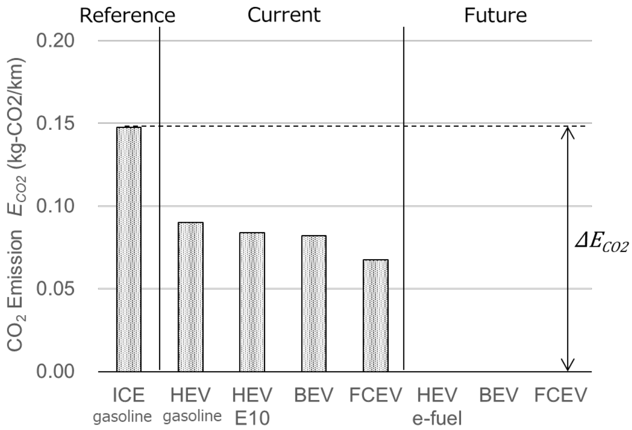

Fig. 2 CO_2 emissions per kilometer traveled

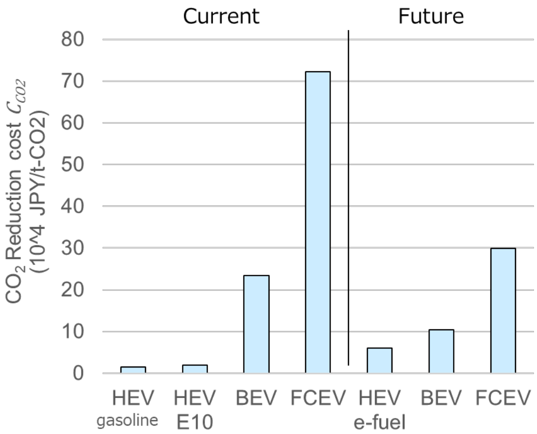

Fig. 3 CO_2 reduction cost

In the future case, HEVs using e-fuels exhibit CO_2 reduction costs that are lower than those of BEVs and FCEVs. This indicates that HEVs using e-fuels have strong cost competitiveness. These results suggest that HEVs using e-fuels offer competitive performance in terms of both CO_2 reduction potential and cost relative to BEVs, and therefore warrant consideration in future decarbonization strategies for passenger vehicles.

3.3 CO_2 Reduction Potential and Total Cost

Figure 4 illustrates the relationship between total annual CO_2 emissions from passenger vehicles and the total annual cost required for CO_2 reduction, assuming large-scale deployment of next-generation vehicles in the current and future cases. The vertical axis shows total CO_2 emissions (10^4 t-CO_2/year), while the horizontal axis shows the total cost of CO_2 reduction (trillion JPY/year). The CO_2 emissions at zero total cost correspond to the CO_2 emissions from privately owned passenger vehicles in fiscal year 2023[11].

As next-generation vehicles are deployed, total CO_2 emissions decrease, although the total cost required for CO_2 reduction increases. If all existing passenger vehicles are replaced by BEVs or FCEVs, the total cost of CO_2 reduction reaches approximately 8 trillion JPY/year and 33 trillion JPY/year, respectively. In addition, a difference of approximately 40–50 million t-CO_2/year is observed in CO_2 reduction potential between the current case (solid lines) and the future case (dashed lines).

The slope of each curve in Figure 4 represents the effectiveness of CO_2 reduction in terms of cost, with steeper slopes (i.e., curves closer to vertical) indicating more cost-effective CO_2 reduction. From this perspective, HEVs exhibit the highest cost-effectiveness among the technologies considered. However, although gasoline HEVs and HEVs using E10 achieve relatively low total CO_2 reduction costs, their CO_2 reduction potential is limited because they cannot fully eliminate dependence on fossil fuels.

