

# Cost Minimization Control for Smart Electric Vehicle Car Parks

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**Abstract**—The high demand side cost of electric vehicles (EVs) affects the wide use of EVs in practice. In this paper, a mathematical model is built to investigate the cost of the demand side by controlling EVs charging and discharging status, so that the demand side cost can be minimised under given tariffs. The battery degradation cost, the driving probability and the vehicle-to-grid (V2G) rebates are considered in the model. The most economic charging and discharging strategy for each EV can be determined through global optimisation. Simulation studies demonstrate the cost reduction through optimization.

**Keywords**—electric vehicle (EV); demand side cost; battery degradation; vehicle-to-grid (V2G); driving probability; optimisation.

## I. INTRODUCTION

Pollution from transport systems is one of the biggest challenges to the environment and climate change in the world [1–3]. The adoption of electric vehicles (EVs) can be a feasible solution to solve this pollution problem and improve transport system energy efficiency [4–6].

There are many existing studies on the bidirectional power flow between EVs and the grid. A number of challenges are listed in [7] brought by vehicle to grid (V2G) such as stress to power system and congestion in feeders, which will lead to system overload and uncontrollable load spikes. Smart EV car park is capable of controlling EVs charging and discharging activities, so as to facilitate power flow and energy storage between vehicles and grid [8]. According to [9], more than 90% private vehicles are under parking status during the daytime, either at home or in public car parks. Therefore, EVs can play important roles such as being used as energy storage systems and virtual STATCOMs [10], the latter provides a new option for transmission line protection [11, 12]. Large quantities of vehicles parking at public car parks will also allow owners or managers of car parks to gain additional benefits through V2G technologies from various feed-in tariffs/incentives.

Reference [13] on the analysis of energy efficiency for the Multi-port Power Converters (MPCs) used in EVs discusses the feasibility of V2G technology. According to [14], vehicle owner's cost is roughly halved by using V2G technology. However, the battery degradation cost has not been considered in these work. Yilmaz et al. [15] discussed the benefits and

challenges of V2G technology and mentioned that the battery degradation cost should be considered in V2G; however, there is no evidence to prove that V2G technology is cost beneficial to users. In [16], the authors investigated the opportunities and challenges of V2G, vehicle to home (V2H) and vehicle to vehicle (V2V) without considering the impact of battery degradation. In [17], Lin et al. proposed a scheduling method which can ensure adequate charging condition of EVs, and the power quality of the regulation service can be stabilized at the same time. Moreover, it is further verified through a simulation of the charging/discharging of 1000 EVs without the consideration of battery degradation cost.

The aim of this paper is to build an optimal control model for smart EV car park with consideration of batter degradation cost to minimize the cost of car park, and to find out the condition of V2G. This optimal control model illustrates a complex problem of EVs car park management. The challenge in this model is that each EV in the car park has different characteristics such as the initial state of charge (SOC), non-deterministic use, and others. probabilistic algorithm is added into the model.

The optimal control model aims at cost minimization for park manager given the mobility behaviour and the demand of EVs over a certain period of time. With this car park model, the charging and discharging operation can be determined and described by on-off switching functions. The constraints will be addressed from the following three aspects: the battery characteristics, the non-deterministic use of EVs and the SOC requirement.

The rest of this paper is organized as follow. An EVs control model is proposed to represent the cost of car park in Section II, and the effect of charging/discharging of EVs on the total cost of the car park is described. A case study is produced by using the proposed model and discusses the impact of rebate, feed in tariff and battery degradation on the total cost of the car park in Section III. Finally, conclusions and future work are given in Section IV.

## II. MODELLING OF SMART CAR PARK

Fig. 1 and Fig. 2 compare the difference of power grid system with and without EVs power transmission controller.

