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A cost-benefit analysis of V2G electric vehicles supporting peak shaving in Shanghai

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ABSTRACT

The costs and benefits of the participants including electric vehicle users, power grid companies and power plants were analyzed when four brands of electric vehicles participated in V2G peak shaving service in Shanghai. Sensitivity analysis was conducted to determine the key parameters that affected the costs and benefits of electric vehicle users and power grid companies. The results show that the total net profit of V2G services is greater than zero under the appropriate set of parameters. The net incomes of electric vehicles users are greater than zero in V2G peak shaving services when the peak price of electricity fed into the grid is more than three times the valley price. The lower the cost of electric vehicle battery, the more the net income of single user. The net incomes of power grid companies are always very negative and the higher the peak shaving load, the greater the net loss of the power company. The benefits of power plants are the biggest among three participants and are far greater than those of electric vehicle users. A fair market distribution mechanism of V2G profits should be built among three participants in order to promote the healthy development of V2G applications.

1. Introduction

China's government actively encouraged the development of electric vehicles and constantly introduced incentives to stimulate consumers to buy electric vehicles in the last ten years. Electric vehicles have made considerable progress in China. Electric vehicle sales in 2018 achieved 1,256,200 and were 61.67% higher than those in 2017. The sales volume of electric vehicles in China has ranked the first in the world for four years in a row [1]. Suppose that the average battery capacity is 20 kWh per vehicle, the battery capacity of 1,256,200 electric vehicles in 2018 will reach 25,124 MWh, which is also a potentially large source of energy storage for the power grid. The cumulative installed capacity of China's electrochemical energy storage market is nothing but 3103 MWh by the end of 2018 [2]. If 20% of the electric vehicles participate in V2G services each year, they can not only improve the stability of the power grid and the quality of power, but also make enormous arbitrage profits from peak and off-peak power price difference.

The V2G mode is described as a system that an electric vehicle can either be charged from the grid or fed back into it. In general, the surplus power of the grid is stored in electric vehicles during the period of low power while electric vehicles feedback power to the grid at peak hours in the V2G mode [3,4]. Through this peak shaving mode, electric vehicle users can purchase electricity from the power grid when the electricity price is low and sell electricity to the power grid when the electricity price is high, thus obtaining arbitrage benefits. The V2G mode not only provides new opportunities for value-added services of electric vehicles, but also helps the efficient and smooth operation of power generation and power supply enterprises. Except V2G energy storage is used for peak shaving and valley filling in power grid, it can also be used for such energy storage as regulation services [4–7], renewable energy reserves [8–10], and spinning reserves [11–13].

There is always an imbalance between the generated power and the load because electric energy has characteristics that are difficult to store on a large scale. For example, if the real-time demand for electricity is higher than the generation power in a short time, power plants need to generate more electricity immediately [14,15]. If the load power is lower than the generation power at another time, the generation of power plants decreases accordingly. As a result, it is an elaborate job to maintain the stability and reliability of electric power supply. The

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number of electric vehicles is increasing fiercely in China now and electric vehicles tend to be equipped with large capacity battery. Moreover, most vehicles are used for commute and have long idle time. Even it is reported that 90% of vehicles are still parked during rush hour in California [16]. The idle time of electric vehicles can be well matched with the load shifting time of V2G mode in most cases. The essence of V2G energy storage is the energy storage of lithium-ion batteries, which has the advantages of quick response speed and high energy conversion efficiency. Moreover, its adjustment is more effective for the power quality improvement than that of gas turbine power generation within the very limited peak power demand time every day [17].

Although V2G energy storage technology has many advantages, it still faces several social and economic challenges. Zeng et al. [18] analyzed the costs and revenues of plug-in electric vehicles using unidirectional and bidirectional V2G technologies and the simulation results showed that electric vehicles would gain economic benefit if they participated in the grid ancillary service. Nworgu et al. [19] quantified the economic incentive brought by V2G infiltration in power distribution network and believed that V2G had a significant economic incentive effect. Salah et al. [20] thought that a deadline differentiated pricing for electric vehicles would increase the revenue of charging service providers by 17%. Hui et al. [21] found that V2G strategy effectively reduced contamination emissions and cut down the investment of variable load plants. Mostafa et al. [22] also considered that the participation of V2G into power systems could reduce peak power generation costs. Lance et al. [23] believed that V2G application of heavy-duty electric vehicles was not only possible but also necessary for more profits while electric buses without V2G revenue would not be cost-effective compared with traditional diesel buses. A research from Zhao et al. [24] showed that electric trucks could generate an additional enormous income for owners if they provided V2G regulation service.

Even so, there are also some academic peers who doubt the feasibility of V2G technology. Feng et al. [25] felt that commercial electric vehicles were not economical compared with conventional diesel vehicles unless the battery cost was low enough or the price of fossil fuels was too high. Rebecca et al. [26] believed that V2G service would accelerate the battery degradation and V2G profits could not cover the cost of battery degradation related to V2G cycle. Hill et al. [27] also concerned about whether the revenue from V2G ancillary services can cover the loss of battery capacity caused by it. Peterson et al. [28] found that the use of a 1/2C discharge in V2G mode will exacerbate the degradation of battery. Besides, Mullan et al. [29] believed that the V2G mode required too much additional infrastructure investment and faced huge commercial risks in western Australia.