In the future case, HEVs using e-fuels, BEVs, and FCEVs have the potential to reduce total CO_2 emissions to zero and are therefore essential options for achieving carbon neutrality. At the same time, the total cost required for CO_2 reduction with these technologies is substantial, ranging from approximately 5 to 25 trillion JPY/year. This highlights a key challenge for future decarbonization strategies: achieving deep CO_2 reductions while managing the associated economic burden.

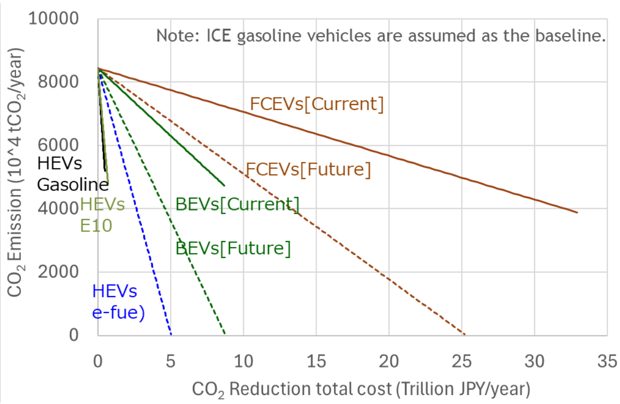

Fig. 4 Total cost and reduction potential of CO_2 emissions

3.4 Sensitivity Analysis and Key Challenges

To further examine key factors influencing the CO_2 reduction cost in the future case, a sensitivity analysis is conducted for HEVs using e-fuels and BEVs. Based on the driving-cost breakdown shown in Figure 1, the analysis focuses on fuel cost for HEVs using e-fuels and vehicle purchase cost for BEVs, as these components are major contributors to their respective CO_2 reduction costs.

3.4.1 Sensitivity of CO_2 Reduction Cost to Fuel and Vehicle Costs

As shown in Figure 1, HEVs using e-fuels have higher fuel costs than the other cases, and fuel cost is a major driver of their driving cost and, consequently, their CO_2 reduction cost. Figure 5 illustrates how the CO_2 reduction cost of HEVs using e-fuels varies with the e-fuel price. Under the baseline assumption of an e-fuel price of 300 JPY/L, the CO_2 reduction cost is 60,000 JPY/t-CO_2. However, if the e-fuel price increases to 700 JPY/L, the upper bound of the range presented in previous public–private studies on synthetic fuel deployment, the CO_2 reduction cost rises substantially to approximately 170,000 JPY/t-CO_2. This result indicates that the CO_2 reduction cost of HEVs using e-fuels is highly sensitive to fuel price.

Fuel cost is also influenced by fuel efficiency. In the baseline case, the fuel efficiency of HEVs using e-fuels is assumed to be