In Fig.1, the grid is directly connected to the charging slots and other loads. There is no feed back from charging slots to the grid. In Fig.2, the grid and charging slots connected via a EV controller which makes the V2G activities become possible. The EVs can not only buy power from the grid, but they can also sell extra energy to the grid through the charging slots. This bi-directional energy transmission can potentially provide profit for the demand side and in the meantime stabilize the power system.

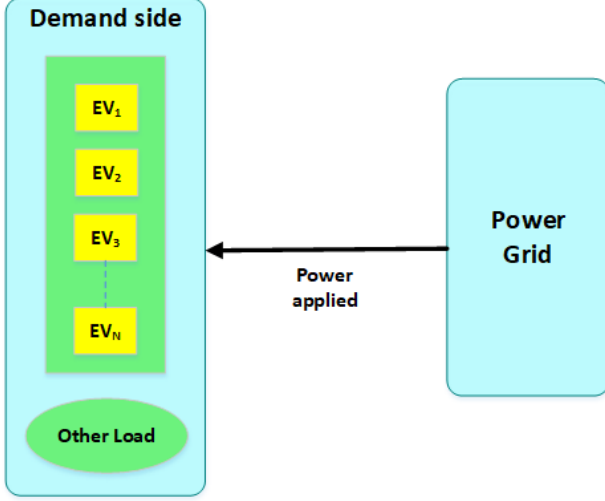


Figure 1. EV car park without power transmission controller

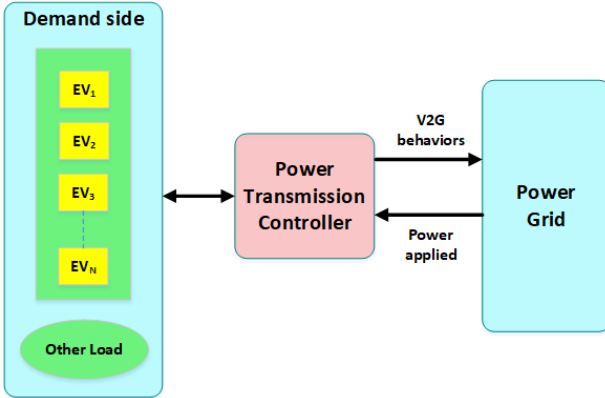


Figure 2. EV car park with power transmission controller

Assuming the charging status of the  $i$ th vehicle at time  $t$  is  $u_i(t)$ , EVs have three statuses; charging (G2V) when the grid sells power to vehicle owners, discharging (V2G) when the grid buy extra power from vehicle owners and disconnect when there is no power transmission between the grid and vehicles. The variable of control model can be represented by the following function.

$$u_i(t) = \begin{cases} -1, & \text{charging at time } t \\ 1, & \text{discharging at time } t \\ 0, & \text{disconnect} \end{cases} \quad (1)$$

Since the target is to maximize the car park profit, the objective function is set to be the total cost of the car park during the monitoring time, which can be written as

$$C_{total} = C_{charging} - C_{discharging} + C_{loss} - C_{rebate} \quad (2)$$

where  $C_{total}$  is the total cost of the car park from the start time  $t_0$  to the final time  $t_f$ .  $C_{charging}$ ,  $C_{discharging}$ ,  $C_{loss}$ ,  $C_{rebate}$  are the cost of charging, cost of discharging, losses caused due to battery degradation, and the rebate income from encourage foundation given by government or energy company. Here the devices investment and maintenance fees are ignored.

#### A. Cost of Charging

Considering a general car park with  $N$  EVs, the cost of charging can be calculated by summarizing the money cost when  $u_i(t) = 1$ ,

define

$$sgn^+(x) = \begin{cases} x, & \text{if } x > 0 \\ 0, & \text{if } x \leq 0 \end{cases} \quad (3)$$

From time  $t_0$  to  $t_f$ , the cost can be written as

$$C_{charging} = \sum_{i=0}^N \int_{t_0}^{t_f} p(t) \cdot sgn^+(-u_i(t)) \cdot P_{EV} dt \quad (4)$$

where  $p(t)$  is the price of electricity and  $P_{EV}$  is the power of charging and discharging.