Although many scholars have analyzed various advantages and disadvantages of V2G, people seldom pay attention to the correlation between costs and benefits of electric vehicle users, power grid and power plants in the entire V2G system and the influence of the electric vehicle battery parameters and the electricity price of power grid companies on costs and benefits of all participants in the V2G system. All these factors also determine the total net benefits of the entire V2G system. In this paper, the costs and benefits of the participants including electric vehicle users, power grid companies and power plants were investigated when four brands of electric vehicles participated in V2G peak shaving service in Shanghai, China. Sensitivity analysis was conducted to determine the key parameters that affected the costs and benefits of electric vehicle users and power grid companies. Subsequently the total net benefits of the entire V2G system were analyzed under different peak loads shaved by four brands of electric vehicles. The purpose of this study is to analyze the feasibility of V2G peak shaving and valley filling in Shanghai, and to discuss suitable factors for profitable V2G service. Suggestions on the sustainable development of V2G applications are given.

This article is divided into five sections. Besides the introduction to the first section, the second section establishes the methodology for a cost-benefit analysis of a V2G system. The third section presents a description of the case study definition. The fourth section demonstrates simulation results according to the characteristics of peak power load in Shanghai, the performance parameters of different electric vehicle batteries, the peak electricity prices and the costs of charge–discharge piles. The fifth section is the conclusion of this paper.

2. Methodology

One of the main functions of the V2G mode is peak shaving and valley filling, which can reduce the peak generation load of power plants and improve the scrimpy generation load in the valley time. Therefore, power generation companies are one of the main beneficiaries of the V2G mode. In addition, the implementation of V2G mode can reduce or defer the construction of power transmission and transformation facilities, thus cutting down the cost of power grid upgrade. Meanwhile, power grid companies take charge of most of the V2G infrastructure costs, such as the investment cost of charge–-discharge piles. Additional V2G charge–discharge will increase the deterioration of vehicle batteries for electric vehicle users. Expected return that they are involved in V2G activities should not just cover the costs of battery degradation.

2.1. The costs and benefits of electric vehicle users

The costs of electric vehicle users participating in the V2G include the additional electricity charges for V2G charging and the depreciation cost of batteries. According to the literatures [30–32], the allowable daily discharge capacity E_v (kWh) of electric vehicles is calculated by Eq. (1).

$$E_v = \left(TES \cdot DOD - \frac{RB}{EFF}\right) \cdot \eta_{dis} \tag{1}$$

where *TES* represents the battery capacity (kWh) of electric vehicles; *DOD* signifies the allowable discharge depth of vehicle battery; *RB* denotes the daily driving distance (km) of an electric vehicle; *EFF* stands for the energy efficiency (km/kWh) of vehicle battery and η_{dis} represents the discharge loss coefficient of vehicle battery.

The energy storage cost c_b ($/kWh) of electric vehicles is calculated by Eq. (2).

$$c_b = \frac{BRC}{DOD \cdot CL} + c_l \tag{2}$$

where *BRC* is the cost of the vehicle battery ($/kWh); *CL* represents the cycle life of vehicle battery; and c_l denotes the charging price for electric vehicles at valley time.

The selected electric vehicles are divided into two groups. The first group including BYD e6 and Tesla model S have larger battery capacity and use charge–discharge piles of 50 kW rated power while the second group containing Roewe e50 and Nissan Leaf have relatively small battery capacity and employing charge–discharge piles of 7 kW rated power. The number of electric vehicles N_v is usually calculated using Eq. (3).

$$N_v = \frac{P_p \cdot h}{E_v} \tag{3}$$

where P_p represents the total discharge power of electric vehicles every year, namely the peak load transferred by the V2G serves annually and h stands for the number of hours that electric vehicles are discharged into power grid every day.

Eq. (4) is proposed for the number of electric vehicles N'_v if $\frac{E_v}{h}$ of BYD e6 and Tesla model S is greater than 50 kW or $\frac{E_v}{h}$ of Roewe e50 and Nissan Leaf is greater than 7 kW.

$$Nv' = \frac{P_p}{P'} \tag{4}$$

where P' is the rated power of charge–discharge piles.

The cost C_u of electric vehicle users participating in V2G can be calculated by Eq. (4).

$$C_u = \sum_{t=1}^{T} \frac{1}{(1+i)^t} \cdot \frac{c_b}{\eta_{ch}} P_p \cdot h \cdot n \tag{5}$$

where n represents the number of days that electric vehicles are discharged into the power grid; η_{ch} signifies the charging efficiency of the battery; T denotes the years of benefit assessment; and i is the time-value of money per year.

The benefit of electric vehicle users (B_u) participating in V2G comes from the benefit that the electricity in electric vehicle batteries sells to power grid companies in the peak period.

$$B_u = \sum_{t=1}^{T} \frac{1}{(1+i)^t} \cdot c_d \cdot P_p \cdot h \cdot n \tag{6}$$

where c_d is the sale price that the electricity in electric vehicle batteries discharges to the power grid at peak time.

2.2. The costs and benefits of power grid companies

The costs of implementing V2G technology in power grid companies include investment costs of related equipment (such as investment costs of charging facilities, technology development costs and publicity costs, etc.), project management costs and loss of electricity sales revenue.

$$C_p = C_{p1} + \sum_{t=1}^{T} \frac{1}{(1+i)^t} \cdot [C_{p2} + c_d \cdot P_p \cdot h \cdot n] \tag{7}$$

$$C_{p1} = c_f \cdot N_v \tag{8}$$

where C_p is the total costs of power grid companies implementing V2G technology; C_{p1} is the total investment costs of related equipment, mainly referring to the investment costs of charge–discharge piles; C_{p2} represents the annual project management cost; and c_f stands for the investment cost of charge–discharge piles per electric vehicle.

