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Economic Operation of a Workplace EV Parking Lot under Different Operation Modes

Jiwen Qi
Faculty of Engineering and IT
University of Technology Sydney
Sydey, Australia
Jiwen.Qi@student.uts.edu.au

Li Li
Faculty of Engineering and IT
University of Technology Sydney
Sydey, Australia
Li.Li@uts.edu.au

Gang Lei
Faculty of Engineering and IT
University of Technology Sydney
Sydey, Australia
Gang.Lei@uts.edu.au

Abstract— ***In this paper, an electric vehicle (EV) charging station model at a workplace EV parking lot with energy storage system (ESS) and renewable energy sources (RESs) is proposed. Its economic operation under different operation modes is further explored. By comparing the paid charging mode at different prices with the free charging mode, the results show that although a sufficiently high charging price can obtain higher profit, the free charging model will bring greater profit growth with appropriate RES and ESS size as EVs will used for vehicle-to-grid (V2G) and grid-to-vehicle (G2V) transactions in return.***

Keywords— ***Electric vehicles (EV), Charging station, Energy storage system (ESS), Renewable energy source (RES), Vehicle-to-grid (V2G), Grid-to-vehicle (G2V).***

I. INTRODUCTION

Due to air pollution, global warming and the fossil fuel depletion, electric vehicles (EV) as one of the solutions have begun to develop rapidly. The International Energy Agency reports that by the end of 2020, there were more than 10 million EVs globally, and the number may increase to 230 million by the end of 2030 [1]. Under this trend, EV charging stations and corresponding revenue and expenditure issues have begun to receive widespread attention. The study in [2] proposes a non-cooperative game model. The EV charging period is shifted to off-peak time to minimize the charging cost. A smart charging strategy is presented in [3], which increases the photovoltaic (PV) self-consumption to minimize the grid power usage. A smart charging strategy considering EVs behaviour and prediction of their initial state-of-charge is presented in [4]. The similar strategy of reducing charging costs [5] [6] [7] or maximizing profit [8] [9] has also been discussed. Energy storage system (ESS) deployed at the charging station can solve the intermittency issues of its RESs and reduce the impact on the grid caused by the connected EVs. However, these mentioned charging strategies do not take ESS into account. To maximize profit, expenses incurred in investment, maintenance, operation and punishment of charging stations are considered in [10]. The studies of [11] and [12] also discuss the impact of ESS on EV charging price. Nonetheless, they didn't take vehicle-to-grid (V2G), grid-to-vehicle (G2V) or grid feed-in into account.

In the previously mentioned literature, the discussion on the profit of EV charging stations mainly focuses on the impact of different components of charging stations and related costs on profit while ignoring the potential profit under different operating or business models. Hence, in this paper, a model including RES and ESS to maximize the profit of the parking lot with charging station will be proposed. The profit under different EV numbers and charging prices is discussed by comparing the operation modes of paid charging and free charging with V2G support in return.

II. PROBLEM FOMULATION

The case of a workplace parking lot with EV charging stations including PV, wind turbine, and ESS is considered. EV owners can book the charging station before they come the next day, which needs them to provide their arrival and departure times. All the EVs will be fully charged when they depart from the parking lot. It is assumed that EV charging is free to EV owners under the free charging mode, while EVs can be freely used by the parking lot as energy storage to provide grid support through V2G/G2V operations in return. Thus, the parking lot can make profit through providing grid support, which is, storing energy from the grid during the off-peak time and delivering energy to the grid during the peak time. The model will be presented as follow.

A. RESs modelling.

Eq. (1) shows the power generated by the PV panel [13]. The power generated by the wind turbine is shown in (2).

$$P_t^{PV}=r_t*s_{pv}*e_{pv} \tag{1}$$

$$P_t^W=\begin{cases} 0 & v_t^{wind}\le V_{ci} \\ P_r\left(A+B*v_t^{wind}+C*v_t^{wind^2}\right) & V_{ci}<v_t^{wind}\le V_r \\ P_r & V_r\le v_t^{wind}\le V_{co} \\ 0 & v_t^{wind}\ge V_{co} \end{cases} \tag{2}$$

where P_t^{PV} is the power generated by the PV panel; r_t is the solar radiation at time t; s_{pv} is the surface area of PV panels; e_{pv} is the PV panel efficiency; P_t^W is the power generated by the wind turbine; v_t^{wind} is the wind speed; P_r indicates the rated power output; A, B, C are constant coefficients of the wind turbine [14]; V_{ci}, V_r, V_{co} represent the cut-in, rated and cut-out wind speed, respectively.