#### B. Cost of Discharging

EV is discharging when the  $u_i(t) = 1$ . During time  $t_0$  to  $t_f$ , the money income can be written as

$$C_{discharging} = \sum_{i=0}^N \int_{t_0}^{t_f} q(t) \cdot sgn^+(u_i(t)) \cdot P_{EV} dt \quad (5)$$

where  $q(t)$  is the feed in tariff.

#### C. Degradation Cost

In Hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicle, the battery is mostly suffering from various stress factors such as high current rates, deep discharge conditions, low and high operating temperatures.

The battery degradation cost happens during charging and discharging time. A fixed degradation rate is used in this model to calculate the battery degradation cost.

$$C_{losses} = \sum_{i=0}^N \int_{t_0}^{t_f} D_r \cdot (sgn^+(u_i(t)) + sgn^+(-u_i(t))) dt \quad (6)$$

where  $D_r$  is the battery degradation cost rate.

#### D. Rebate Income

The rebate depends on the energy sold via V2G technology. The rebate cost can be calculated by

$$C_{rebate} = \sum_{i=0}^N \int_{t_0}^{t_f} p_r \cdot P_{EV} \cdot sgn^+(u_i(t)) dt \quad (7)$$

where  $p_r$  is the rebate price, the unit is pounds per kilo-watt hours (£/kWh). Substituting equations (4) - (7) to (2), the final cost model can be calculated as

$$C_{total} = \sum_{i=0}^N \left\{ \int_{t_0}^{t_f} p(t) \cdot sgn^+(-u_i(t)) \cdot P_{EV} dt - \int_{t_0}^{t_f} q(t) \cdot sgn^+(u_i(t)) \cdot P_{EV} dt + \int_{t_0}^{t_f} D_r \cdot (sgn^+(u_i(t)) + sgn^+(-u_i(t))) dt - \int_{t_0}^{t_f} p_r \cdot P_{EV} \cdot sgn^+(u_i(t)) dt \right\} \quad (8)$$

This problem is a mixed non-linear integer programming problem which can be solved by a heuristic global optimization method, Genetic Algorithm (GA), in order to find the best charging/discharging conditions of each vehicles along the whole monitoring time.

### E. Constraints

There are some constraints for the minimization of cost. Because of the battery character, the limitation of EV battery is between  $SOC_{min}$  and  $SOC_{max}$ . It can be written as:

$$SOC_{min} \leq SOC_i(t) \leq SOC_{max} \quad (9)$$

where  $SOC_i(t)$  is the SOC of  $i$ -th EV at time  $t$ ;  $SOC_{min}$  and  $SOC_{max}$  are the minimal and maximum values of SOC.

The  $SOC_i$  needs to meet the requirement when the vehicle is driving outside, which can be written as

$$SOC_{final} \geq a\% \quad (10)$$

$SOC_{final}$  is the required SOC value before the next drive value of each vehicle.

Reference [18] proposes an equation to calculate the battery  $SOC_i$  when EVs are working.

$$SOC_{out} = (1 - \frac{d_d}{d_r}) \times 100\% \quad (11)$$

where  $d_d$  is the driven distance since EVs are fully charged;  $d_r$  is the maximum range that EV can travel. The model can be reformulated by considering the travel probabilities which is given as

$$SOC_{out} = \int_{t_0}^{t_f} (\frac{\sum_{j=0}^{N^t} d_j p_j}{d_r}) P_i dt \quad (12)$$

where  $d_j$  is the distance travelled;  $p_j$  is the probability which corresponds to the distance of each vehicle;  $N^t$  is the number of travels; and  $P_i$  is the probability of EV driving out of the car park.