The benefits of power grid companies (B_p) are mainly avoidable capacity costs after the implementation of V2G. The avoidable capacity costs refer to the reduced investment cost of the power grid companies, which can be determined according to the average costs of the substations, transformers, transmission lines and their corollary equipment that can be built sparsely or postponed.

$$B_p = c_t \cdot P_p + \sum_{t=1}^{T} \frac{1}{(1+i)^t} \cdot c_l \cdot P_p \cdot h \cdot n \tag{9}$$

where c_t represents the investment costs of power grid companies per avoidable capacity.

2.3. The costs and benefits of power generation companies

The implementation of V2G can reduce the investment in power generation equipment and power generation costs. The benefits from reducing the investment in power generation equipment can be determined according to the average costs of reducible peak-regulating units and their assorted equipment. The benefits from reducing generation cost can be determined by the difference of generation costs between peak load power and base load power. Since power generation companies have almost no investment costs in V2G applications compared with power grid companies, the costs of power generation companies are negligible. Therefore, the benefits of power generation companies (B_g) are counted by Eq. (10).

$$B_g = c_o \cdot P_p + \sum_{t=1}^{T} \frac{1}{(1+i)^t} \cdot \Delta c_g \cdot P_p \cdot h \cdot n \tag{10}$$

where c_o denotes the investment cost per unit capacity of generating unit, and Δc_g signifies the difference of generation costs between peak load power and base load power.

Table 1
Number of days and hours that peak load emerges in Shanghai in a certain year.

Lower load limit (MW)	Days of more than lower load limit	Hours of more than lower load limit
25,900	1	0.75
25,800	1	1.25
25,700	2	3.00
25,600	2	3.75
25,500	3	8.25
25,400	4	12.00
25,300	5	16.00
25,200	6	19.25
25,100	6	22.00
25,000	6	25.25
24,900	6	27.25
24,800	6	28.50
24,700	6	29.75
24,600	7	35.25
24,500	7	37.00

2.4. The net profit of V2G peak shaving

The net profit of implementing V2G peak shaving can be calculated according to Eqs. (1)–(11).

$$G = B_u + B_p + B_g - C_u - C_p \tag{11}$$

3. Case study definition

Typical metropolitan load characteristics are the low load rate of power grid, the large difference between peak load and valley load and the short time for peak load in Shanghai. The trend of slow growth of valley load and fast growth of peak load is more obvious in recent years. The contradiction between the actual peak-shaving capacity of power grid and the ideal peak-shaving needs is very sharp. Table 1 shows the number of days and hours that peak load emerges in Shanghai in a certain year according to the load data of Shanghai power grid. The maximum load is 25,992 MW and the number of days and hours with electricity load greater than 25,000 MW is only 6 days and 25.25 h, respectively. The number of days with electrical load greater than 25,500 MW is only 3 days and the total time is 8.25 h while the number of days with electrical load greater than 25,900 MW is only 1 day and the total time is 0.75 h, suggesting the short time for peak load in Shanghai.

The typical curves of power load in one day and time-of-use electricity price in Shanghai are shown in Fig. 1. It can be seen from Fig. 1 that electricity load has an obvious gap in the peak and valley time and the peak load is far higher than the valley load. The specific values of time-of-use electricity price in Fig. 1 are shown in Table 2. The research in this paper is based on the following market rules that the time-of-use electricity price is implemented on the demand side of the power market and the fixed feed-in electricity price is implemented on the power generation side.

Our case study focuses on the net profit of V2G peak shaving based on the data in Tables 1 and 2. The years of benefit assessment T is set as 10 years while the time-value of money per year i is 8%. The charging price c_l is set as 0.04452 \$/kWh in the valley time. In general, at least 1:1 ratio of electric vehicles and charging piles are required. Assuming that the ratio of electric vehicles and charge–discharge piles is 1:1 and the investment cost c_f of a 50 kW charge–discharge pile is 5600 \$ [30], the investment cost c_f of a 7 kW charge–discharge pile is about 800 \$. The investment costs of power grid companies per avoidable capacity c_t = 110 \$/kW; the investment cost per unit capacity of generating unit c_o = 725 \$/kW; the difference of generation costs between peak load

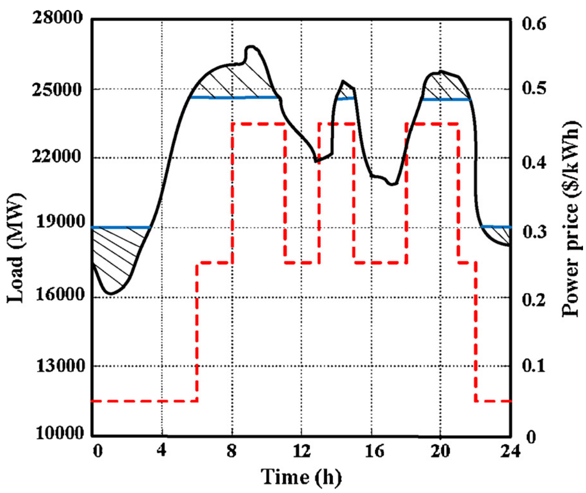

Fig. 1. The typical curves of power load in one day and time-of-use electricity price in Shanghai, China.

power and base load power Δc_g = 0.01015 $/kWh; and the annual project management cost C_{p2} = 725,000 $. Only when the discharging price paid by the power company to electric vehicle users is greater than the energy storage cost of electric vehicles, the users can feed electricity back into the grid. The sale price c_d that the electricity in electric vehicle batteries discharges to the power grid at peak time is set as ten times the charging price (c_l) for electric vehicles at valley time, e.i. 0.4452 $/kWh [33].

