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Electric vehicle charge patterns and the electricity generation mix and competitiveness of next generation vehicles

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ABSTRACT

The nuclear accident of 2011 brought about a reconsideration of the future electricity generation mix of power systems in Japan. A debate on whether to phase out nuclear power plants and replace them with renewable energy sources is taking place. Demand-side management becomes increasingly important in future Japanese power systems with a large-scale integration of renewable energy sources. This paper considers the charge control of electric vehicles (EVs) through demand-side management. There have been many studies of the control or operation methods of EVs known as vehicle-to-grid (V2G), and it is important to evaluate both their short-term and long-term operation. In this study, we employ energy system to evaluate the impact of the charge patterns of EVs on both the electricity generation mix and the technology competitiveness of the next generation vehicles. An advanced energy system model based on Market Allocation (MARKAL) is used to consider power system control in detail.

1. Introduction

The nuclear accident caused by the 2011 Tohoku earthquake had a great impact on Japanese energy policy. The issue of whether to phase out nuclear power plants and install renewable energy sources, such as wind power or photovoltaic (PV) generation, on a large-scale is being debated. In such a situation, attention is focused on the installation of new energy technologies, such as energy saving appliances or energy storage. Energy technology based on electricity and those based on other energy mediums often compete, as with electric heat pump water heaters and gas-latent heat-recovery water heaters; electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs); and battery energy storage and hydrogen energy storage. An energy technology based on electricity tends to be superior to one based on other energy mediums. In conventional power systems where the ratio of generation from nuclear power plants is high, the generation cost is supposed to be cheap, and controllable power plants, such as hydro and thermal power plants, stably maintain the supply and demand of electricity. It has been seen as natural that the economy and environment can be enhanced by increasing the ratio of electrification [1]. However, the trend will be impacted by the change of the electricity generation mix and power system control and operation because of the decrease of nuclear power plants and increase of renewable energy sources [2]. However, demand-side management, which applies electric appliances to power system control and operation as controllable loads, has gained much attention. An energy technology based on electricity, which has controllability, may be superior to that based on other mediums precisely because of the large-scale integration of uncertain renewable energy sources. Control methods for demand-side management using controllable appliances have been investigated [3–6]; however, both the short-term evaluation of the effectiveness of such methods in daily or weekly operation [3–5] and the long-term evaluation of the impact of them on power system generation planning [6] and the diffusion of such appliances themselves are also important.

Vehicle-to-grid (V2G) [7], a supply and demand control using the charge/discharge of EVs, typifies such demand-side management. Various objectives have been targeted in the study of V2G [6–14], including the minimization of operational cost, the leveling of electricity load demand, the reduction of emissions, the regulation of power system frequency, and so on. Researchers [6–10] have focused on the contribution of the charge/discharge of EVs

Abbreviations: EDC, economic-load dispatching control; EV, electric vehicle; FCV, fuel cell vehicles; ICEV, internal combustion engine vehicle; IEA, International Energy Agency; LFC, load frequency control; LNG, liquefied natural gas; LPG, liquefied petroleum gas; MARKAL, market allocation; PV, photovoltaic; V2G, vehicle-to-grid.

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to the power system frequency control. Fazelpour and his colleagues [11] propose an optimization method of charge allocation for plug-in hybrid electric vehicles to improve voltage profiles and to minimize power losses. Other scholars [12] suggest a minimization method for both total operational costs and emissions by the decentralized control of EVs. The leveling of the electricity load demand is proposed for the charge control of EVs [13,14]. This paper focuses on demand-side management through the charge control of EVs in a long-term evaluation case study. The charge control of EVs, which is a kind of V2G, enables efficient power system operation by shifting the charge period of the peak cut or peak shift of electric power demand. Although the number of EVs is currently still small (about 25,000 passenger EVs in 2012 in Japan [15]), their dispersal can be enhanced by charge control if they are cheaply charged and have cost advantages. In this study, we evaluate the impact of the charge patterns of EVs on power system operation, the future electricity generation mix, and the technology competitiveness of next generation vehicles by energy system analysis. We simultaneously consider the effectiveness of EV charge control and the competitiveness of EVs, which is an alternative approach to verify the feasibility of V2G. An advanced energy system model [16], which was developed based on Market Allocation (MARKAL) [17] and considers the characteristics of power system control, including demand-side management, is used for the analysis. By employing this model, we plan a future generation mix of all energy sectors, in which we consider the balance between electricity and the other sources, although studies on power system generation planning usually only focus on the electric energy sector [18–20]. Moreover, we can compare the competitiveness of EVs to vehicles based on other energy mediums. Two charge patterns are assumed; one is a nighttime load pattern, where EVs are charged during the nighttime; the other is a controllable load pattern, where EVs are charged during the optimal time for total system cost minimization.