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B. EV modelling

It is assumed that the parking lot knows the arrival and departure time of all the EVs in advance. The available energy of the EV at charging point *i* for the parking lot to use is shown in (3). Before EV's arrive and after EV's departure, the available energy to the charging point the EV is connected to is zero. When the EV arrives, the available energy to the charging point *i* is the initial energy of the EV, that is, E_i^{ini}. In the following time, between the time of EV's arrival and departure, the EV energy variation depends on the energy at the previous time step and the charging or discharging energy at the current time step. Then EVs will be charged to the allowed maximum energy at the departure time, which is normally 80% of the EV battery capacity to prevent the adverse effects of overcharging, as shown in (4). Eqs. (5-6) indicate that the EV cannot charge and discharge simultaneously. Eq. (7) presents the lower and upper bounds of the EV energy. Eq. (8) means that charging and discharging are not needed if EV is not at the charging station.

$$E_{i,t}^{EV} = \begin{cases} 0, & t < t_{a,i} \\ E_i^{ini}, & t = t_{a,i} \\ E_{i,t-1}^{EV} + \left(\eta_{ch} * P_{i,t}^{EV+} - \frac{1}{\eta_{dis}} * P_{i,t}^{EV-}\right) \triangle t, & t_{a,i} < t \le t_{d,i} \\ E_{i,max}^{EV}, & t = t_{d,i} \\ 0, & t > t_{d,i} \end{cases} \tag{3}$$

$$E_{i,t_{d,i}}^{EV} = E_i^{ini} + \sum\nolimits_{t=t_{a,i}+1}^{t_{d,i}} \left(\eta_{ch}^{EV} * P_{i,t}^{EV+} - \frac{1}{\eta_{dis}^{EV}} * P_{i,t}^{EV-}\right) \triangle t = E_{i,max}^{EV} \tag{4}$$

For $t_{a,i} \le t \le t_{d,i}$

$$0 \le P_{i,t}^{EV+} \le \mu_i * P_{i,max}^{EV+} \tag{5}$$

$$0 \le P_{i,t}^{EV-} \le (1-\mu_i) P_{i,max}^{EV-} \tag{6}$$

$$E_{i,min}^{EV} \le E_{i,t}^{EV} \le E_{i,max}^{EV} \tag{7}$$

For *t* otherwise

$$P_{i,t}^{EV+} = P_{i,t}^{EV-} = 0 \tag{8}$$

where $E_{i,t}^{EV}$ is the available energy of the EV at charging station *i* for the parking lot to use. $t_{a,i}$ and $t_{d,i}$ are the EV's arrival and departure time; E_i^{ini} in is the initial energy of the EV at charging station *i*; $P_{i,t}^{EV+}$ and $P_{i,t}^{EV-}$ are the EV charging and discharging power; η_{ch}^{EV} and η_{dis}^{EV} are the EV charging and discharging efficiency; $\triangle t$ is the time interval. $P_{i,max}^{EV+}$ and $P_{i,max}^{EV-}$ are the maximum EV charging and discharging power; A binary variable μ_i is set as the EV charging/discharging status which is 1 when EV is charging and 0 otherwise; $E_{i,min}^{EV}$ and $E_{i,max}^{EV}$ are the allowed minimum and maximum EV energy.

C. ESS modelling

Similar to the EV part, Eq. (9) shows the energy dynamic of ESS. It depends on the energy at the previous time step and the charging or discharging energy at the current time step. Constraint (10) is to ensure that, at the end of the day, ESS have the same energy as the initial energy. Eq. (11) presents the lower and upper bounds of the ESS energy. Eqs. (12-13) indicate that the ESS cannot charge and discharge simultaneously.