The economic benefits of electric vehicle users and power grid companies are highly correlated to the parameters of electric vehicle batteries. There are many electric vehicle brands in the market and different vehicle manufacturers have different battery technologies. The battery performance parameters vary from one electric vehicle to another. Table 3 shows the battery system parameters of four brands of electric vehicles such as BYD e6, Tesla model S, Roewe e50 and Nissan Leaf. The mileage of each electric vehicle (*RB*) is assumed to be 50 km per day. Table 4 presents the allowable daily discharge and energy storage cost of four brands of electric vehicles according to Eqs. (1) and (2).

4. Results and discussion

4.1. Cost-benefit analysis of electric vehicle users

4.1.1. Cost-benefit analysis of users employing four brands of electric vehicles

By analyzing the cost, benefit and net benefit of users employing four brands of electric vehicles, it can provide value judgment for users participating in the V2G service. Fig. 2 shows the cost-benefit analysis of the users participating in peak shaving using the four brands of electric vehicles. It can be seen from Fig. 2 that the costs, benefits and net incomes of the four brands linearly increase with the peak shaving load. The benefits of the four brands are always greater than their costs, respectively. And the net incomes of the users increase proportionally with the peak shaving load. The net incomes of the four brands are very small when the peak shaving load is below 400 MW, which is almost negligible. Therefore, the peak shaving load should be higher than 400 MW considering the user benefits. The larger the electric vehicle fleets participate in V2G service, the more the peak shaving load is, the greater the users' incomes will be.

Table 3
Battery system parameters of four brands of electric vehicles.

Electric vehicle	BYD e6	Tesla model S	Roewe e50	Nissan Leaf
Battery capacity (kWh)	82	85	22.4	24
Depth of discharge (%)	80%	80%	80%	80%
Energy efficiency (km/kWh)	5.13	6.32	7.52	5.6
Battery cost ($/kWh)	122	170	324	230
Cycle life	2000	1500	2000	2000

Four brands of electric vehicles have different net income due to different battery parameters such as battery capacity, energy efficiency, battery cost and cycle life. Fig. 3 shows the net incomes of the users participating in peak shaving using the four brands of electric vehicles. BYD e6 has the largest net income under the same load among the four brands of electric vehicles, and then Tesla model S, Nissan Leaf and Roewe e50 are ranked in a decreased manner. The sequence is consistent with that of their energy storage costs (c_b). The smaller the energy storage cost, the larger the net income. The net income of Tesla model S is a little more than that of Nissan Leaf because the energy storage cost of the former is slightly lower than that of the latter (Table 4).

4.1.2. Sensitivities of peak price and battery cost to user net incomes

Peak price has a strong correlation with user net incomes. After considering the energy storage cost of electric vehicle users participating in V2G service, the sensitivity of peak price to user net income is analyzed. In this case, BYD e6 is used for V2G electric vehicle and peak load above 24,500 MW will be shaved by V2G service of BYD e6. The number of electric vehicles N_v calculated using Eq. (3) is 149,435 for shaving peak load above 24,500 MW. The net income of single user equals the total net income of users divided by 149,435. The relationship between peak price and net income of single user is shown in Fig. 4. There is a proportional relationship between peak price and net income of single user. The higher the peak price offered by grid companies, the more the net income of single user. The net income of single user will be negative when the peak price is less than 0.1357 $/kWh, suggesting that the peak price of electricity fed into the grid should be more than three times the valley price (0.04452 $/kWh) in order to ensure the positive net incomes of electric vehicle users and encourage them to actively participate in V2G ancillary services.

Battery cost is another important factor affecting user net income. The rapid development of battery technology has prompted a substantial decline of battery cost in recent years. Lower battery costs will bring greater benefits to users. The above case is still adopted and the sale price c_d at peak time is set as 0.4452 $/kWh. The relationship between battery cost and net income of single user is displayed in Fig. 5, which is a negative linear correlation. The lower the cost of electric vehicle battery, the more the net income of single user, indicating that users with low-cost batteries are more likely to participate in V2G activities.

Table 2
The specific values of time-of-use electricity price in Shanghai, China.

Load conditions	Electricity price ($/kWh)	Load period
Peak load (feed-in)	0.4452	8:00–11:00, 13:00–15:00, 18:00–21:00
Basic load (feed-in)	0.2226	6:00–8:00, 11:00–13:00, 15:00–18:00, 21:00–22:00
Valley load	0.04452	22:00–6:00

Table 4
Allowable daily discharge and energy storage cost of four brands of electric vehicles.

Electric vehicle	BYD e6	Tesla model S	Roewe e50	Nissan Leaf
Allowable daily discharge E_v (kWh)	53.06	57.08	10.71	9.76
Energy storage cost c_b (\$/kWh)	0.1208	0.1862	0.2470	0.1883

