Article

Evaluation of the Daily Load Curve by Taking V2G of PEVs into Consideration

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Abstract: This paper presented a method for calculating daily load curves by considering charging and discharging locations of electric vehicles to help to understand the impact of loads generated by charging and discharging of electric vehicles on the power grid. Based on the estimated PEVs' share, the PEVs discharge power was calculated to reflect both the characteristics of the arriving vehicle in the morning and the SMP plan after establishing a assumption that the electric vehicle arrived at work in the morning and the electric vehicle arrived at home in the afternoon for each of the charging/discharging locations, that is, work and home, of electric vehicles in the city. After calculating the daily load curve for each charging/discharging power type for the PEVs charging strategy, which takes into account both the characteristics of the vehicle arriving at home in the afternoon and the TOU fare system and the characteristics of the vehicle arriving at work in the morning and the SMP fare system, it was analyzed by comparing the impact assessment on the grid by adding the existing load. The results of this paper provide an accurate understanding of the impact of PEVs charging and discharging loads on the power grid. The results should help to establish PEVs charging and discharging load management plans to prevent overloading the power grids with appropriate SMP and TOU tariffs while curbing the reinforcement and expansion of power grids as much as possible.

Keywords: Charging location; Discharging location; Time of Use(TOU); System Marginal Price(SMP)

1. Introduction

Efforts to promote plug-in electric vehicles (PEVs) have been spreading worldwide as part of measures to address air pollution caused by CO2 in automobile exhaust gases. Thus, the number of PEVs linked to the distribution systems is expected to increase rapidly in the future. This expansion is expected to pose a potential burden to utilities eventually.

Power companies and governments work together to predict the demand for power generated by charging and discharging PEV batteries to support relevant technical standards and transaction regulations and prepare for the expansion of PEVs worldwide. Various studies are underway to determine whether they will meet the increased demand for charging and discharging power. Most studies are focused on assessing the impact of charging PEVs on the grid. However, studies reflecting the impact of charging and discharging PEV batteries on the grid and the plans to reduce this impact are insufficient [1, 2].

Various studies of PEVs' energy consumption (the load on PEV battery charge) have shown that large-scale deployment of PEVs could significantly affect the national power grid and residential distribution systems. The studies also demonstrate that a substantial increase in the number of PEVs not having a very high impact on the national power grid,

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and a direction of study is required to produce accurate results that suit national conditions [3-7]. Also, the studies should focus on researching optimal locations for PEVs' charging stations [8].

In particular, a study [9] was conducted in New York City, US, on applying the intelligent PEV charging scheme to reduce load balancing of the grid and cost by charging PEV load during valley-fill hours and another study [10] was conducted in Ireland on using DSM (Demand Side Management) to optimize the PEV charging cycle, thereby saving cost for consumers and peak load demand on the grid. In another study [11], PEV scheduling algorithms were developed that satisfy the charging requirement of PEV owners through impact analysis on DRM (Demand Response Management). There is also a study [12] conducted in Winnipeg City, Canada, where PEV charging was predicted and analyzed through stochastic method using vehicle usage data.

Also, there are several studies on PEVs' time-of-use (TOU) tariffs, which are necessary to minimize the impact of charging PEVs on the grid. There is insufficient research on how flat a metropolitan area grid's daily load curve could be due to charging and discharging PEVs based on the TOU and system marginal price (SMP) tariff systems.

Some studies investigate the models of TOU tariff systems to minimize PEVs' charging costs in the regulated market [13] and research reducing the impact of PEVs' charging on the grid [14, 15]. Most research is limited to suggesting sequential charging, decreasing power loss, reducing charging fees for PEVs' owners, TOU strategies for peak reduction, and charging management at PEVs' charging stations using energy storage systems (ESS). There is no analysis of the grid's daily load curve's flattening effectiveness due to charging and discharging electric vehicles in large metropolitan areas based on the TOU and SMP tariff systems simultaneously.

It is essential to evaluate the impact of PEVs' charging and discharging on the grid in large cities to solve these problems. Also, PEVs' charging and discharging impact assessment should be completed beforehand.

Most owners of PEVs in large cities use their vehicles to commute to and from work. Thus, they want to charge and discharge PEVs at work or home. Therefore, to minimize the impact of PEVs' charging and discharging on the grid, it is necessary to model and calculate the impact of PEVs' charging and discharging on the grid per charging and discharging location at home or workplace.

Thus, this study develops the method of calculating PEVs' charging and discharging daily load curves based on charging and discharging locations in the metropolitan area. Specifically, it makes assumptions about discharging strategies to reduce grid peaks by going to work at PEVs discharging locations, such as a workplace, and charging from the grid at home in the afternoon in Seoul, South Korea, based on the PEVs' share scenarios for 2030 and 2040.

2. Daily load curves Calculation Method

This chapter proposes a calculation method of the daily load curve of vehicle charging and discharging in various charging and discharging locations in large cities. The load estimation assumed that the vehicle was charged from the grid when people went home in the afternoon. It also assumed that the vehicle discharged electricity to the grid when people went to work in the morning to relieve the grid peak.