$$E_t^{ESS} = E_{t-1}^{ESS} + \left(\eta_{ch}^{ESS} * P_t^{ESS+} - \frac{1}{\eta_{dis}^{ESS}} * P_t^{ESS-}\right) \Delta t \tag{9}$$

$$E_T^{ESS} = E_1^{ESS} \tag{10}$$

$$E_{min}^{ESS} \le E_t^{ESS} \le E_{max}^{ESS} \tag{11}$$

$$0 \le P_t^{ESS+} \le s * P_{max}^{ESS+} \tag{12}$$

$$0 \le P_t^{ESS-} \le (1-s) * P_{max}^{ESS-} \tag{13}$$

where E_t^{ESS} is the ESS energy; P_t^{ESS+} and P_t^{ESS-} are the ESS charging and discharging power; η_{ch}^{ESS} and η_{dis}^{ESS} are the ESS charging and discharging efficiency; T is the number of time steps in one day. E_{min}^{ESS} and E_{max}^{ESS} are the allowed minimum and maximum ESS energy; P_{max}^{ESS+} and P_{max}^{ESS-} are the maximum ESS charging and discharging power; A binary variable *s* is set as the ESS charging/discharging status which is 1 when ESS is charging and 0 otherwise.

D. Constraints for the grid

Eqs. (14-15) indicate that the grid cannot sell and buy electricity simultaneously.

$$0 \le P_t^{Feed\text{-}in} \le b * P_{max}^{Feed\text{-}in} \tag{14}$$

$$0 \le P_t^{Grid} \le (1-b) * P_{max}^{Grid} \tag{15}$$

where $P_t^{Feed\text{-}in}$ and P_t^{Grid} are the feed-in to and selling power from the grid; $P_{max}^{Feed\text{-}in}$ and P_{max}^{Grid} are the maximum grid feed-in and selling power; a binary variable *b* is set as the grid power flow direction status, which is 1 when the power is fed into the grid and 0 otherwise.

E. Balance equation

Eq. (16) represents the power balance. The EV charging, ESS charging, and the grid feed-in power are satisfied by the power from PV, wind turbine, grid, ESS discharging and EV discharging.

$$\sum\nolimits_{i=1}^{N} P_{i,t}^{EV+} + P_t^{ESS+} + P_t^{Feed-in} = P_t^{PV} + P_t^W + P_t^{Grid} + P_t^{ESS-} + \sum\nolimits_{i=1}^{N} P_{i,t}^{EV-} \tag{16}$$

F. Objective function

The objective function in the following is to maximize the profit of the parking lot by selling electricity in low-price periods and selling electricity in high-price periods through managing charge and discharge of EVs and ESS. It consists of three parts: feed-in income, grid electricity purchase cost, PV and wind turbine operating cost, and ESS degradation cost.

$$
\begin{aligned}
Maximize\ z = {} & \sum_{t=1}^{T} P_t^{Feed-in} * \lambda_{1,t} \\
& - \sum_{t=1}^{T} P_t^{Grid} * \lambda_{2,t} \\
& - \sum_{t=1}^{T} (P_t^{PV} * \lambda_{pv} + P_t^{W} * \lambda_{w} \\
& + P_t^{ESS+} * \lambda_{de})
\end{aligned} \tag{17}
$$

where $\lambda_{1,t}$ is the feed-in price; $\lambda_{2,t}$ is electricity purchase price; λ_{pv} and λ_w are the operating cost coefficient for PV and wind turbine, respectively; λ_{de} are the degradation cost coefficient of ESS. The parameters will be introduced in the next section.

III. SIMULATION AND RESULTS

In this section, the proposed model will be compared with cases under different charging rates and different EV numbers to explore their impact on the profit of the parking lot. In the proposed model, EVs will use the parking lot and its charging stations for free, but will be freely used by the parking lot to offer V2G service in return. In contrast, in the comparison model,all the EVs will not offer V2G service but will pay for charging cost. Like the free charging mode, all the EVs will be charged to the maximum allowable energy when departing from the charging station.In this mode, the cost function in (17) will be modified to include the EV charging cost. The charging price will be set in the range of $0.2-0.25/kWh [18]. For clarity, it is set as the maximum value of 0.25, the median value of 0.23 and the minimum value of 0.2 within the simulation interval.

A. Model parameter

The related optimization parameters are shown in TABLE I. Note that λ_{pv} and λ_w appear in the objective function due to considering the operating cost of PV and wind turbine. However, in many studies, these costs are ignored or assumed to be the sunk cost [3][15][16]. Hence, λ_{pv} and λ_w will be considered as 0 here. The typical solar radiation data are imported from [14]. The simulation time T is set as 24 hours. A one-day real-time electricity price data in July are imported from the Australian Energy Market Operator [17], and the feed-in price λ_1 is considered lower than the electricity purchase price λ_2, which is λ_1=0.9λ_2 [3]. The charging/discharging efficiency of ESS and EVs are considered to be the same. Fig. 1 shows the dynamic electricity purchase and feed-in price. EVs initial energy is presented in Fig. 2, and their arrival and departure time are shown in Fig. 3.