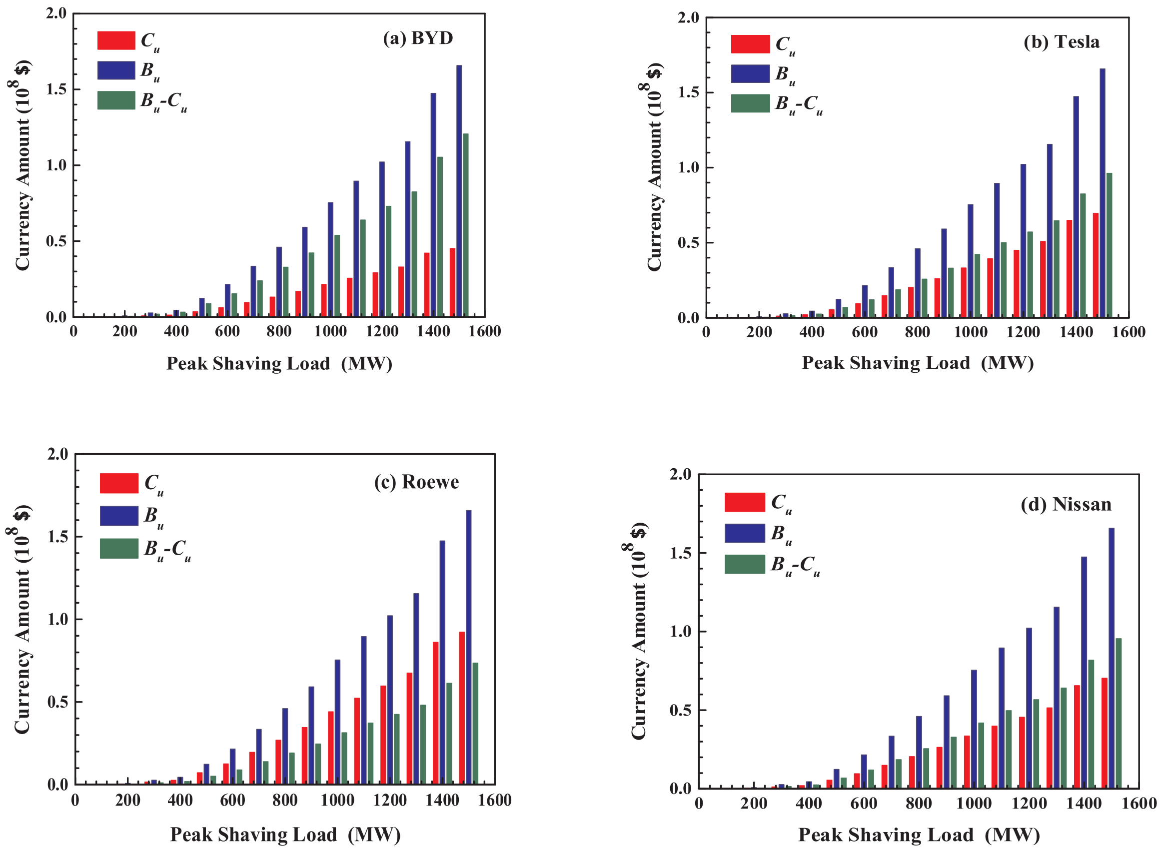

Fig. 2. Cost-benefit analysis of the users participating in peak shaving using the four brands of electric vehicles.

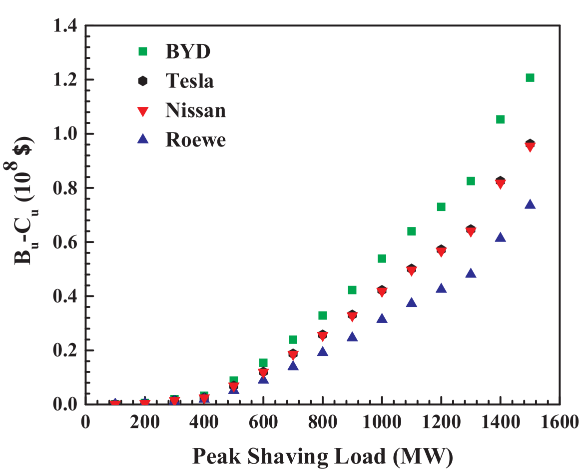

Fig. 3. The net incomes of the users participating in peak shaving using the four brands of electric vehicles.

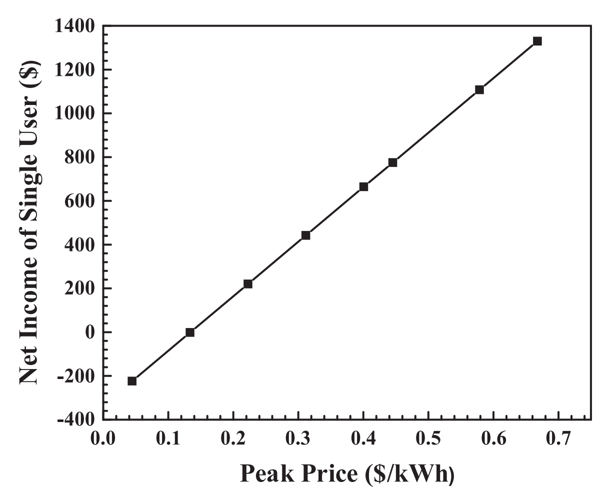

Fig. 4. Relationship between peak price and net income of single user.

