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Market penetration speed and effects on CO_2 reduction of electric vehicles and plug-in hybrid electric vehicles in Japan

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ABSTRACT

In order to reduce CO_2 emissions in the passenger vehicle sector, mass introduction of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) is required despite their high battery costs. This paper forecasts the rate at which EV/PHEV will penetrate into the market in the future and the effects of that spread on CO_2 reduction by using a learning curve for lithium-ion batteries, distribution of daily travel distance for each vehicle, and an optimal power generation planning model for charging vehicles. Taking into consideration each driver's economical viewpoint, the speed at which the EV/PHEV share of the new passenger vehicle market grows is fairly slow. The optimum calculation in our base case shows that the share of EV/PHEV is only a quarter even in 2050. However, the initial price and progress rate of batteries have a great effect on this share. Therefore, long-term economic support from the government and significant R&D innovation are required to reduce CO_2 drastically through cutting down battery price. The results also show how much the CO_2 emission intensity of power generation affects the CO_2 reduction rate by introducing EV/PHEV.

1. Introduction

The total CO_2 emission in Japan is about 1.14 trillion kg in FY2009, and about 31% of it is from power generation, 28% from industry, and 19% from transportation sector. In order to significantly reduce CO_2 emission in Japan, it is essential to reduce CO_2 emission also from private-use passenger vehicles which is 0.115 trillion kg and accounts for a half of transportation sector and 10% of the total (National Institute for Environmental Studies, Japan, 2011).

In 2008, Japan's prime minister announced that to reduce the country's CO_2 emissions by 14% from the current level by 2020, it must achieve several ambitious goals such as introducing next-generation vehicles at a rate of one in every two new units sold (Prime Minister of Japan and his Cabinet, 2008).

The policy is followed by METI's (the Ministry of Economy, Trade and Industry, Japan, 2010) "Next-Generation Vehicle Plan 2010", which sets the government targets of the sales share of ordinary hybrid vehicles (HV) at 20–30%, electric vehicles (EV)+plug-in hybrid electric vehicles (PHEV) at 15–20% for a furthermore challenging target to reduce CO_2 emissions by 25% in 2020, and the target sales share in 2030 is 30–40% and 20–30%, respectively.

Recently, commercial production of PHEVs and EVs has started. It is expected that PHEVs and EVs will be more widely purchased by users who rarely travel long distance on a single day, and therefore, do not require a large capacity of expensive battery. However, it is not easy to forecast to what extent these vehicles will be adopted and what sort of impact the battery charging demand created by PHEVs and EVs will have on the power supply system, because PHEVs run on electricity up to a certain distance, and then run on gasoline for longer distance just as HVs, and the CO_2 emissions vary considerably depending on the daily travel distance. It is necessary to assess the probability distribution of daily travel distance, which differs considerably for each vehicle unit.

On the other hand, costs of rechargeable batteries accounts for a large percentage of initial PHEV and EV costs, which include costs of a vehicle-mounted charger, a large-capacity-battery module and so on, in addition to regular HV or GV-less-gasoline-engine costs. So the declining speed of battery price, which is decided by mass production, technological innovation and other factors, is a key in evaluating the impact and pace at which such vehicles will become more widespread. In above-mentioned METI's plan, the ministry sets challenging and aggressive battery cost-down targets of 1/7 in 2015 and 1/40 in 2030 compared with the cost in 2006. This would require experts to make a practical forecast for the speed of cost declines.

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Previous studies, including Eppstein et al. (2011), Kang and Recker (2009), Skerlos and Winebrake (2010), Sovacool and Hirsh (2009), analyze lifetime fuel cost of PHEVs, considering driving distance on a single day and the environmental and economical benefits.

Sciau et al. (2009) focuses upon the effect of battery capacity and weight on lifetime cost and GHG emissions of PHEVs. They assess the average lifetime cost per mile as a function of distance between battery charges. Their results show that PHEVs are less expensive than HVs only when charging intervals are less than 20 miles in a base case (battery cost is $1000/kWh), and that large capacity PHEVs, whose all electric range (AER) is 40 miles or more, cannot be the lowest cost option in any simulation scenarios in spite of their greater CO_2 reduction effect.

Sioshansi et al. (2010) assess the cost and emissions impacts of PHEVs on the Ohio power system, focusing on the comparison between a controlled and an uncontrolled charging scenario. In the controlled case, PHEVs are charged mainly in early morning hours (2 am to 6 am) with power generated by more economical coal-fired power plants, and emit more amount of CO_2, SO_2 and NO_x than in the uncontrolled case, where PHEVs use electricity from natural gas-fired plants in addition to coal just after arriving home or office. The results also show that CO_2 emissions from a PHEV could be up to 24% lower than that of conventional vehicles in the uncontrolled case, however, SO_2 and NO_x emissions would increase in both cases. On the other hand, Japan's CO_2 emission intensity of power generation is 0.373 kg-CO_2/kW h in 2008, including Kyoto mechanism credit (0.444 kg-CO_2/kW h without the credit). This relatively small intensity comes from the power generation composition, that is, nuclear 29%, LNG 30%, coal 25%, oil 6%, hydro 8%, wind, solar, etc. 2%. Therefore, CO_2 emissions can be reduced much more than in Ohio, by introducing PHEVs/EVs to Japan.