The PEVs' share was estimated based on the scenarios for Seoul, South Korea, in 2030 and 2040. For estimating the charging and discharging rates, the numbers of vehicles driven per hour from work (in the afternoon) and to work (in the morning) were obtained from the Seoul city's database. Subsequently, the KEPCO SMP and TOU tariff systems were combined with the discharging and charging rates to yield the charging and discharging daily load curves for Seoul in 2030 and 2040.

This method's steps are described below:

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- Calculation of the probability density function for PEVs' discharging in the morning at work
- Calculation of the probability density function for PEVs' charging in the afternoon at home
- Calculation of the initial state of charge (SOC) status of the PEV battery at work and home;
- Calculation of the hourly charging and discharging power of PEVs using the PEVs' charging and discharging probability density function and the SOC status of the PEV battery at work and home;
- Calculation of the charging and discharging daily load curves of PEVs in Seoul in 2030 and 2040 using PEVs' charging and discharging power by PEVs' charging and discharging hours at work or home.

The proposed calculation method will provide an accurate daily load figure based on the charging and discharging loads of PEVs at work and home in Seoul. Also, it is expected to provide the basis for establishing charging TOU and discharging SMP tariffs and management plans to prevent the overload of Seoul's system

2.1 Charging and discharging modeling of PEVs by charging and discharging locations

For an analysis of grid impact based on PEVs' charging and discharging locations, the amount of traffic flowing in and out of downtown Seoul was analyzed based on data from the Seoul Metropolitan Police Agency's Comprehensive Traffic Information Center (Seoul Metropolitan Police Agency) [16]. Figure 1 presents the analysis results. And Table 1 presents self-consumption PEVs charging costs with TOU prices in South Korea.

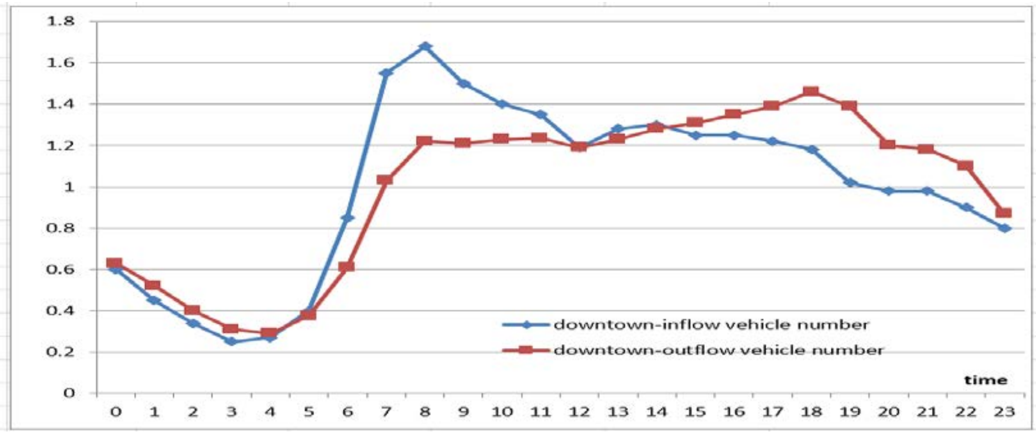

Figure 1. Inflow and Outflow Traffic Data for Downtown Seoul.

Table 1. Self-consumption PEVs charging cost with TOU tariff.

classification		Demand charge (KRW/kW)	Energy charge(KRW/kWh)*		
			Summer	Spring/fall	Winter
Low voltage	Off-peak load	2,320	55.8	56.9	78.2
	Mid load		140.8	68.3	124.2
	Peak load		225.3	73.1	184.9
High voltage	Off-peak load	2,500	50.9	51.8	67.7
	Mid load		107.3	62.3	97.9
	Peak load		158.6	66.1	134.5
Time-period classification in Winter: off-peak (23:00-09:00), peak (10:00-12:00, 17:00-20:00, 22:00-23:00), mid load (other times)					

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Time-period classification in Summer and Spring/fall: off-peak (23:00-09:00), peak (11:00-12:00, 13:00-17:00), mid load (other times)
Source : Electricity tariff structure by Korea Electric Power Company

As shown in Fig. 1, the traffic flow into the city for work peaks from 7 to 9 a.m. However, it can be seen that the amount of traffic flowing out of the city for work is evenly distributed from 5 p.m. to late at night.

In this paper, the following assumptions were made for the inflow and outflow of vehicles downtown to assess the effects of the grid on charging and discharging PEVs:

- Going to work (inflow vehicles – outflow vehicles) → PEVs' discharging (6 a.m. - 3 p.m.);
- Going home (outflow vehicles – inflow vehicles) → PEVs' charging (4 p.m. - 5 a.m.).

Based on these assumptions, the method of using traffic data modeling as the uncontrolled mode due to differences in the inflow and outflow of PEVs and using the traffic volume data as the controlled mode due to differences in the inflow and outflow to the city to minimize the grid impact through the strategic control of PEVs charging and discharging were calculated together with the SMP and TOU fares by KEPCO [17] for the probability of PEVs charging and discharging respectively.

2.1.1. Probability density function of PEVs discharging start time at the workplace

First, it was assumed that PEVs' discharge probability density function at work was the uncontrolled type, which was calculated by subtracting the difference between the outflow traffic and the inflow traffic by hour in downtown Seoul considering the one-hour driving time in the morning (formula 1).