Reference [19] proposes an equation to calculate the EVs under charging.

$$SOC_{connect} = SOC_{in} - \int_{t_0}^{t_f} (\frac{i_{bat}}{C_{usable}}) dt \quad (13)$$

where  $SOC_{in}$  is initial SOC of each EV. The  $SOC_{in}$  can be measured when EVs come into the car park and connect to the grid.  $C_{usable}$  is the battery usable capacity, it changes depending on capacity degradation.

Therefore,  $SOC_i$  can be calculated by the following function:

$$SOC_i(t) = SOC_{in} - \int_{t_0}^{t_f} (\frac{i_{bat}}{C_{usable}}) (1 - P_i) dt - \int_{t_0}^{t_f} (\frac{\sum_{j=0}^{N^t} d_j p_j}{d_r}) P_i dt \quad (14)$$

The battery degradation cost happens during both charging and discharging time periods. A fixed degradation rate is used in this model to calculate the battery degradation cost.

$$C_{losses,charging}^i = \int_{t_0}^{t_f} D_r (sgn^+(u_i(t))) (1 - P_i) dt \quad (15)$$

$$C_{losses,discharging}^i = \int_{t_0}^{t_f} D_r (sgn^+(-u_i(t))) (1 - P_i) dt \quad (16)$$

The discharging makes profit for the car users when V2G is applied. The income from discharging time period can be calculated as follows:

$$C_{income,discharging}^i = C_{rebate}^i + C_{discharging}^i - C_{income,discharging}^i \quad (17)$$

it can be extended into:

$$C_{income,discharging}^i = \int_{t_0}^{t_f} p_{rebate} \cdot P_{EV} \cdot (sgn^+(u_i(t))) (1 - P_i) dt + \int_{t_0}^{t_f} p_r \cdot P_{EV} \cdot (sgn^+(u_i(t))) (1 - P_i) dt - \int_{t_0}^{t_f} D_r \cdot P_{EV} \cdot (sgn^+(u_i(t))) (1 - P_i) dt \quad (18)$$

This income encourage the car users to attend the V2G activities to make profit, so the limitation needs to be

$$C_{income,discharging}^i \geq 0 \quad (19)$$

## III. SIMULATION AND DISCUSSION

### A. System Description

An EV car park near an office building with 50 EVs charging slots is selected for the case study. It can be monitored during a working day from 9am to 5pm as a rated time cycle. There are lots of famous EV products such as Tesla, Nissan Leaf, BMW i3. According to Tesla, which is well known as the best sells EV in the world, the maximum driving distance is 120 miles. The maximum SOC is 90% and the minimum SOC is 20%.

There are three major types of charging stations. The first one is called Level 1 device whose charging process is often equivalently referred to as low power charging. EVs are directly plugged in to low voltage receptacles that leads to very slow recharging rate. It takes up to 15 hours or more for an average charge. The second type of charging station is termed as Level 2 device which can be faster by using a low voltage power to fully charge an EV in 5 hours. The third type of charging station, a Level 3 charging stations, or fast charging station, is not available to residential customers currently, only at public stations. The Level 2 charging device is selected in this model. The voltage is 380 volt industrial electric voltage and the charging and discharging power is 13.2 kw.

The rebate price is selected to be 0.02 £/kWh and feed in tariff chooses 0.0485 £/kWh. According to [20], the battery degradation cost is 0.32 £/kWh. The price of power from grid is 0.28 £/kWh. These parameters will be used in this case study. All the values of probabilities in this paper come from a reliable survey face to EV owners.

For the rated time period from 9.am to 5.pm, it is divided into 32 slots with 15 minutes of each. The parameter selection is shown in the following table

From the perspective of the customers, the charging/discharging activities of each EV is monitored individually at residential level. The maximum profit for each EV with different initial SOC is firstly examined which is given in Table II and Fig. 3.

