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Unit Commitment of a Power System Including Battery Swap Stations Under a Low-Carbon Economy

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Abstract: Battery swap stations (BSSs) are of great importance as an energy supplement for electric vehicles (EVs). The batteries in these stations not only charge instantaneous energy from the grid (G2B) but also discharge stored energy to the grid (B2G). This bidirectional energy consuming scheme provides more flexibility to the grid operation options, and henceforth, may bring in new challenges to the systems as well. In the meanwhile, the carbon trading mechanisms for the low-carbon economy can also have impacts on the generation scheduling of the power system. Therefore, a unit commitment (UC) model of the power system with BSSs in the low-carbon economic background is proposed to coordinate the G2B/B2G process of BSSs. Our model weighted the carbon dioxide emission in the cost function and tightened the constraint set with BSSs limits and the carbon trading mechanism. Case studies on a 10-unit test system demonstrate the effectiveness of the proposed model.

Keywords: battery swap stations (BSSs); carbon trading mechanism; electric vehicles (EVs); low-carbon economy; unit commitment (UC)

1. Introduction

Nowadays, reducing carbon dioxide (CO_2) emissions has become a worldwide consensus that is accepted by many countries as an important strategy of sustainable development [1,2]. As one of the two major sources of CO_2 emissions, the electricity generation sector has the obligation to implement low-carbon technologies to reduce their emissions [3]. Hence, more and more renewable energy sources, such as wind and solar, are introduced into the power system as clean substitutions for fossil fuels [4]. Besides the renewable energy, the carbon trading mechanisms, in which the CO_2 emission allowance is regarded as a kind of commodity that can be traded in the carbon trading market, are required for the grid to restrict CO_2 emissions [5]. On the other hand, another major emission source is the traditional gasoline combustion vehicles, which is gradually being replaced by electric vehicles (EVs) with zero CO_2 emissions [6]. However, the adoption of a carbon trading mechanism and the arising of EVs industries bring in new challenges to the power system operation.

The low-carbon economy policies restrict the CO_2 emissions tightly such that whoever exceeds the regulation needs to buy the additional emission allowance or to pay the penalty. Thus, not only the generation and start-up costs but also the relevant cost arising from emission transactions or penalties should be considered in the unit commitment (UC) problem. In such a case, many studies have investigated how the power system should operate with policies of a low carbon economy. In Reference [7], the impact of carbon emission policies on generation scheduling is analyzed and an economic dispatch model is established based on the cap-and-trade mechanism, and the case studies show how the carbon emission prices and allowances influence generation scheduling results.

Renewable energy generation is regarded as a low-carbon solution in Reference [8], and a low-carbon economic dispatch model with wind power accommodation is built by considering carbon trading costs. In addition to renewable energy, the electrification of the transportation industry is able to reduce the overall primary energy consumption and CO_2 emissions due to the electricity and transportation sector [9]. Therefore, the EV is regarded as a low-carbon solution, and a coordination operation model of EVs and the power system is developed on the basis of a low-carbon economy [10].

For a successful rollout of EVs, it is required that an adequate charging infrastructure be established to cope with the limited EV range and long charging times. An efficient solution to these problems involves the deployment of battery swapping stations (BSS) because BSSs offer a fast and reliable alternative to charging batteries, namely swapping the discharged battery with a charged one. Meanwhile, BSSs charge batteries in Grid-to-Battery mode (G2B), and operate in Battery-to-Grid mode (B2G) by discharging batteries to the grid, rendering the two-way flow of electricity between the power system and BSSs. The main operational features of BSS are depicted and an optimization model of BSS is proposed in Reference [11]. In References [12,13], an optimal operation and services scheduling model for an electric vehicle battery swapping station in an electricity market is established based on the evaluation of the electricity price and battery demand. However, these models only studied the operation of BBS and did not consider the interaction between the BSSs and generators, which neglects the coordinated optimal operation of the power system and BSSs, which makes it difficult to fully exploit BBS's potential of carbon emission reduction. Therefore, this paper attempts to address these drawbacks, proposing a coherent optimization framework to incorporate BBS in the power system under a low-carbon economy. The major contributions of this paper are summarized as follow.