This is a controlled type to minimize the grid impact, which is calculated as shown in formula (2) by applying the difference between the inflow and outflow traffic over time and the SMP tariff together. The probability density function for the discharging start time in the workplace is calculated based on formula (1) because the PEVs entering the downtown were assumed to be used for driving to workplaces. Therefore, these PEVs were thought to start discharging after a certain time (e.g., one hour) after driving into the downtown area. The probability density function for the controlled charging mode's start time at work is calculated based on formula (2) because the higher the SMP tariff, the higher the probability that PEVs will discharge after arriving at work.

Probability of discharging start time at work (uncontrolled mode):

$$P_{uw}(t) = \frac{(PEVs_{inflow}(t) - PEVs_{outflow}(t))}{whole\ PEVs} \tag{1}$$

Probability of discharging start time at work (controlled mode):

$$P_{cw}(t) = \frac{\left(PEVs_{inflow}(t) - PEVs_{outflow}(t)\right)}{whole\ PEVs} \times SMP(t) \tag{2}$$

Table 2 shows the estimated discharge probability density at work in uncontrolled mode considering the difference in the traffic volume driving in and out of the city. Table 2 also shows the discharge probability density results, including the SMP tariff, for a comparison. In contrast to Table 2, Table 3 represents the discharge probability density in the controlled mode where the SMP tariff is highly adjusted during the peak hours.

Table 2. Discharge Probability Density in the Uncontrolled Mode at Workplace.

Time (H)	SMP1 (kWh/KRW)	Discharge probability density	
		Vehicle operation	Vehicle operation + SMP1
6	69	0.01	0.01
7	70	0.13	0.14

8	70	0.27	0.30
9	69	0.24	0.26
10	53	0.15	0.13
11	47	0.09	0.07
12	47	0.06	0.05
13	47	0.01	0.01
14	47	0.03	0.02
15	47	0.01	0.01

Table 3 Discharge Probability Density in the Controlled Mode at Workplace.

Time (H)	SMP_2 (kWh/KRW)	Discharge probability density	
		Vehicle operation	Vehicle operation + SMP_2
6	70	0.01	0.01
7	13	0.13	0.01
8	94	0.27	0.20
9	105	0.24	0.20
10	118	0.15	0.14
11	247	0.09	0.18
12	390	0.06	0.19
13	160	0.01	0.01
14	195	0.03	0.05
15	70	0.01	0.01

Table 4 shows the estimated charging probability density at home in the uncontrolled mode considering the difference between the inflow and outflow traffic volume. Table 3 also shows the charge probability density results, including the TOU tariff, for a comparison.

Table 5 shows the charging probability density in the controlled mode where the TOU tariff is lowlily adjusted during the afternoon hours.

Table 4 Charging Probability Density in the Uncontrolled Mode at Home.

Time (H)	SMP_2 (kWh/KRW)	Discharge probability density	
		Vehicle operation	Vehicle operation + SMP_2
0	55.8	0.03	0.05
1	55.8	0.02	0.04
2	55.8	0.03	0.06
3	55.8	0.03	0.06
4	55.8	0.03	0.06
5	55.8	0.01	0.02
16	225.3	0.03	0.01
17	225.3	0.05	0.02
18	140.8	0.09	0.07
19	140.8	0.15	0.11
20	140.8	0.20	0.14
21	140.8	0.12	0.09
22	140.8	0.11	0.08

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23	55.8	0.10	0.19

Table 5 Charging Probability Density in the Controlled Mode at Home.

Time (H)	SMP_2 (kWh/KRW)	Discharge probability density	
		Vehicle operation	Vehicle operation + SMP_2
0	50.9	0.03	0.05
1	50.9	0.02	0.03
2	50.9	0.03	0.05
3	50.9	0.03	0.05
4	50.9	0.03	0.05
5	50.9	0.01	0.02
16	158.6	0.03	0.01
17	158.6	0.05	0.03
18	107.3	0.09	0.07
19	107.3	0.15	0.12
20	107.3	0.20	0.16
21	107.3	0.12	0.10
22	107.3	0.11	0.09
23	50.9	0.10	0.17

2.1.2. Analysis of the probability density function for PEVs' charging and discharging

As shown in the probability density function for the uncontrolled and controlled discharge in the workplace presented in Table 2, in the case of the uncontrolled mode, the probability density gradually increases from 6 a.m. to 8 a.m. and then gradually decreases from 9 a.m. It can be seen that the rate of reduction increases in the afternoon. Notably, the probability density reaches its maximum at 8 a.m.

In the case of the controlled $mode_1$ (Table 3), the probability density is higher than the uncontrolled mode to some extent, albeit the difference is small, by the effect of the SMP tariff. However, in the case of the controlled mode 2 (Table 4), unlike the controlled $mode_1$, the probability density increases from 6 a.m. to 7 a.m., sharply increases from 8 a.m. to 9 a.m., stays almost the same until noon, and then slowly decreases. The maximum is reached during the 8 a.m - 9 a.m period. The differences among the controlled $mode_1$, controlled $mode_2$, and the uncontrolled mode could be attributed to the fact that the SMP tariff is relatively high from 8 a.m. to 2 p.m.