In Fig. 3, the X axis is the initial SOC from 0.2 to 0.9; the Y axis is the minimum cost of each vehicle. The green line is the

TABLE I  
PARAMETER SETTING

Quantity	Value	Comment
$N$	50	Number of vehicles
$n_x$	1600	Number of variables
$SOC_{final}$	0.7	Final SOC requirement
$\Delta t$	0.25h	Monitor every 15 minutes
$P_{EV}$	13.2kw	Power of EV battery
$SOC_{min}$	0.2	Minimal SOC
$SOC_{max}$	0.9	Maximum SOC
$V$	380V	Industrial electric voltage
$c_{usable}$	85 kW	Battery usable capacity
$P_{rebat}$	- £/kWh	Rebate price
$D_r$	0.3 £/kWh	Battery degradation rate
$p(t)$	-	Power price
$q(t)$	0.045 £/kWh	FIT
$N^t$	-	Number of travels vehicle
$d_r$	120miles	The maximum driving distance
$p_i$	0.79	Probability of EV parking in
$d_j$	-	Distance of each EV travelled
$p_j$	-	Probability to each distance

TABLE II  
THE MAXIMUM COST (£) FOR EACH EV WITH RANDOM INITIAL SOC

SOCin	0.61	0.6	0.86	0.25	0.65
Cost (£)	1.800	1.800	0	7.371	0.900
SOCin	0.55	0.52	0.24	0.29	0.23
Cost (£)	2.700	3.714	7.314	6.414	7.713
SOCin	0.35	0.36	0.75	0.38	0.59
Cost (£)	4.4570	5.514	0	5.4570	1.800
SOCin	0.42	0.5	0.66	0.84	0.57
Cost (£)	4.500	3.600	0.900	0	2.700
SOCin	0.58	0.82	0.46	0.81	0.85
Cost (£)	2.700	0	4.557	0.216	0
SOCin	0.64	0.21	0.68	0.22	0.32
Cost (£)	1.800	8.271	0.900	8.499	6.3570
SOCin	0.76	0.54	0.88	0.51	0.37
Cost (£)	0	2.700	0	3.657	5.628
SOCin	0.74	0.43	0.79	0.53	0.31
Cost (£)	0.4557	0	2.757	6.357	0
SOCin	0.67	0.87	0.77	0.3	0.28
Cost (£)	0.9000	0	0	6.414	7.257
SOCin	0.48	0.76	0.81	0.71	0.26
Cost (£)	3.600	0	0	0	7.314

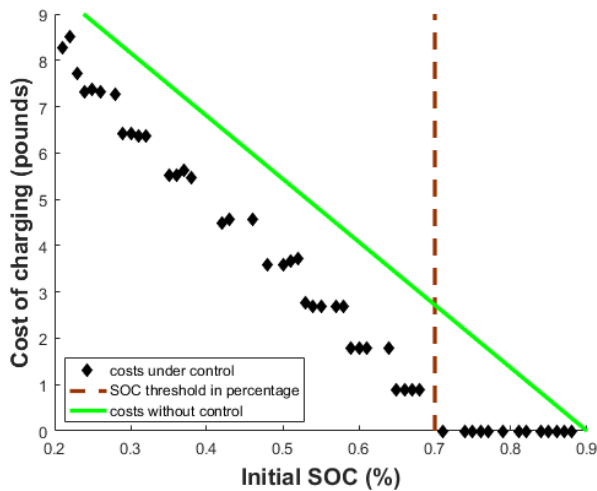


Figure 3. Relationship between the maximum cost (£) and initial SOC

TABLE III  
COST RESULTS COMPARISON

	No rebate	With rebate
Minimum cost	£190.28	£66.67
Number of 1 (charging)	0	24
Number of -1 (discharging)	71	83

uncontrolled charging cost. The brown line is the final SOC requirement which is set to be 70%. The diamond marks show the minimized cost. It is obvious that the cost by using the optimal controlled charging strategy is much cheaper than that from the uncontrolled condition, especially when the initial SOC is over than 70%. It can also be found that there is no active V2G activities when EV cost is calculated individually. Those EVs, which have initial SOC higher than 70%, are disconnected from grid, and no charging and discharging activities are taking place. This is because the degradation rate is higher than FIT. Hence, individuals or small scale car park cannot get the profit from the FIT strategy.