B. Results

Fig. 4-Fig. 11 present the charging/discharging power variation of EVs and ESS in the parking lot during the day, where positive/negative values indicate charge/discharge. Fig. 4 shows that the EVs will charge when the electricity price is low. When the feed-in price is high, they start to discharge to gain profit. With more EVs connected, the higher discharging and charging power occurs. Fig. 5 also shows the same trend of ESS as EVs' charging and discharging. The obtained results also reflect the profit of parking lot increases with the increase in the number of EVs, as seen in TABLE II. The similar results for different charging price modes are also shown in Fig. 6-Fig. 11. Note that there is no EV discharge under paid charging modes. It can be seen from Fig. 6 that during the arrival and departure times of all EVs, charging also occurs at the lower point of the grid electricity price. Charging power is concentrated at the time of the low electricity price, 12 o'clock, because the number of EVs connected to the charging station is also the largest at that time. With the increase in charging prices, as shown in Fig. 8 and Fig. 10, in order to maximize profits, the charging power at 6 o'clock where the grid electricity price is lower also increases. This trend is gradually increasing with the increase in the number of EVs. The number of EVs at 19 o'clock is relatively small, so although the electricity price is lower at this time, the charging power is not high. Because of the ESS capacity limitation, the charging and discharging trends are the same under different operating modes and charging prices. Specifically, its discharge occurs at 8 o'clock, 9 o'clock, 16-18 o'clock and 21 o'clock, and there are variations in the discharge power due to the variation in feed-in prices to obtain optimal benefits; the ESS charging takes place at 3, 4, 12, 19, and 23 o'clock, at low electricity prices to reduce expenditure, as shown in Fig. 7, Fig. 9 and Fig. 11. Fig. 12 shows the export (feed-in)/import power to/from the grid in the base case, where positive/negative values indicate export/import. It can be seen that when the purchase price is low, the power imported from the grid increases, and when the feed-in price is high, the stored power is sold to the grid to obtain the maximum benefit.

TABLE II and TABLE III give the results of profit and its increasing rate. When the EV charging price is $0.23/kWh, which is close to the feed-in average price, the profit of parking lot is also close to the base case. When the price is greater than $0.23/kWh and set as $0.25/kWh, the profit is higher than that of the free charging scenario. However, in the paid charging scenarios, although all the profit results share the same increasing trend and the profit growth rates are positive overall, the profit growth rates gradually decline after the number of EVs begins to increase and then start to increase after the number of EVs reaches 20.

In contrast, in the free charging scenario, the profit growth rate is the 3rd at the beginning, but higher than those in the paid charging modes until the EV number increases to 16. It declines significantly when the EV number reaches 20.

As presented in Fig. 13, because of paid charging, the profit growth is relatively stable across all paid charging scenarios. However, in the free charging scenario, as the number of EVs in the parking lot continues to grow, the grid power demand will gradually increase. The profit growth starts to decrease when more ESS and RESs power is used for charging. When the capacity of ESS and RESs is not big enough to support EV charging, the growth rate starts to decline sharply.

TABLE I. SIMULATION PARAMETERS

Parameter	Symbol	Value
Charging and discharging efficiency	$\eta_{ch}^{EV}/\eta_{dis}^{EV}, \eta_{ch}^{ESS}/\eta_{dis}^{ESS}$	0.9
ESS battery degradation cost	λ_{de}	0.038 $/kWh
PV panel and wind turbine operating cost	$\lambda_{pv}, \lambda_{w}$	0 $/kWh
PV panel surface area	s_{pv}	40 m^2
PV panel efficiency	e_{pv}	0.16
Wind turbine cut-in speed	V_{ci}	3.5 m/s
Wind turbine rated speed	V_{r}	9 m/s
Wind turbine cut-out speed	V_{co}	22 m/s
ESS allowed maximum capacity	E_{max}^{ESS}	32.4 kWh
ESS allowed minimum capacity	E_{min}^{ESS}	8.1 kWh
ESS initial energy	E_{1}^{ESS}	25 kWh
ESS maximum input and output power	P_{max}^{ESS+} , P_{max}^{ESS-}	5 kW
EV allowed maximum capacity	$E_{i,max}^{EV}$	30 kWh
EV allowed minimum capacity	$E_{i,min}^{EV}$	6 kWh
EV maximum input and output power	$P_{i,max}^{EV+}, P_{i,max}^{EV-}$	10 kW