1. Considering the flexible interaction between the BSSs and the grid based on the G2B and B2G modes, this paper builds an operation model of an electric vehicle battery swap station.
2. The carbon emission costs due to generation dispatch are evaluated base on the Clean Development Mechanism (CDM) and are incorporated with the generation costs and battery wear cost of BSSs whilst considering the B2G mode.
3. Then, the unit commitment model of the power system with BSSs considered under low-carbon economy is established in this paper.

The framework of the unit commitment model of the power system with BSSs considered under a low-carbon economy is illustrated in Figure 1. The remainder of this paper is organized as follows. The model of BSS participating in the power system operation is established in Section 2. The CO_2 emission cost and relevant constraints arising from the low-carbon economy are discussed in Section 3. Based on Sections 2 and 3, the whole unit commitment model under a low-carbon economy with BSSs being considered is established in Section 4. Case studies based on a 10-unit test system are analyzed in Section 5, and some relevant conclusions are drawn in Section 6.
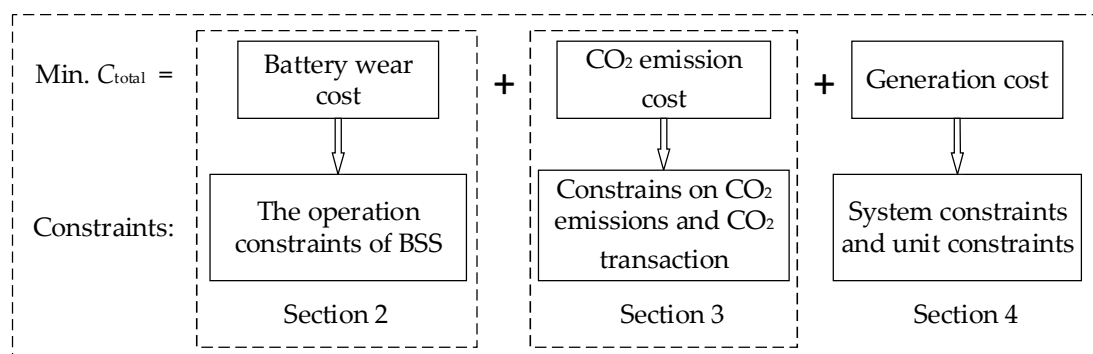

Figure 1. Framework of the proposed model.

2. Operation Model of Electric Vehicle Battery Swap Station

2.1. Energy Flow Model of a Battery Swap Station

A battery swap station is an important energy supply place for EVs, where depleted batteries can be replaced with fully-charged ones quickly. Usually, a BSS contains a power supply system, charging system, battery swapping system, battery testing and maintenance system, etc. [14]. The main operation characteristics of the BSS are illustrated in Figure 2.
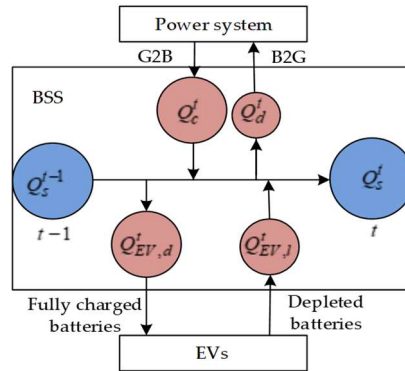

Figure 2. Main operation characteristics of a battery swap station.

It shows that the BSS can communicate bi-directionally with the power system and EVs. The BSS can draw energy from the grid to charge batteries (G2B), discharge energy from batteries to the grid (B2G), or replace depleted batteries with full ones for EVs. These flexible operation mechanisms will give the BSS an advantage when participating in the generation scheduling of the power system. At times when the power load increases, the batteries of the BSS will be scheduled to discharge to keep a load balance, instead of increasing the output of units. At times when power load decreases, the extra power can be used to charge batteries to satisfy the energy needed by the BSS. Hence, the BSS can be considered as a flexible load or generator to coordinate with the output of units, so as to obtain the best comprehensive benefit in both economic and environmental terms.