Table 3 also shows that, in the case of the uncontrolled mode, the probability density gradually increases from 4 p.m. to 8 p.m., starts to decrease from 9 p.m., and rapidly decreases from midnight to 5 a.m. It reaches its maximum at 8 p.m.

The results for the controlled mode did not differ significantly from the uncontrolled mode. However, the controlled mode is shown to have a relatively low charging probability density in the afternoon due to the effects of the TOU tariffs and a slightly higher charging probability density from midnight to 5 a.m. Also, the controlled mode shows a relatively constant probability density from 6 p.m. to 6 a.m. due to the application of the TOU tariffs.

The probability density stays low from 6 p.m. to 6 a.m. because the TOU tariffs are applied, in contrast to the uncontrolled mode. However, as shown in Table 4, in the case of the controlled mode 2, the probability density sharply increases from 4 p.m. to 10 p.m. and then relatively slowly increases from 11 p.m. to 5 a.m., unlike the controlled $mode_1$.

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There are significant differences among the uncontrolled mode, controlled mode$_1$, and controlled mode$_2$ because the TOU tariffs are relatively low from 4 p.m. to 10 p.m.

Figure 2, 3, and 4 present the uncontrolled charge and discharge probability density function by time estimated using the vehicles' inflow and outflow volumes and that of the controlled mode$_1$ and mode$_2$ for the sum of the SMP and TOU tariffs on the vehicles driving in and out of the downtown.

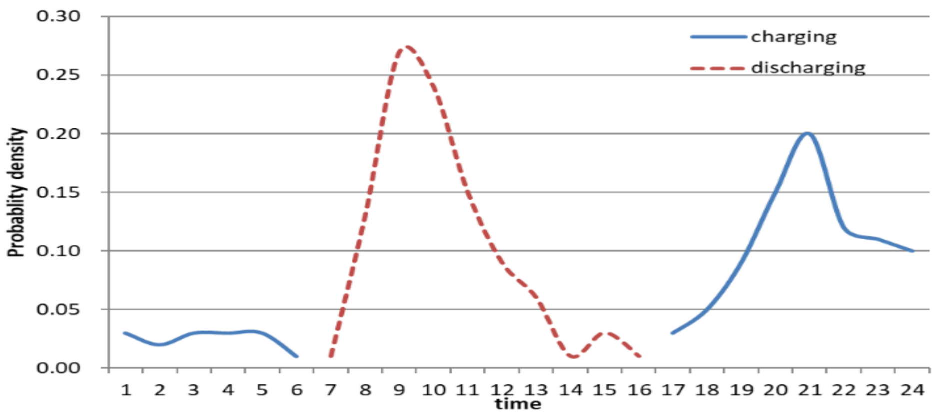

Figure 2 Charging and Discharging Probability Density Function by Hour for the Uncontrolled Mode (vehicle operation).

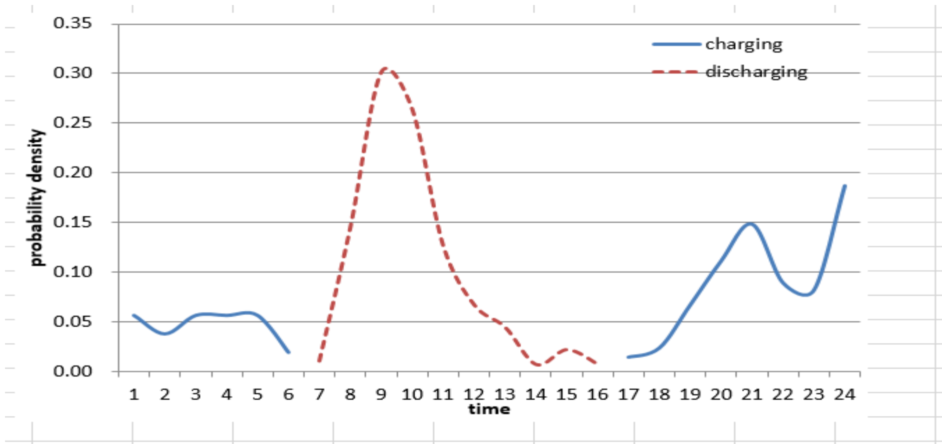

Figure 3 Probabilistic density function for the Controlled Charging Start Time in the Workplace.

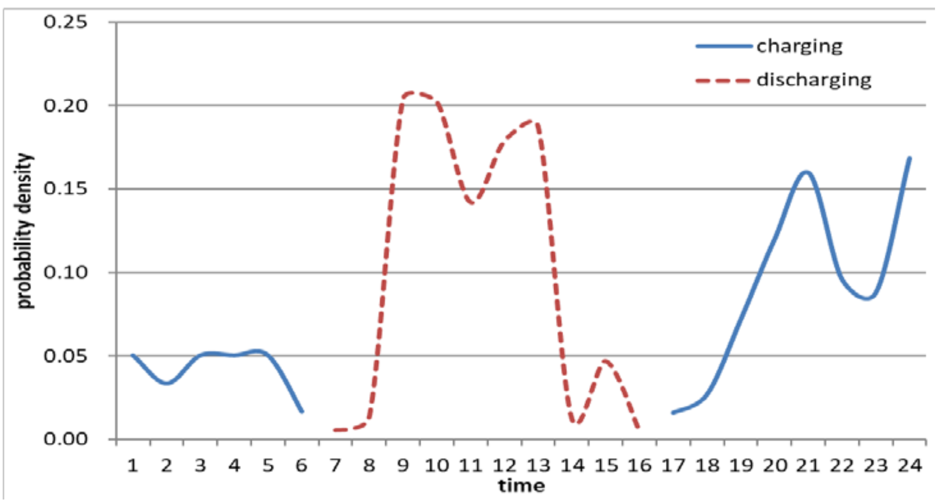

Figure 4 Probabilistic density function for the Controlled Charging Start Time in the Workplace.