4.2. Cost-benefit analysis of power grid companies

4.2.1. Cost-benefit analysis of power grid companies involved in V2G services

Power grid companies take charge most of the costs, such as the investment costs of charge–discharge piles and the management costs of the project in the entire process of V2G service. Therefore, the power company is a key player in implementing V2G services, who is responsible for setting peak price of electricity fed into the grid in the V2G service. Therefore, it is necessary to understand the costs and benefits of

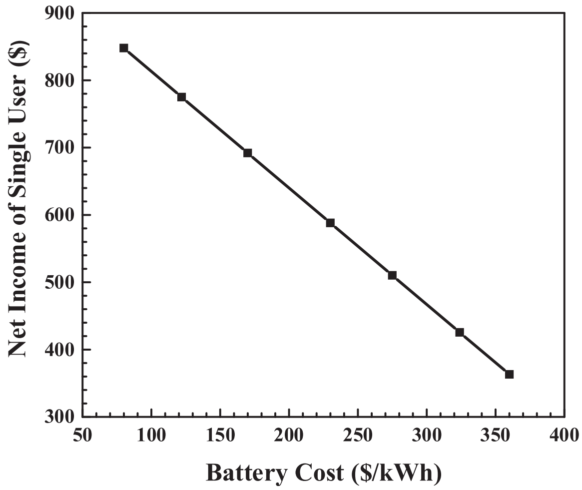

Fig. 5. Relationship between battery cost and net income of single user.

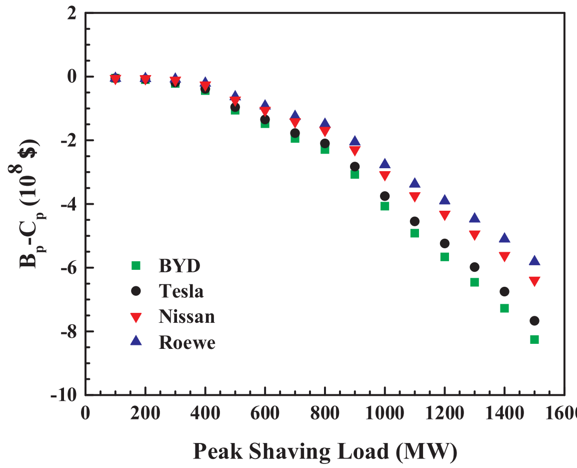

Fig. 7. The net losses of power grid companies in the case of peak shaving using the four brands of electric vehicles.

power grid companies in the V2G service. Fig. 6 shows the cost-benefit analysis of power grid companies in the case of peak shaving using the four brands of electric vehicles. It can be seen from Fig. 6 that the costs, benefits and net incomes of power grid companies increase proportionally with the peak shaving load in the case of peak shaving using four brands of electric vehicle. Power grid companies' costs always largely outweigh their benefits no matter what brand of electric vehicles participates in V2G service. As a result, the net incomes of power grid companies are always very negative and the higher the peak shaving load, the greater the net loss of the power company. Therefore, it is necessary to design a reasonable benefit distribution mechanism or compensation mechanism for power grid companies in order to encourage them to actively participate in V2G ancillary services.

Despite all this, the net loss of power grid companies is dissimilar in the case of peak shaving using electric vehicles of different brands. Fig. 7 illustrates the net losses of power grid companies in the case of peak shaving using the four brands of electric vehicles. It can be seen from Fig. 7 that the net losses of power grid companies employing BYD