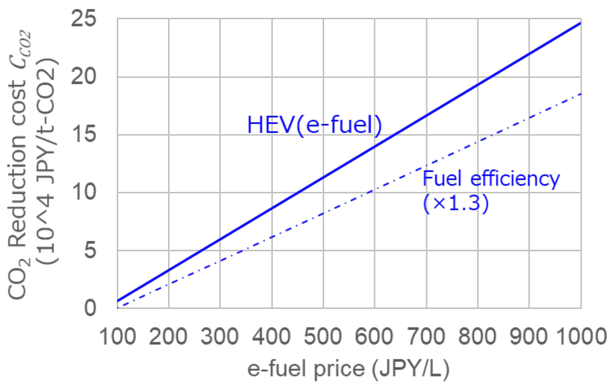

Fig. 5 CO_2 reduction cost as a function of e-fuel price

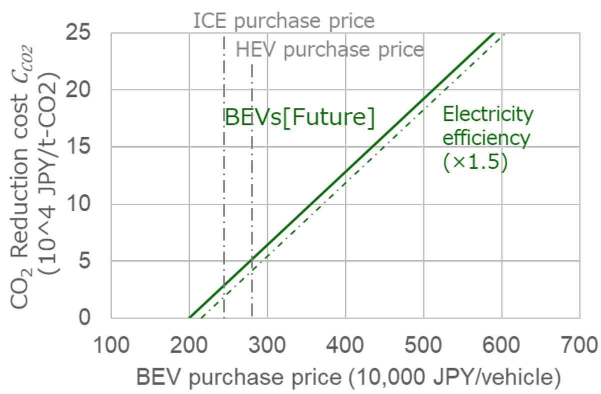

Fig. 6 CO_2 reduction cost as a function of BEV purchase price

25.4 km/L. If fuel efficiency improves by a factor of 1.3 to 33 km/L, the CO_2 reduction cost decreases from 60,000 JPY/t-CO_2 to approximately 42,000 JPY/t-CO_2 at an e-fuel price of 300 JPY/L, as shown by the dashed line in Figure 5. This result suggests that improvements in vehicle fuel efficiency can also contribute to reducing the CO_2 reduction cost of HEVs using e-fuels.

For BEVs, vehicle purchase cost is identified as the primary challenge. Figure 6 shows the relationship between BEV vehicle price and CO_2 reduction cost. If the BEV purchase price decreases from the baseline value of 3.62 million JPY per vehicle to 2.80 million JPY—comparable to that of HEVs—the CO_2 reduction cost decreases from 104,000 JPY/t-CO_2 to approximately 52,000 JPY/t-CO_2. In addition, the baseline analysis includes a battery replacement cost of 0.6 million JPY as part of maintenance costs, and a reduction in this cost would further lower the CO_2 reduction cost of BEVs.

By contrast, improvements in electricity consumption have a relatively limited impact on the CO_2 reduction cost of BEVs. Even if electricity consumption improves by a factor of 1.5, the resulting reduction in CO_2 reduction cost is on the order of 10,000 JPY/t-CO_2, as indicated by the dashed line in Figure 6. These results indicate that reducing vehicle purchase price and battery-related costs is more critical for improving the economic performance of BEVs than further improvements in energy efficiency.

These results indicate that the key factors influencing CO_2 reduction costs differ across vehicle technologies and warrant careful consideration.

Table 3 Comparison between HEVs (using e-fuel) and BEVs

Item	HEV (using e-fuel)	BEV
CO_2 reduction cost (baseline condition)	60,000 JPY/t-CO_2 *(42,000 JPY/t-CO_2 with fuel efficiency of 33 km/L)*	104,000 JPY/t-CO_2 *(52,000 JPY/t-CO_2 with a vehicle purchase price of 2.8 million JPY)*
Major cost driver	Fuel cost (e-fuel price and fuel efficiency)	Vehicle cost
Key economic challenges	Establishing a low-cost, low-carbon e-fuel supply chain; improvement in HEV fuel efficiency	Reduction in vehicle purchase price and battery costs

3.4.2 Relative Cost Competitiveness between HEVs Using e-Fuels and BEVs

Based on the sensitivity analysis above, the relative cost competitiveness between HEVs using e-fuels and BEVs is examined by jointly varying the key parameters that dominate their CO_2 reduction costs. Specifically, the analysis considers changes in the vehicle purchase price of BEVs and the fuel price of HEVs using e-fuels, and evaluates which technology achieves a lower CO_2 reduction cost under different combinations of these parameters.

Figure 7 illustrates this relationship, with the BEV vehicle price on the horizontal axis and the e-fuel price for HEVs on the vertical axis. The figure is divided into regions according to which technology exhibits a lower CO_2 reduction cost. The black line represents the boundary at which the CO_2 reduction costs of HEVs using e-fuels and BEVs are equal. For example, when the e-fuel price is 300 JPY/L or 700 JPY/L, the CO_2 reduction costs of the two technologies become equal at BEV vehicle prices of approximately 2.93 million JPY and 4.53 million JPY per vehicle, respectively.