2.1.3. Calculating the SOC Condition of the PEV Battery

The battery's SOC condition when going to and leaving work can be calculated according to the average mileage information predetermined for charging and discharging PEVs. Thus, SOC_0 is calculated by taking into account daily driving distance and maximum PEVs driving distance. Then, The daily commuting distance of 46.2 km was applied by quoting the Vehicle Mileage Analysis Report of the Seoul Metropolitan Government Korea Transportation Safety Authority [18] to calculate the initial SOC_0 for the workplace or home locations.

Hence, considering the 46.2 km of commuting distance in Seoul, the remaining battery's SOC at work and home is 21.6 kWh considering BERR reports [19]. In other words, the battery's initial SOC_0 status for charging and discharging PEVs after going to or leaving the workplace is as following

$46.2km \times 0.16kWh/km = 7.4kWh$

$SOC_0 = 29kWh - 7.4kWh = 21.6kWh$

The PEVs' charging and discharging power consumption at work and home after work is calculated by assuming that 10% (2.9 kWh) of battery capacity for emergency movement is left in the battery's initial SOC_0. Also, the time required for PEVs charging and discharging power consumption at work and home is calculated by considering hourly charging and discharging characteristic curve of 29 kWh of lithium-ion batteries as following.

Discharging power consumption:

$SOC_0(21.6kWh) - 2.9kWh = 18.7kWh$

Charging power consumption:

$29kWh - 2.9kWh = 26.1kWh$

Discharging time at work:

$18.7kWh / 6.5kW \fallingdotseq 2.75h$

Charging time at home:

$26.1kWh / 6.5kW \fallingdotseq 4.00h$

2.2. Grid Impact Analysis by PEVs Charging and Discharging Locations

Charging model algorithms for each location and the resulting probability density functions of charging and discharging for the controlled and uncontrolled modes at home and in the workplace were suggested in section 2.1. Subsequently, the daily load curve for charging and discharging PEV batteries has been developed considering the probability density function, the PEV initial SOC status, charging and discharging times, and hourly charging and discharging power.

The number of PEVs was calculated by setting the PEVs' share to 10% and 30% of all vehicles in 2030 and 2040, respectively. This calculated the number of uncontrolled and controlled modes' charging and discharging daily load in the single PEVs charging and discharging daily load curve was calculated based on the number of vehicles.

Also, based on the results of Korea Energy Management Corporation's Analysis of Acceptance Specifications Load Patterns [20] in 2018, the Seoul Metropolitan Government calculated the existing load curve. Fig. 5 presents the results of this calculation.

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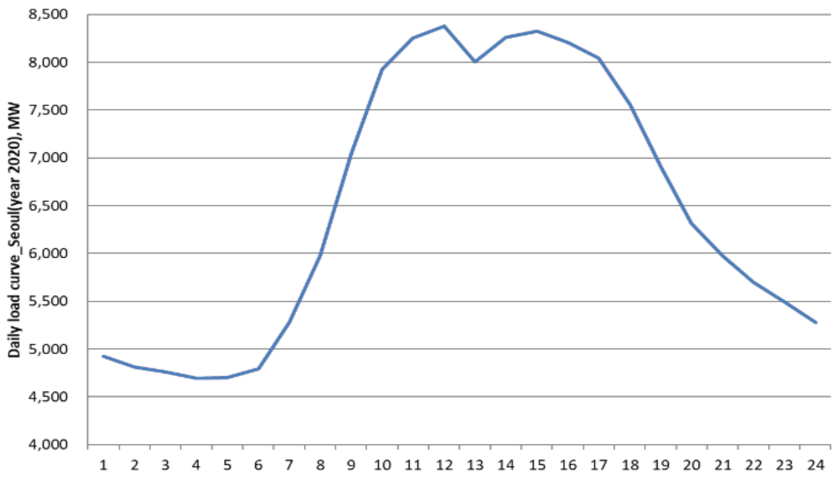

Figure 5 Daily Load Curve in Seoul, South Korea.

Based on Figure 5, a load increase trend technique is applied to calculate the existing load curve for Seoul Metropolitan Government in 2030 and 2040. The total daily load curve for uncontrolled and controlled modes of PEVs' charging and discharging in 2030 and 2040 was calculated based on the PEVs' charging and discharging probability density function by charging and discharging location previously described in Figures 2-4. Figure 6 presents the overall flowchart of daily load curve calculations based on PEVs' charging and discharging locations in Seoul, South Korea.