Nakaue et al. (2010) assess the future share of PHEVs and volume of CO_2 reduction under optimal power supply, taking charging demand into account. They obtain, from surveys of automobile starting points and destination points, many patterns of daily travel distance distributions, which vary depending on the purpose of driving, such as commuting or pleasure, and the size of vehicles. They simulate life cycle costs of different vehicles using these distributions to forecast a change in shares of PHEVs, assuming that car owners replace their vehicles with PHEVs if PHEV life cycle cost becomes the most economical. The biggest difference between their paper and our paper is that while their paper sets a certain degree of a battery price fall in the future as a precondition, our paper assumes the battery price will follow a learning curve of the correlation between the cumulative lithium ion battery production volume and its price.

In our previous studies (Shinoda et al., 2009a, 2010, 2011), the authors constructed a model capable of calculating up to 25 years in the future the optimal share of vehicle types and power sources both for the power supply sector and the passenger vehicle sector in Japan. In this model, owners of private-use passenger vehicles have been divided into groups according to the annual travel distance, and a daily travel distribution has been configured for each of the respective groups to calculate the running cost. As for the PHEV initial cost, a loop effect – the effect of an increase in groups selecting PHEVs, when they replace their older vehicles, pushes down the unit battery cost while lowering of the PHEV initial cost promotes popularization of such vehicles – has been considered. Moreover, changes in power generation costs and the power source types as a result of the growing demand for battery charging has also been taken into account. In the model used in the previous studies, the sum total for costs in the power supply sector and the automobile sector has been set as the objective function. The parameters have been the progress rate of the learning curve and the initial unit price of batteries. The authors have solved the optimization problem of minimizing this objective function to forecast the spread speed and CO_2 emission impact of PHEVs, and discussed effective subsidies or incentives to decrease the battery cost and the total cost.

In the results of simulations conducted so far, progress in reducing the price of batteries has not proceeded as expected, even though HVs, which have smaller increments in initial cost, have become more widespread. So, it was learned that, unless preferential measures like a tax reduction or subsidies suited to the effect of further reducing CO_2 from PHEVs compared with HVs are instituted, it would take a considerable amount of time before PHEVs become widespread on a large scale. In the same way, EVs seemed to take longer time to become widespread because of their higher initial cost and inconvenience of frequent charges.

However, large-scale production of EV/PHEVs has recently begun, and the possibility has arisen that adoption will proceed faster than our forecasts had predicted. Development of lithium-ion batteries has also moved ahead on a global scale and the possibility of price reduction has also increased.

So, in this paper, EVs are added to PHEVs when replacement vehicles are considered. In order to reflect a weak point of EVs, which is that they have a short cruising radius and long charging time, the number of long distant travelling vehicles to be replaced with EVs is limited in the following simulations.

To the extent possible, CO_2 reduction measures should be assessed according to their effectiveness and economic efficiency over the long-term. So the computation period is extended to the year 2050 or 40 years from the present. In investigating the feasibility up to 40 years into the future to be consistent with recent policies of achieving significant CO_2 reductions, it is considered necessary to take an improved ratio over the long term of zero emission power supplies into consideration. However, because there is a great deal of uncertainty in augmenting zero emission power supplies particularly after the huge tsunami followed by the severe accident in Fukushima 1 nuclear power plant, in this paper, the authors assessed CO_2 reduction rate by setting the ratio of zero emission power generating sources as a parameter. The distinguishing feature of this paper is to study an optimal long-term solution for the nation as a whole through the predictive assessment over the ultra long-term by using as parameters the ratio of zero emission power generating sources and the economic efficiency of HVs, PHEVs and EVs, all of which have a mutual influence on each other in price reductions resulting from mass production of batteries.

Below, in this paper, after an explanation of the model and a computational method, the authors discuss the outlook for penetration of EVs and PHEVs and the impact on reducing CO_2 emissions as a result of such penetration as well as the effect of CO_2 emission intensity on the power supply side.

2. Computational model and calculation method

2.1. Computational model

The above mentioned optimization problem is fairly complex because it comprises many non-linear functions including a learning curve for batteries, probability distributions of one day travel distance and so on. Accordingly, the following practical optimization method was used. That is the repeated computation to find a better solution to keep increasing the amount of battery production slightly while the total cost of the automobile and power supply sectors decreases.

The model, which the authors developed, can assess the amount of CO_2 emitted as well as the total cost of the private-use passenger vehicle sector and the power supply sector throughout Japan (passenger vehicle model and power supply model), and can optimize the