In the region to the right of this boundary (the blue-shaded area in Figure 7), HEVs using e-fuels achieve a lower CO_2 reduction cost than BEVs, whereas in the region to the left, BEVs are more cost-effective. The baseline assumptions adopted in this study are located within the region where HEVs using e-fuels are more cost-competitive.

Future changes in e-fuel prices and BEV vehicle prices may shift the relative position across these regions. By plotting prospective values of BEV vehicle prices and e-fuel prices on Figure 7, it is possible to readily assess which technology is likely to achieve a lower CO_2 reduction cost under different future conditions. In this sense, Figure 7 provides a useful framework for evaluating the relative cost competitiveness of HEVs using e-

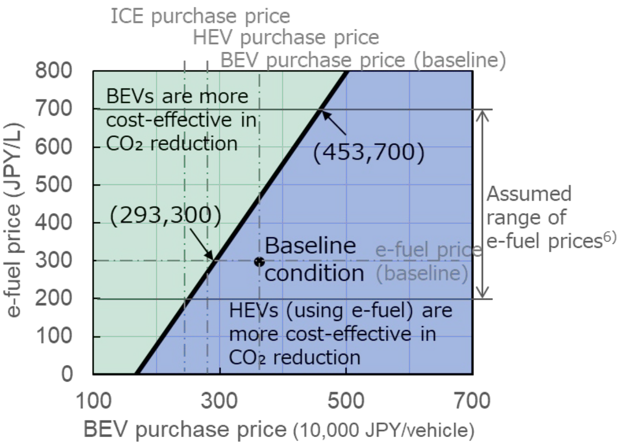

Fig. 7 Relative CO_2 reduction cost of HEVs (using e-fuel) and fuels and BEVs.

3.5 CO_2 Reduction Cost of Plug-in Hybrid Electric Vehicles (PHEVs)

Although PHEVs have not been explicitly discussed in the preceding analysis, they are also attracting attention as one of the future next-generation vehicle options. PHEVs operate in two modes: an electric driving mode using externally charged electricity, similar to BEVs, and a fuel-based driving mode, similar to HEVs. The fuel cost of PHEVs, therefore, depends on the relative share of distance traveled in each mode.

To capture this characteristic, the share of distance traveled in electric mode is defined as R_{BEV}, as shown in Eq. (7):

$$R_{BEV} = \frac{D_{BEV}}{D_{BEV} + D_{HEV}} \tag{7}$$

where D_{BEV} is the annual distance traveled in electric mode (km/year), and D_{HEV} is the annual distance traveled in fuel-based mode (km/year).

Based on this definition, the fuel cost per kilometer for PHEVs is calculated using Eq. (8):

$$C_{f.PHEV} = R_{BEV} \times \frac{P_{f.BEV}}{\eta_{BEV}} + (1 - R_{BEV}) \times \frac{P_{f.HEV}}{\eta_{HEV}} \tag{8}$$

where $C_{f,\text{PHEV}}$ is the fuel cost of PHEVs (JPY/km), $P_{f,\text{BEV}}$ is the electricity price (JPY/kWh), $P_{f,\text{HEV}}$ is the fuel price (JPY/L), η_{BEV} is the energy efficiency in electric mode (km/kWh), and η_{HEV} is the fuel efficiency in fuel-based mode (km/L).

Figure 8 shows the CO_2 reduction cost of PHEVs as a function of vehicle purchase price for several assumed values of R_{BEV}, representing different driving patterns. In this analysis, e-fuel is assumed as the fuel used in the HEV mode, and the e-fuel price and fuel efficiency are fixed at their baseline values of 300 JPY/L and 25.4 km/L, respectively.

For a given vehicle purchase price, a lower value of R_{BEV}—that is, a higher share of driving in HEV mode using e-fuels—results in higher fuel costs and, consequently, a higher CO_2 reduction cost. However, because PHEVs generally require a smaller battery than BEVs, their vehicle purchase price is expected to be lower than that of BEVs. A reduction in vehicle purchase price, therefore, contributes to lowering the CO_2 reduction cost of PHEVs.