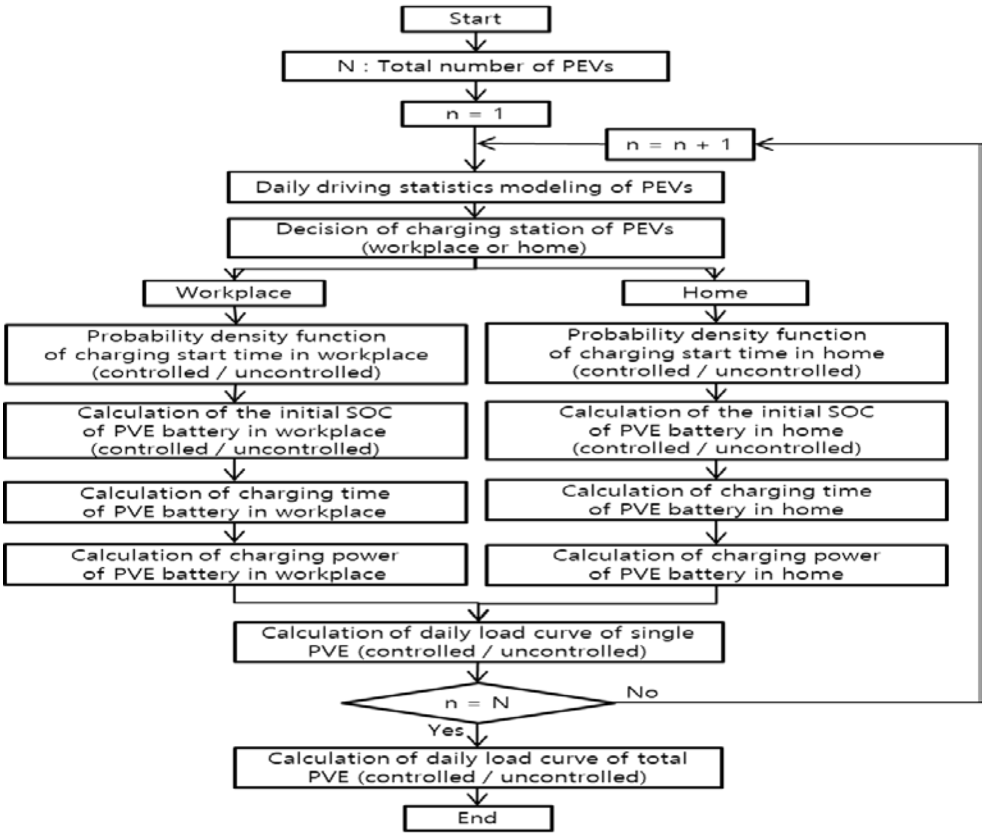

Figure 6. Daily Load Curve Calculation Flowchart Based on PEVs' Charging and Discharging Locations in Seoul, South Korea.

According Fig. 6, the overall uncontrolled mode, controlled mode$_1$, and controlled mode$_2$ of Seoul's daily load curve in 2030 and 2040 was calculated. The calculation results are illustrated in Fig. 7-12. Therefore, the results of the calculations of the total daily load curves for uncontrolled and controlled modes based on the PEVs' share in 2030 and 2040 in Seoul are as follows.

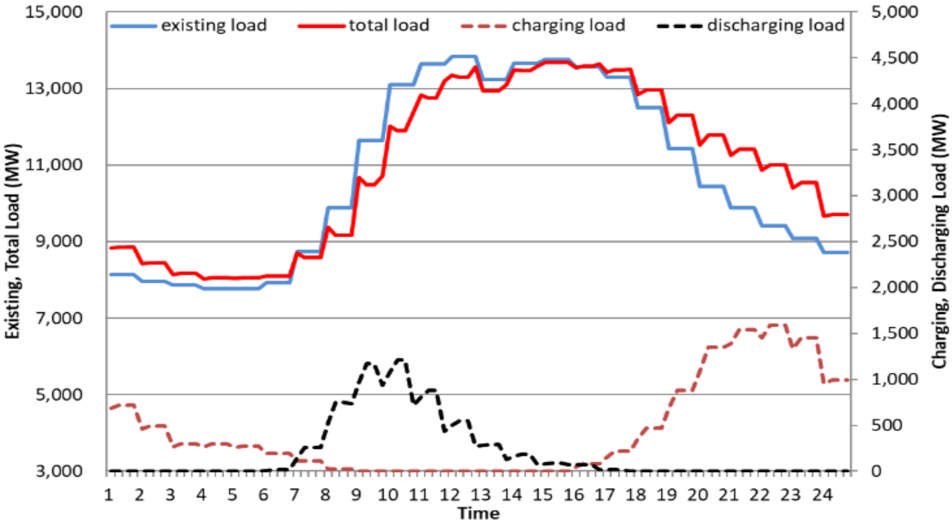

Figure 7 Daily Load Curve in Seoul in 2030 (uncontrolled mode).