TABLE II. SIMULATION RESULTS

Cases	Profit ($)				
	4 EVs	8 EVs	12 EVs	16 EVs	20 EVs
Free charging (Base case)	26.2474	28.8541	32.5030	36.3747	38.9519
With $0.2/kWh charging price	24.6359	26.0818	27.5262	28.8262	30.3394
With $0.23/kWh charging price	26.2390	29.3345	32.2951	35.0781	38.2408
With $0.25/kWh charging price	27.3586	31.5430	35.5191	39.2917	43.5585

TABLE III. PROFIT GROWTH RATE

Cases	Rate (%)			
	From 4 to 8 EVs	From 8 to 12 EVs	From 12 to 16 EVs	From 16 to 20 EVs
Free charging (Base case)	9.931269	12.64604	11.91182	7.085144
$0.2/kWh charging price	5.869077	5.537961	4.722773	5.249391
$0.23/kWh charging price	11.79732	10.09255	8.617406	9.016167
$0.25/kWh charging price	15.29464	12.60533	10.62133	10.85929

IV. CONCLUSION AND FUTURE STUDY

In this paper, an electric vehicle charging station model with RESs and ESS in the workplace parking lot was proposed to explore the economic operation under different operating modes. EV owners will reserve the next day's parking/charging space in advance and provide arrival and departure times. An optimization problem was formulated to maximize the profit of parking lot. Two operating modes were compared, namely paid charging mode (without V2G/G2V transactions), and free charging mode (with G2V/V2G transactions). When ESS and RESs are of the right size and the EV number increases, the free charging case or the paid charging case with above-average feed-in pricing will generate increasing profit growth. It is found that when the number of EVs is at a certain range, the profit growth of free charging case will be greater than that in the paid charging cases. Within this range, the free charging business model may even be able to introduce price incentives to attract more EVs to gain more benefit.

This article only discusses the profit of parking lot under different operation modes when the size of ESS and RES is fixed. The future study will combine investment or sizing issues to determine the overall profit of parking lot. Besides, an optimal pricing mechanism, the best ESS and RES size, accurate prediction of PV/wind power generation and electricity price, and the impact of EV behaviour on the profit will also be important topics in the follow-up research.