These results indicate that the CO_2 reduction cost of PHEVs can be flexibly evaluated by defining the share of electric driving R_{BEV} based on driving patterns, allowing for a range of assessments, including comparisons of relative cost competitiveness with BEVs and HEVs.

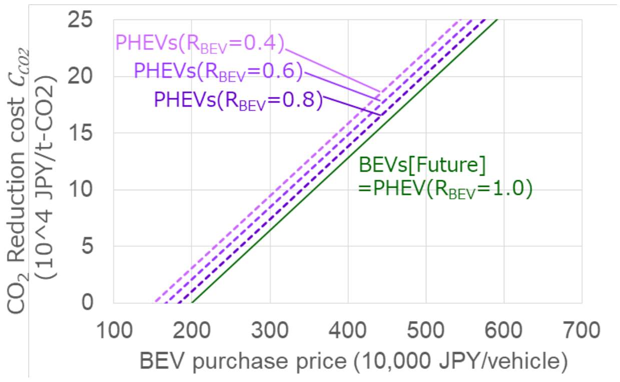

Fig. 8 CO_2 reduction cost of PHEVs (fuel: e-fuel)

3.6 Notes and Limitations of the Analysis

In this analysis, the annual driving distance of passenger vehicles is assumed to be constant at 7,950 km per vehicle for all vehicle types. If commercial vehicles are considered instead, their annual driving distance would be several times higher than that of privately owned passenger vehicles, resulting in proportionally higher fuel costs. Under such conditions, the CO_2 reduction cost (and driving cost) of BEVs and FCEVs could become relatively lower than that of HEVs using e-fuels.

In addition, in the future case, the carbon intensity of electricity and e-fuels is assumed to be zero (e.g., 0 kg-CO_2/MJ). If this assumption is not fully realized, the resulting CO_2 reduction costs would be higher than those estimated in this study. Therefore, achieving a decarbonized power mix, as well as establishing supply chains and production methods for carbon-neutral fuels, is crucial not only for reducing CO_2 emissions from vehicles but also for lowering the associated CO_2 reduction costs.

4. Conclusion

This study assessed the economic performance of introducing next-generation fuels and vehicles for passenger cars in Japan by calculating CO_2 reduction costs (JPY/t-CO_2), using conventional gasoline internal combustion engine vehicles (ICEs) as the reference case. In addition, the CO_2 reduction potential of each option was evaluated.

Under current conditions, the introduction of gasoline HEVs and HEVs using E10 was found to be a highly cost-effective means of reducing CO_2 emissions, with CO_2 reduction costs of approximately 15,000–19,000 JPY/t-CO_2. However, even if these vehicle types were deployed to their maximum extent, their CO_2 reduction potential remains limited to roughly 40% of total emissions, as complete decarbonization cannot be achieved due to continued reliance on fossil fuels.

In future scenarios where carbon neutrality becomes a central objective, HEVs using e-fuels, BEVs, and FCEVs are effective options for CO_2 reduction. The CO_2 reduction costs for these technologies were estimated to be approximately 60,000 JPY/t-CO_2 for HEVs using e-fuels, 104,000 JPY/t-CO_2 for BEVs, and 300,000 JPY/t-CO_2 for FCEVs, respectively.

The analysis further revealed that the primary factors influencing CO_2 reduction costs differ by vehicle technology. For HEVs using e-fuels, fuel-related factors—specifically e-fuel price and fuel efficiency—play a dominant role, whereas for BEVs, vehicle purchase cost and battery-related costs are the key determinants. Sensitivity analysis was conducted, and a graphical framework was developed to enable a rapid comparison of the relative CO_2 reduction costs of HEVs using e-fuels and BEVs under varying cost assumptions.

By quantifying CO_2 reduction costs, this study enables a transparent comparison of diverse vehicle and fuel options whose relative economic performance is otherwise difficult to assess.

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