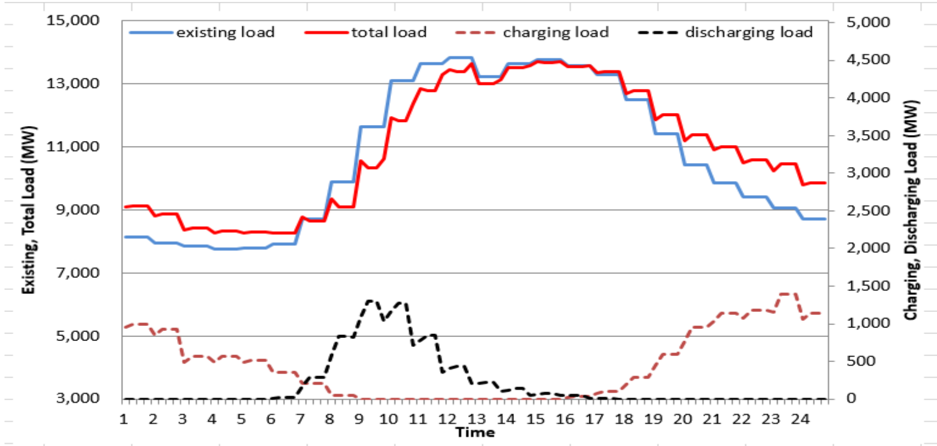

Figure 8 Daily Load Curve in Seoul in 2030 (controlled mode1).

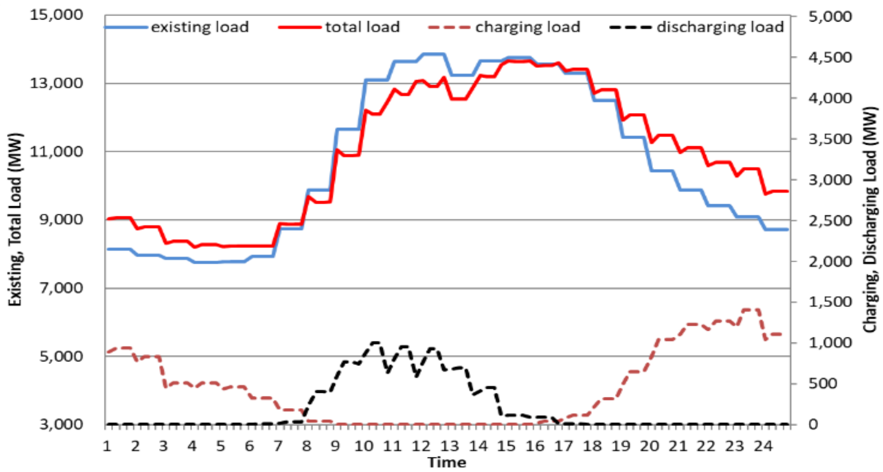

Figure 9 Daily Load Curve in Seoul in 2030 (controlled mode2).

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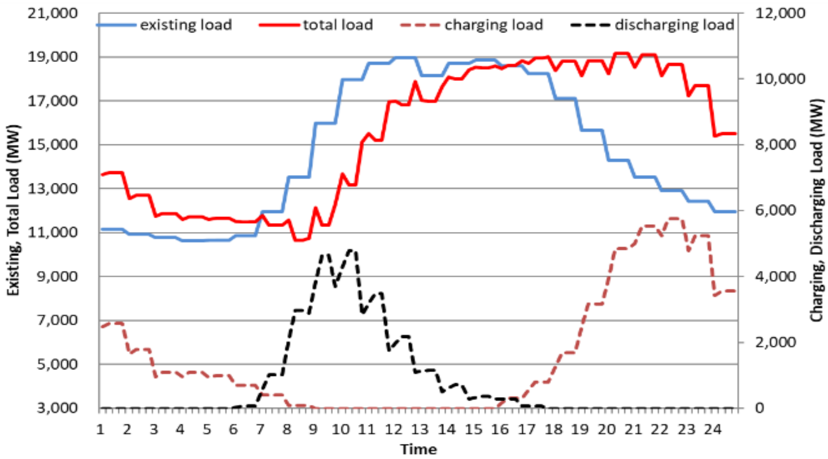

Figure 10 Daily Load Curve in Seoul in 2040 (uncontrolled mode).

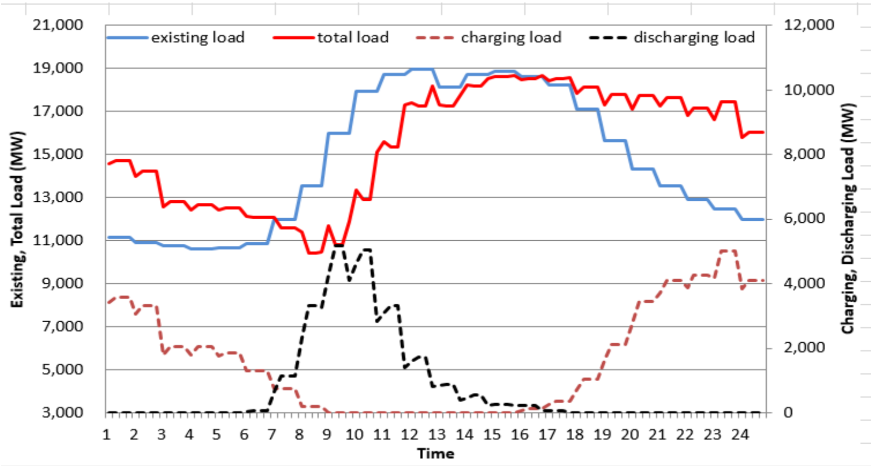

Figure 11 Daily Load Curve in Seoul in 2040 (controlled mode1).