As shown in Figure 2, the procedure of G2B/B2G via chargers, as well as battery swapping demand of EVs, influences the total energy in the BSS. At the end of each period t, the energy flow model of a BSS can be given as

$$Q_s^t = Q_s^{t-1} + \eta_c Q_c^t - Q_d^t/\eta_d + Q_{EV,l}^t - Q_{EV,d}^t \tag{1}$$

$$Q_c^t = P_{rate}^{CH} N_{charge}^t \Delta t \tag{2}$$

$$Q_d^t = P_{rate}^{CH} N_{discharge}^t \Delta t \tag{3}$$

$$Q_{EV,l}^t = \lambda E_b N_{EV}^t \tag{4}$$

$$Q_{EV,d}^t = E_b N_{EV}^t \tag{5}$$

where Q_s^t is the overall stored energy of the BSS at time t, and Δt is the time interval. During period t (from time $t-1$ to time t), Q_c^t is the charging energy from the grid to the BSS, Q_d^t is the discharging energy from the BSS grid to the grid, $Q_{EV,l}^t$ is the overall energy of batteries unloaded from EVs, and $Q_{EV,d}^t$ is the total energy of batteries used for swapping. η_c and η_d are the charging and discharging efficiency of each charger, respectively. P_{rate}^{CH} is the rated charging/discharging power of each charger, N_{charge}^t is the number of chargers used for charging from the grid in period t, and $N_{discharge}^t$ is the number of chargers used for discharging to the grid in period t. N_{EV}^t is the number of batteries for EVs

that need battery swapping during period t. E_b is the battery capacity of each EV. λ is the average state of charge of battery for EVs when arriving at the BSS.

2.2. Operation Model of Battery Swap Station

The cost of a BSS participating in the power system operation is computed from battery wear cost due to discharging batteries to the grid in B2G mode. Considering the large-scale EVs access to the grid, there are enough batteries to discharge to the gird. Therefore, it is reasonable to assume that the discharging batteries are substituted with the others in every period to maintain a shallow depth-of-discharge (DoD) and then extend the battery lifetime. In this case, the battery wear cost is described as the product of the number of discharging batteries, i.e., the number of chargers used for discharging to the grid, and the wear cost in one discharging process is [15]:

$$C_w^t = N_{discharge}^t \cdot \frac{C_{bat}}{L} \tag{6}$$

where C_w^t is the battery wear cost due to discharging batteries to the grid in period t, C_{bat} is battery capital cost, and L is battery lifetime in cycles determined by the DoD.

The operation constraints of BSS include the constraint on the number of chargers, constraints on the maximum and minimum energy stored in the BSS, and the energy balance constraint of the BSS. During each period t, the batteries used for swapping are not available to participate in the G2B/B2G process. Thus, the number of chargers used for charging from the grid and discharging to the grid are limited by the total number of batteries that can be used. Also, the sum of them should not be more than the total number of chargers in the BSS. Therefore, the following constraint must be satisfied:

$$0 \le N_{charge}^t + N_{discharge}^t \le \min\left(N_c, N_b - N_{EV}^t\right) \tag{7}$$

where N_c is the total number of chargers in the BSS, and N_b is the total number of batteries in the BSS.