It can be seen that some EVs where the differences among their initial SOC are very small, but the final cost is the same. This is because the resolution of the time ( $dt$  is set to be 0.25 hours) is not small enough.

#### B. Impact of rebate, FIT and Degradation Rate

Without adding rebate into the simulation, there is no discharging happened during the monitoring time. With adding rebate which give £200 cash paid at the time total V2G power arrived 500 kWh, the V2G is encouraged happening. The results shows in Table III.

When the battery degradation cost is much higher than the FIT, no V2G activities will happen even when EVs are connected to the grid.

The rebate is included in this model to discuss the conditions to allow V2G benefits in terms of cost. With the consideration of the rebate, the unit electricity price and the rate of degradation cost should be reduced, or the FIT should be increased.

FIT is increased to 5 times of its current level and the battery degradation cost is reduced to 0.05 £/kWh, and then V2G take place for the EVs which have higher SOC initials. The results are compared and shown in Table IV.

If the car park system has sufficiently high FIT and relatively low battery degradation cost, V2G only happens in those cars which have initial SOC higher than 70%. In this study, 50 cars are divided into 2 groups. One group contains EVs which have initial SOC higher than 70%, and another group contains EVs with initial SOC lower than 70%. For the first group, the battery can sell the extra power to the grid in order to get profit from the grid. The profit can cover the cost of battery degradation loss. On the other hand, those EVs with low initial SOC only get charged from the grid, and no discharging activity will happen because of the cost.

#### C. FIT & Battery cost

When FIT is increased from 0.0485 to 0.32 £/kWh, the minimum cost is calculated, given in Table IV.

TABLE IV  
PARAMETER SETTING

FIT (£/kWh)	Cost (£)	FIT (£/kWh)	Cost (£)
0.0485	190.2793	0.2	191.0000
0.06	198.4241	0.24	190.4100
0.08	194.4442	0.26	187.4100
0.10	193.4110	0.28	198.0411
0.12	188.4047	0.30	168.0114
0.14	193.4110	0.32	159.411
0.16	192.2100		

The cost can be changed by increasing the FIT until it is higher than battery degradation rate. When the FIT is greater than battery degradation rate, FIT and the minimum cost is inversely proportional. Then the battery degradation rate is reduced from 0.30 to 0.04 £/kWh, the minimum cost can be determined, given as follows in table V.

TABLE V  
RELATIONSHIP BETWEEN THE DEGRADATION RATE AND THE MINIMUM COST

$D_r$ (£/kWh)	Cost (£)	$D_r$ (£/kWh)	Cost (£)
0.30	190.2793	0.10	165.0144
0.25	184.5421	0.05	160.7417
0.20	176.6521	0.04	132.1417
0.15	171.4141		

Similarly, the minimum cost is changing only when the battery cost rate is lower than FIT. Combining the above two conditions, the relationship between FIT, degradation rate and the minimum cost is given in Table VI and Fig. 4.

In Fig. 4, the X axis is the FIT which is changed from 0.06 to 0.32 £/kWh and the Y axis is the minimum cost. Before the curves passed point  $FIT \geq D_r$ , they are nearly horizontal lines. At these time, there is no V2G occurred. After the curves passed point  $FIT \geq D_r$ , they are downwards curves which means the V2G happened and reduces the minimal cost. The results above show that, only with inconsiderable parameters, the V2G is able to happen during the parking time. The condition of V2G happening in this system is FIT is bigger than battery degradation cost rate. It can be written as  $FIT > D_r$ .