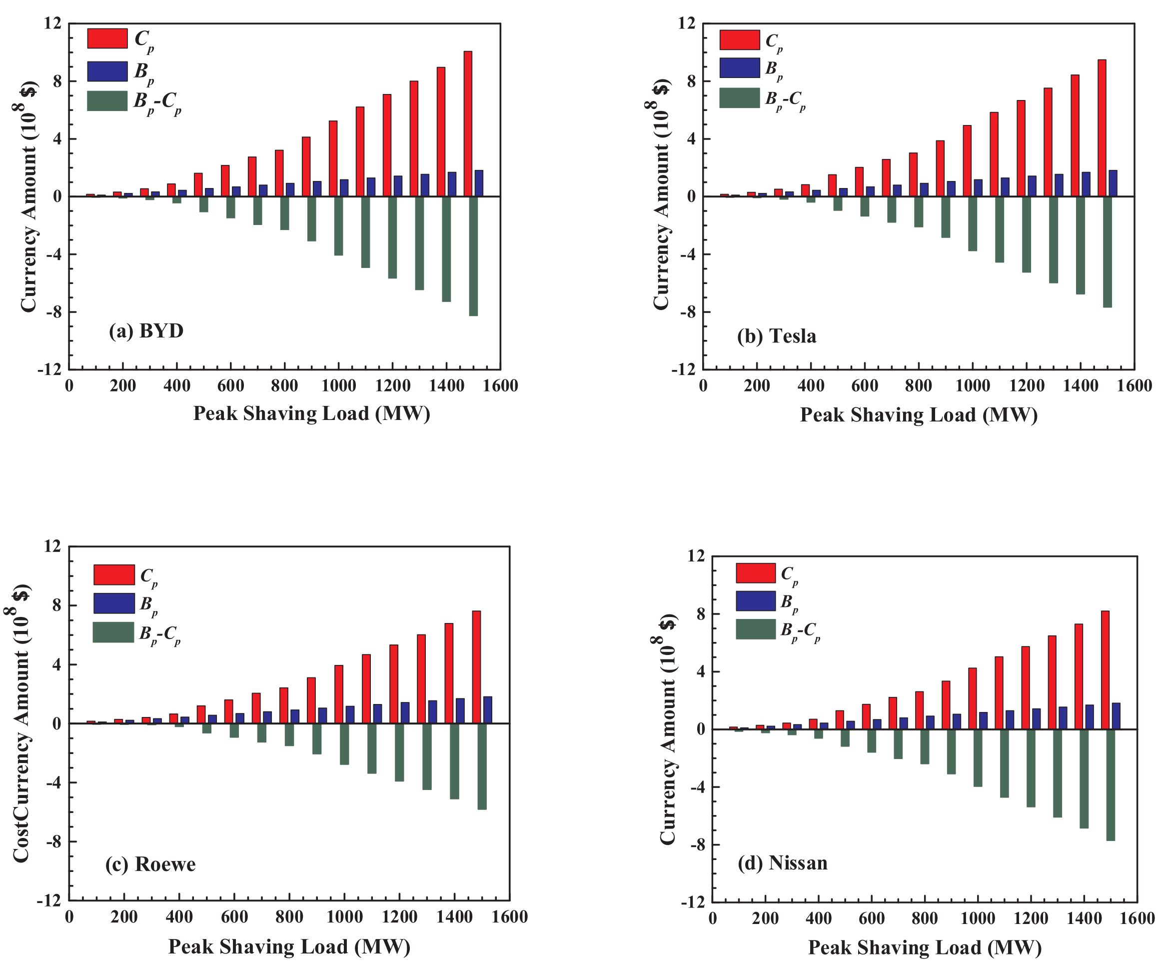

Fig. 6. Cost-benefit analysis of power grid companies in the case of peak shaving using the four brands of electric vehicles.

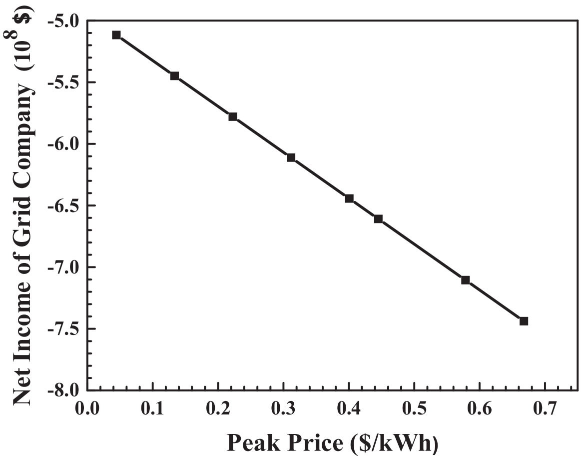

Fig. 8. Relationship between peak price and net income of power grid company.

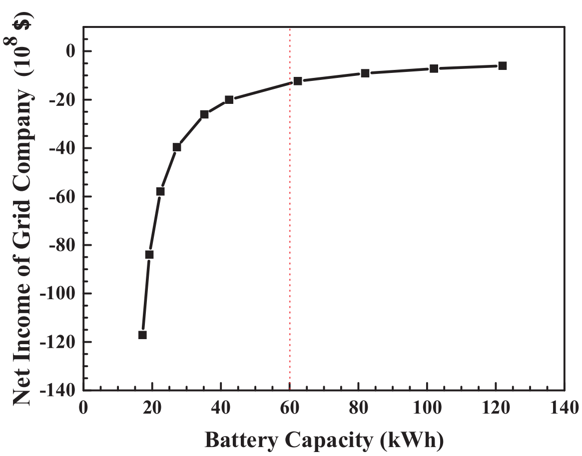

Fig. 9. Relationship between battery capacity and net income of power grid company.

e6, Tesla model S, Nissan Leaf and Roewe e50 are ranked in descending order under the same peak shaving load. The reason that the losses of employing BYD e6 and Tesla model S are more than those of employing Nissan Leaf and Roewe e50 is mainly that BYD e6 and Tesla model S use expensive 50 kW charge–discharge piles while Nissan Leaf and Roewe e50 employ cheap 7 kW charge–discharge piles. In addition, it is found that the available battery capacity of a BYD for peak shaving is smaller than that of a Tesla considering both battery capacity and energy efficiency. Reducing the same peak load requires more BYD cars than Tesla, indicating that more 50 kW charge–discharge piles are needed according to the assumption that the ratio of electric vehicles and charge–discharge piles is 1:1. Therefore, the net loss of using BYD e6 is more than that of using Tesla model S. Nissan Leaf and Roewe e50 have similar phenomena.

4.2.2. Sensitivities of peak price and battery capacity to the net income of power grid company

Peak price and battery capacity are two important factors affecting the net income of power grid company. The case in Part 4.1.2 is still used. Fig. 8 shows the relationship between peak price and net income of power grid company. It can be found from Fig. 8 that the net income of the power grid company decreases linearly with the increase of the peak price. The net income of the power grid company increases from -6.61×10^8 $ to -5.12×10^8 $ when the peak price of electricity discharged to the grid declines from the given peak price of 0.4452 $/kWh to the valley price of 0.04452 $/kWh. However, the net income of the power grid company is still negative even if the peak price is 0 $/kWh. Although peak price has a great impact on the net income of power grid company, adjustment of peak price is not helpful to realize its positive net income.

The biggest cost of V2G investment by power grid companies is the construction of charge–discharge piles. The larger the battery capacity of electric vehicles, the fewer the number of electric vehicles needed to reduce the same peak load, which is beneficial to reduce the investment costs of charge–discharge piles. The case in Part 4.1.2 is also used and the peak price is set as 0.4452 $/kWh. Fig. 9 shows the relationship between battery capacity and net income of power grid company. It can be seen from Fig. 9 that the power grid company's net losses decrease rapidly as the battery capacity increases at first, and then change slowly. The net loss of the power grid company changes very little when the battery capacity exceeds 60 kW h. The demand for long-distance driving promotes the development of electric vehicles with high battery capacity in recent years, implying that more high-capacity electric vehicles can be connected to the grid to participate in V2G services. It will be profitable for grid companies if a reasonable benefit distribution mechanism or compensation mechanism is designed in V2G ancillary services.