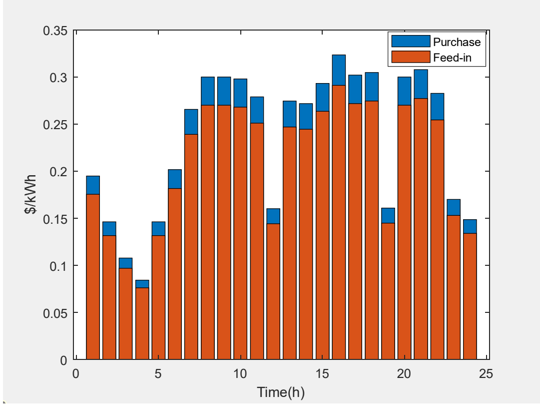

Fig. 1. Dynamic electricity price

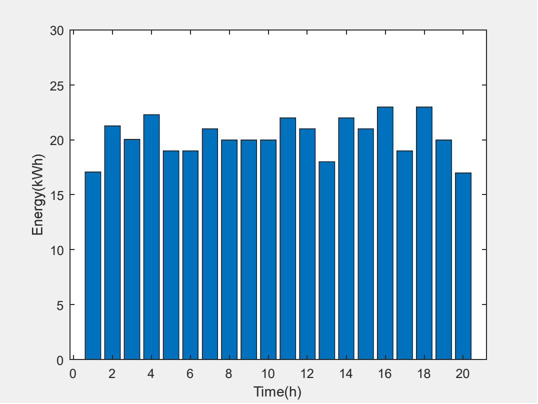

Fig. 2. Initial energy of EVs

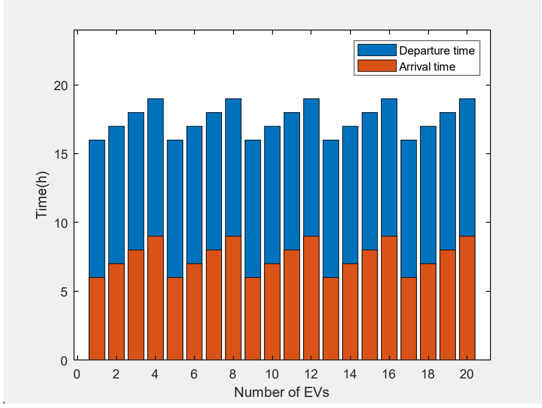

Fig. 3. Arrival and departure time of EVs

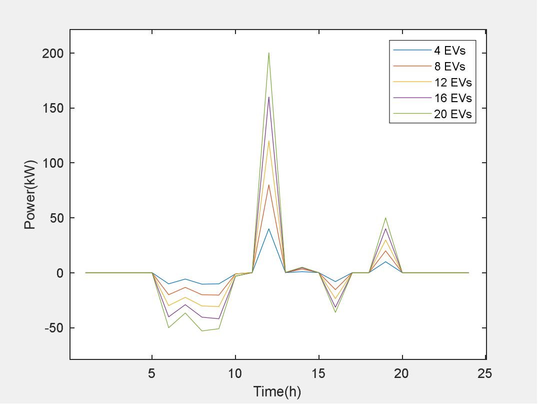

Fig. 4. EVs charging/discharging power (base case)

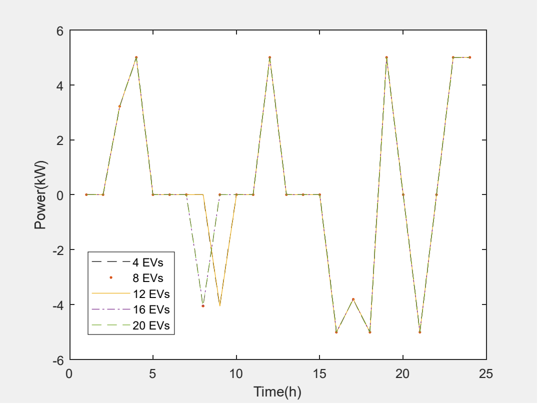

Fig. 5. ESS charging/discharging power (base case)

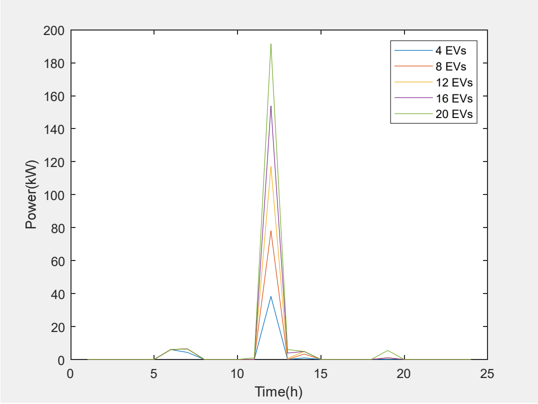

Fig. 6. EVs charging/discharging power ($0.2/kWh charging price)

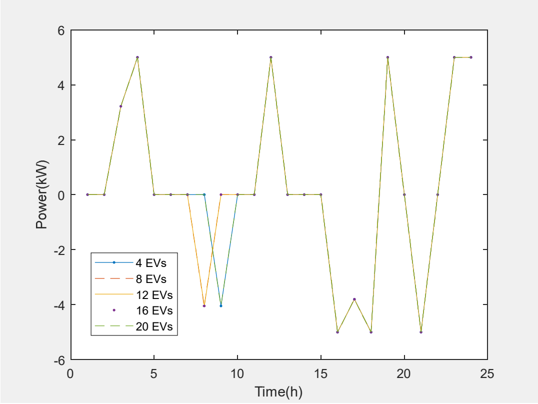

Fig. 7. ESS charging/discharging power ($0.2/kWh charging price)

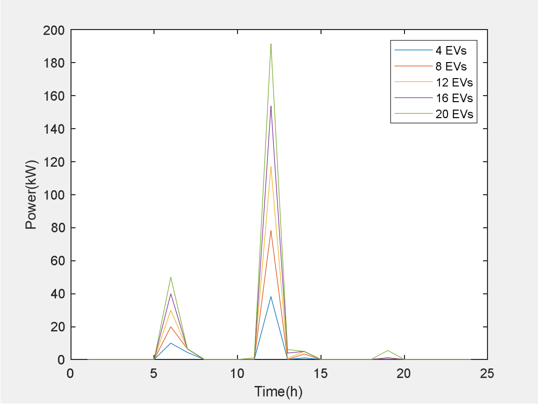

Fig. 8. EVs charging/discharging power ($0.23/kWh charging price)