TABLE VI  
IMPACT OF FIT AND  $D_r$  TO THE MINIMUM COST

Cost (£) \ $D_r$	0.3	0.25	0.20	0.15	0.10	0.05
FIT						
0.06	190.2	191.4	190.2	190.2	190.2	160.4
0.08	191.4	190.0	188.4	191.4	191.4	150.0
0.10	194.0	188.4	192.2	193.4	152.4	139.4
0.12	190.0	193.4	188.4	192.2	140.0	126.5
0.14	188.4	192.2	190.0	193.4	125.4	111.1
0.16	193.4	191.0	192.1	149.9	109.0	106.4
0.2	192.2	193.4	168.0	136.3	97.0	90.40
0.24	191.0	190.4	152.2	120.4	81.02	80.04
0.26	190.4	164.4	138.8	103.7	69.05	67.77
0.28	188.4	155.0	125.9	91.1	68.03	64.32
0.30	168.0	144.3	119.4	77.40	58.03	52.20
0.32	159.4	136.8	105.4	50.04	44.04	41.37

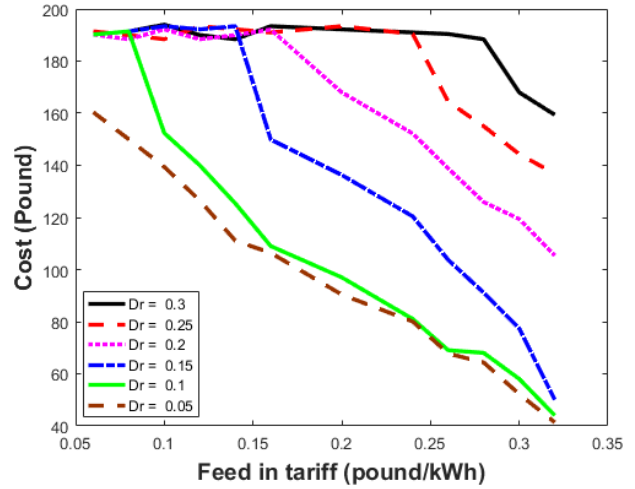


Figure 4. The relationship among the minimum cost, FIT and  $D_r$ .

TABLE VII  
RELATIONSHIP REBATE AND MINIMUM COST

Rebate (£/kWh)	Cost (£)	rebate (£/kWh)	Cost (£)
0.04	190.2793	0.18	188.1771
0.06	191.4141	0.20	190.3140
0.08	190.1700	0.22	190.2793
0.12	188.7771	0.24	189.4141
0.14	194.4173	0.26	175.0952
0.16	193.1416	0.28	169.0221

Considering the rebate situation, the rebate is increased without limited shown as Table VII. The results above show that, only with inconsiderable parameters, the V2G is able to happen during the parking time. In some areas, such as some nations which are short of electrical power, the government needs V2G to keep the balance of the grid and meet the requirement of electrical power.

The relationship between rebate and minimize cost shows that, when the rebate is over battery degradation cost, the minimum totally cost will reduce linearly. It means only when the rebate is higher enough, it can encourage the V2G participation.

Since the V2G rebate is depend on the power sold back to grid, it can be calculated as a part of FIT. Any energy company cannot give a rebate bigger than FIT and energy price. For increased rebate analysis, it does not make sense.

#### IV. CONCLUSION

This paper proposes an intelligent charging and discharging method for EV management facilities in EV car parks. The purpose is to minimize the cost of car park managers.

For EV car park optimization, the charging and discharging are controllable. However, because of battery degradation cost, the smart park also cannot not do V2G to the grid which is caused by the financial reason. The way is to increase FIT in a suitable level and encourage the EV users to supply energy to grid with profits. On the other hand, the EV battery technique

needs a revolution which can reduce the battery degradation rate. Moreover, the government policy such as grid company rebates is another solution.

In reality, the government rebate is not fixed money, it only shows in some areas which are short of power or the area demand side is overload. In these cases, EV Smart Park is a good complement to the grid. In most of the developed areas, EV Smart Park is difficult to join the grid activities with V2G technique because of the financial reason.

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