4.3. Net income analysis of three participants in V2G peak shaving services

The sustainable development of V2G applications depends on the positive total net incomes in V2G services. Fig. 10 displays the net incomes of the whole V2G system and three participants in the case of peak shaving using the four brands of electric vehicles. It can be seen from Fig. 10 that the total net incomes *G* of the V2G systems using the four brands of electric vehicles are all positive, indicating that the whole V2G systems are profitable. In addition, their total net incomes increase with the peak shaving load less than 800 MW, but their increase slows down afterwards. This may be related to the net loss expansion of power grid companies after 800 MW peak shaving load. Therefore, it is economically reasonable to properly control the peak shaving scale. The benefits of power plants are the biggest among three participants in V2G peak shaving services and their benefits are far greater than those of electric vehicle users. Although the total net incomes of the V2G systems are positive, the three V2G participants get completely different rewards. It is an unfair game and not conducive to the sustainable development of V2G applications. A fair market distribution mechanism of V2G services should be built and the net incomes of the whole V2G system should be redistributed reasonably among electric vehicles users, grid companies and power plants in order to promote the healthy development of V2G applications.

5. Conclusions

The healthy development of V2G applications depends on not only the positive total net incomes in V2G services, but also rational distribution of benefits among participants. The net incomes of electric vehicles users are greater than zero in V2G peak shaving services when the peak price of electricity fed into the grid is more than three times the valley price. The larger the electric vehicle fleets participate in V2G service, the more the peak shaving load is, the greater the users' incomes will be. Users with low-cost batteries are more likely to participate in V2G activities because the lower the cost of electric vehicle battery, the more the net income of single user. The net incomes of power grid companies are always very negative and the higher the peak shaving load, the greater the net loss of the power company. Although the decrease of peak price and the increase of battery capacity have a great impact on the net income of power grid company, the adjustment of these two variables are not helpful to realize its positive net income. The benefits of power plants are the biggest among three participants and are far greater than those of electric vehicle users. Although the total net incomes of the V2G systems are positive, the three V2G

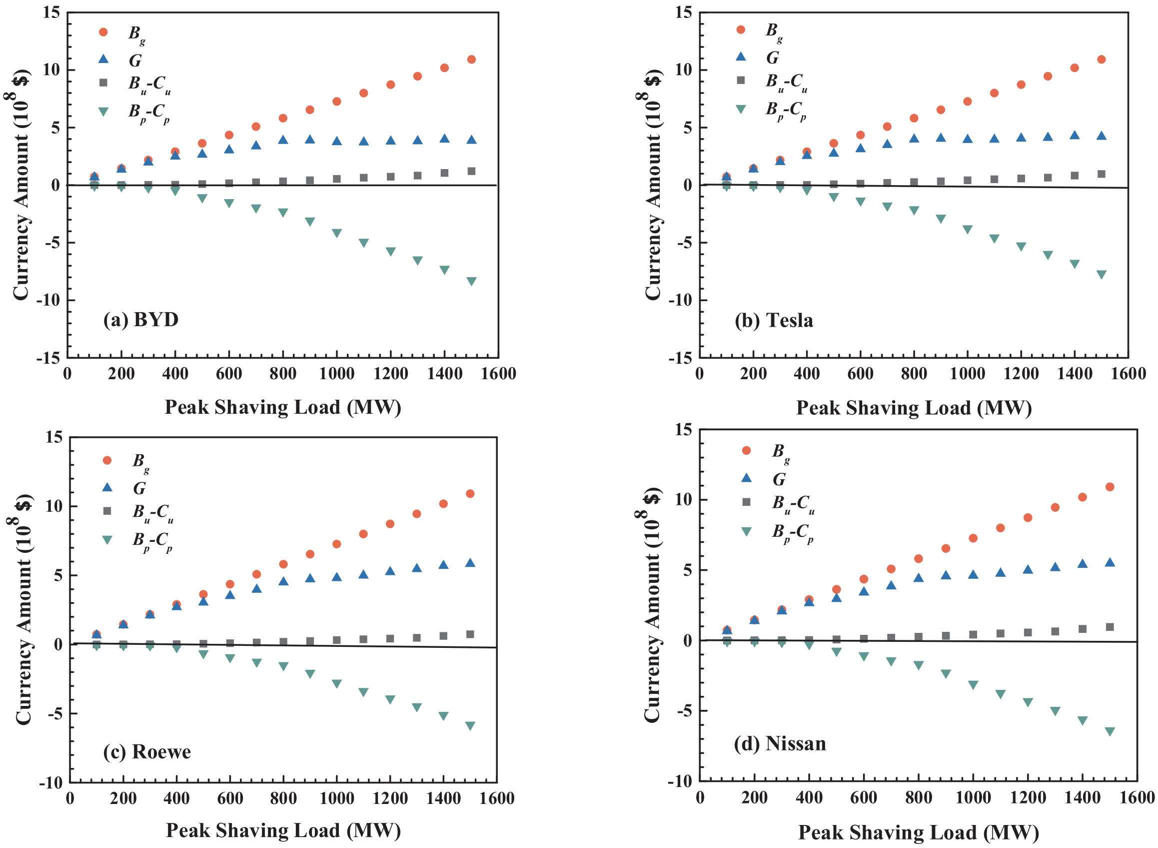

Fig. 10. Net incomes of the whole V2G system and three participants in the case of peak shaving using the four brands of electric vehicles.

participants get completely different rewards. It is not unfavorable to the sustainable development of V2G applications. A fair market distribution mechanism of V2G profits should be built among three participants in order to promote the healthy development of V2G applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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