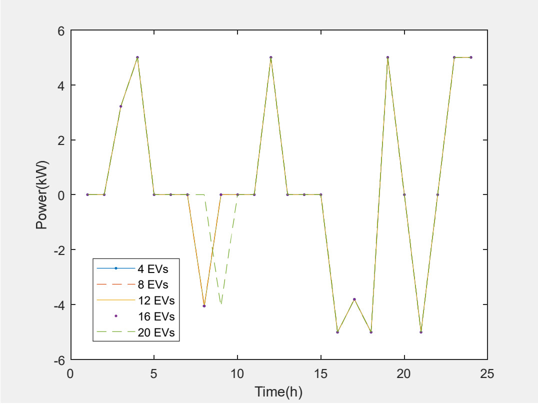

Fig. 9. ESS charging/discharging power ($0.23/kWh charging price)

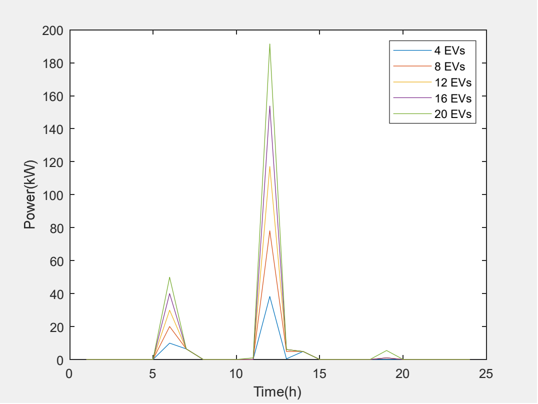

Fig. 10. EVs charging/discharging power ($0.25/kWh charging price)

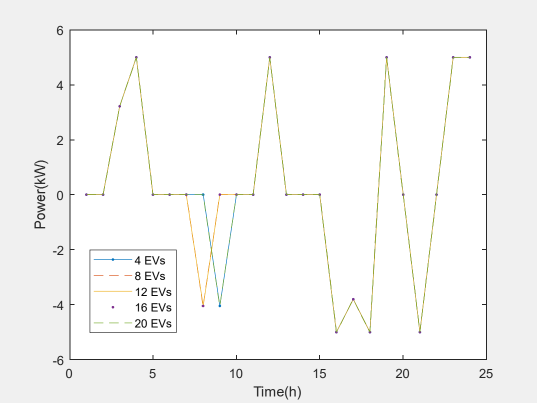

Fig. 11. ESS charging/discharging power ($0.25/kWh charging price)

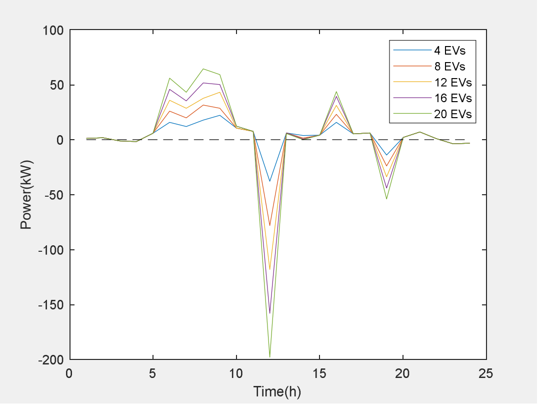

Fig. 12. Export (feed-in)/import power to/from the grid (base case)

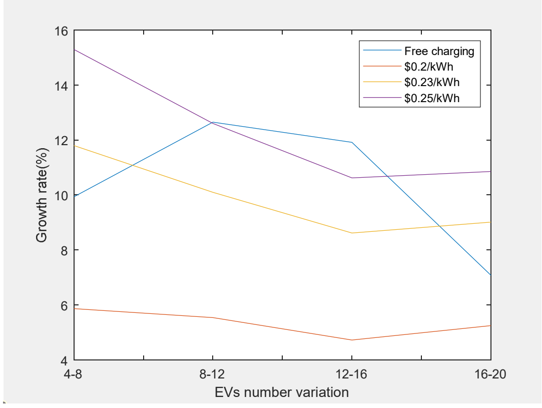

Fig. 13. Profit growth rate under different operation modes

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