2. Energy system model

An advanced energy system model, which was developed by expanding the functions of MARKAL in a previous study [16], is used for the analysis. The characteristics of the advanced model are presented in this section.

2.1. MARKAL

MARKAL was developed in the international cooperation project lead by International Energy Agency (IEA) [17,21]. It is an optimization model that considers all the energy sectors and models an energy system as the network flow from supply to demand. MARKAL can describe energy technologies in detail through their technical characteristics. It determines the multi-period composition of the energy technologies, including final energy consumption and the electricity generation mix. It has been widely applied to energy system analysis studies [22–24]. However, MARKAL does not consider power system control of both the power plants and the demand side in detail, which must, however, be taken into account in an energy system analysis that weighs the time change of the output of renewable energy sources, electric power demand, and demand-side management. Thus, an advanced energy system model [16] is used in this study.

2.2. Indices and parameters

The index of the analysis period is represented by *T* (13 periods from 1990 to 2050 by every 5 years), that of the season by *Z*, and that of the time period by *Y*. *Z* is set as the following 9 patterns (3 daily patterns in 3 seasons); weekday, weekend, and singular day (a week of light-load) in winter; weekday, weekend, and singular day (three days of heavy-load) in summer; and weekday, weekend, and singular day (a week of light-load) in spring/fall. *Y* is set as the hourly time series (24 time periods in a day). The parameters $qhr(Z, Y)$ and $fr(Z, Y, DM)$, which contain the factors *Z* and *Y*, are also set as the time-series data. The terms $qhr(Z, Y)$ represents the proportion of time *Y* in season *Z* to a year. The terms $fr(Z, Y, DM)$ represents the proportion of the demand *DM* used at *Y* in *Z* to a year. $qhr(Z, Y)$ corresponds to the proportion of weekday, weekend, and singular day in each season. The setting of $fr(Z, Y, DM)$ is presented in Section 3.

2.3. Modeling of supply and demand control in power systems

The constraint equations related to the power system considered in MARKAL are the maximum generation output, the balance between supply and demand, the capacity usage, the reserve capacity on peak load, and the base load operation [17,21]. MARKAL is intrinsically designed as an optimization model for multi-time periods in multi-seasons. Therefore, the constraint equations of maximum generation output, the balance between supply and demand, and the capacity usage are used without change in the advanced model. In the advanced model, the reserve capacity constraint equation assumes that the reserve capacity must be more than 5% of the electric power demand at any time.

The load following capability of the power plants is simply approximated in the base-load operation constraint equation in MARKAL by suppressing the output of the base power plants to a certain level. The advanced model used in this study approximates the load following capability in more detail by considering the economic-load dispatching control (EDC) and the load frequency control (LFC). The EDC and LFC are the demand and supply control schemes of controllable power plants (thermal or hydro power plants) in power systems. The EDC is the control for following long-period load variation (several ten minutes-several hours) by the slow change of the output of power plants, whereas the LFC is that for suppressing short-period load variation (several ten seconds-several minutes) by the rapid change of the output of power plants. In general, power plants change the output for the LFC in a certain range (a few percent of the rated capacity, which is called LFC capacity) and that for the EDC for the rest. The constraint equation of the rate of change of the output of the power plants is given by (1), which stands for EDC. $E(T, Z, Y, ELA)$ is the electricity generation of power plant *ELA* at time *Y* in season *Z* in period *T*. $RC_{UP}(ELA)$ is the upper limit of the increasing rate of *ELA*, whereas $RC_{DOWN}(ELA)$ is that of the decreasing rate. $C(T, ELA)$ is the installed capacity of *ELA* in *T*.

$$\begin{cases} E(T,Z,Y,ELA) - E(T,Z,Y-1,ELA) \\ \le RC_{UP}(ELA) \cdot qhr(Z,Y) \cdot C(T,ELA) \\ E(T,Z,Y-1,ELA) - E(T,Z,Y,ELA) \\ \le RC_{DOWN}(ELA) \cdot qhr(Z,Y) \cdot C(T,ELA) \end{cases}$$

Eqs. (2)–(4) stand for the LFC constraints [6]. The constraint equations of the upper limit of the LFC capacity are given by (2) and (3). $C_{LFC}(T, Z, Y, ELA)$ is the LFC capacity of *ELA* at *Y* in *Z* in *T*. $R_{LFC}(ELA)$ is the proportion of the LFC capacity of *ELA* to the rated capacity. $R_{Pmin}(ELA)$ is the proportion of the minimum output of *ELA* to the rated capacity; $af(ELA)$ is the availability factor of the *ELA*. The Eq. (4) indicates that the total LFC capacity must be more than a certain proportion to the total electric power demand. $E_D(T, Z, Y)$ is the total electric power demand at *Y* in *Z* in *T*. R_D is the proportion of the LFC capacity to the total electric power demand, which is set to 2% in this study. The LFC capacity for the output fluctuation of the renewable energy sources is not considered.