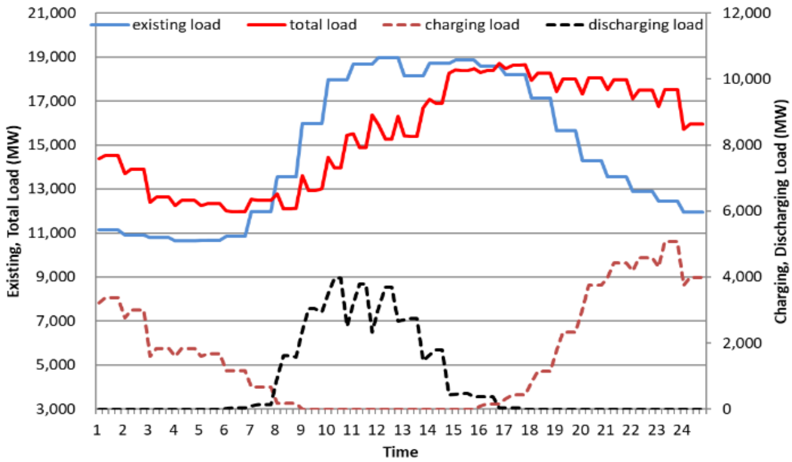

Figure 12. Daily Load Curve in Seoul in 2040 (controlled mode2).

As shown in Fig. 7-12, the conventional 2030 and 2040 daily load curve indicates that the load gradually increases from 9 a.m., decreases from 12 p.m. to 1 p.m., increases from 1 p.m., reaches its peak around 2 p.m., and then gradually decreases from 6 p.m.

In the case of the uncontrolled mode, the discharging starts at 6 a.m. (discharging time at the workplace), and the load gradually increases from that time. It flattens at 9 a.m. and then decreases. In the case of the controlled mode1, the load curve shows a similar behavior with the uncontrolled mode, but the discharge load is higher due to the SMP tariff. The controlled mode2 is different from the controlled mode1 in that the discharging load stays high and continues until the grid peak. Overall, the controlled mode associated with SMP fare has a lower discharge rate in the morning and a higher discharge rate in the afternoon than the uncontrolled mode.

Also the 2030 and 2040 home charging load curves show that, in the case of the uncontrolled one, the charging load gradually increases from 6 p.m. (home charging time), reaches its peak at 10 p.m., and gradually decreases until late at night. The controlled mode1 shows a similar behavior, yet the charging power is relatively lower in the afternoon and higher late at night than the uncontrolled mode due to the TOU tariffs. The controlled mode2 is different from the controlled mode1 in that the charging power is lower in the afternoon and higher late at night. Overall, the controlled mode associated with the TOU tariffs has a higher charging rate in the morning and late at night and a lower charging rate in the afternoon than the uncontrolled mode.

Therefore, based on the combined daily load curves for the uncontrolled mode, controlled mode1, and controlled mode2 in 2030 and 2040, the following conclusions can be derived.

First, when the PEVs' share is 10% (in 2030), both the controlled mode1 and uncontrolled mode2 do not show high charging and discharging loads at home and in the workplace. Thus, concerning the uncontrolled mode, the total load increases by 1-2% from late at night to 10 a.m. (off-peak time). Between 11 a.m. and 5 p.m. (peak time), it decreases by 1-4% for the controlled mode1 and uncontrolled mode2. Therefore, applying the TOU and SMP tariffs can increase the morning load and decrease the load in the afternoon.

Second, when the PEVs' share is 30% (2040), the controlled mode1 and controlled mode2 show high charging and discharging loads at home and in the workplace. In the case of the controlled mode1, the total load increases by 2-3% from late at night to 10 a.m. (off-peak time) and decreases by 3-9% between 11 a.m. and 5 p.m. (peak time). In the case of the controlled mode2, it increases by 3-5% from late at night to 10 a.m. (off-peak time) and decreases by 6-15% between 11 a.m. and 5 p.m. (peak time).

To conclude, the TOU and SMP tariffs could significantly increase the morning load and decrease the load in the afternoon. The controlled mode2 can flatten the load curve most effectively, compared with the other modes.

3. Conclusions

According to the estimated PEVs' share in Seoul in 2030 and 2040, this was based on the condition of discharging PEVs in the morning when they arrive at work and condition of charging PEVs in the afternoon when they arrive home from work. After an additional calculation of PEVs' charging daily load curve for the year by dividing it into the uncontrolled mode (based on the number of hours of vehicle operation) and the controlled mode (SMP and TOU tariffs + the number of vehicle operations per hour) considering whether to reflect the charging and discharging tariff systems, the total daily load curve in Seoul was calculated for uncontrolled and controlled modes by year by adding them to the existing daily load curve.

The results of this paper provide an accurate picture of the daily load by the charging and discharging loads of PEVs at work and home in Seoul. The study should provide a basis for establishing a discharging SMP tariff and charging TOU tariff management plan to prevent the overload of Seoul's system.

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