The batteries unloaded at period t need to be recharged in the latter periods. If depleted batteries are arranged to be charged as soon as possible, the energy of the BSS is maximal. Contrarily, the energy stored in the BSS is minimum if the BSS only has enough fully charged batteries to meet the swapping demand for the next period, while the other batteries are in the minimum state of charge. The constraints on the maximum and minimum energy stored in the BSS can be expressed as Equation (8):

$$Q_{s,\min}^t \le Q_s^t \le Q_{s,\max}^t \tag{8}$$

$$\begin{cases} Q_{s,\max}^t = N_b E_b + \sum\limits_{i=t-T_c+1}^{t}\left(\lambda + (1-\lambda)\frac{t-i}{T_c} - 1\right)N_{EV}^i E_b \\ T_c = \left\lceil E_b(1-\lambda)/\left(P_{rate}^{CH}\eta_c \Delta t\right)\right\rceil \end{cases} \tag{9}$$

$$Q_{s,\min}^t = N_{EV}^{t+1} E_b + \left(N_b - N_{EV}^{t+1}\right)E_b \lambda_{\min} \tag{10}$$

where T_c is the periods required to finish the charging of unloaded batteries from EVs, $\lceil \cdot \rceil$ is the ceiling function of the argument, and $\lambda_{\min}$ is the minimum state of charge of batteries in the BSS.

In order to ensure continuous operation of the BSS, it should obtain enough energy from the grid to fully charge all the unloaded batteries during the dispatch cycle. Then, the following energy balance constraint of the BSS ought to be enforced:

$$\sum_{t\in T}\left(\eta_c Q_c^t - Q_d^t/\eta_d\right) = \sum_{t\in T}(1-\lambda)N_{EV}^t E_b \tag{11}$$

where T is the set of time periods in the dispatch cycle.

3. Evaluation of the CO$_2$ Emission Cost Based on a Carbon Emission Trading Mechanism

3.1. Carbon Emission Trading Mechanism

For the purpose of achieving a CO$_2$ emission reduction effectively, three forms of carbon emission trading mechanisms have been proposed in the Kyoto Protocol, namely the clear development mechanism (CDM), joint implementation (JT), and emissions trading (ET), respectively [16]. Recently, China is mainly engaging in CDM transactions. The CDM allows industrialized countries that have accepted emissions reduction targets to develop or finance projects that reduce greenhouse gas (GHG) emissions in non-Annex 1 countries, which are large GHG emitters such as China, India, Brazil, and Mexico, in exchange for emission reduction credits. This contributes to the sustainable development of the non-Annex 1 countries.

When introducing the CDM transactions into the electric power sector, a limit or cap on the amount of CO$_2$ that is allowed to be emitted (i.e., a carbon emission allowance) is allocated to each generation company. The generation company has to keep the actual CO$_2$ emissions less than the allocated allowances. Otherwise, it may need to purchase additional allowances from the other companies through CDM transactions or pay a penalty for the exceeding emissions. In such a case, however, the operation of the power system would minimize not only the generation costs but also the carbon emission costs arising from the CDM transactions or penalty paid for exceeding emissions. It is imperative to study how a carbon trading mechanism will influence the generation dispatch of the power system.

3.2. Evaluation of the CO$_2$ Emission Cost under CDM Transactions

The carbon emission allowance is allocated to each generation company through various methods, such as grandfathering, benchmarking, and auction [17]. According to the development of the carbon trading market in China, the benchmarking method in which the emission allowances are granted on the basis of a proportion of historical production is used to allocate the initial emission allowances for the generation company [18]. During each period t, the carbon emission allowances of one grid E_d^t can be expressed as:

$$E_d^t = \xi P_{LD}^t \tag{12}$$

where P_{LD}^t is the power demand of the traditional load during period t, and ξ is the benchmarking emission factor of the thermal power system; it is decided by the operation margin (OM) and build margin (BM).

In each period t, the overall CO$_2$ emissions of each unit can be estimated as a quadratic function of the power output. Thus, the total CO$_2$ emissions of all units in the grid E_c^t is as follows:

$$E_c^t = \sum_{i \in I} \alpha_i \left(P_i^t \right)^2 + \beta_i P_i^t + \gamma_i \tag{13}$$

where, α_i, β_i, and γ_i are all the corresponding CO$_2$ emission coefficients of unit i, I is the index set of units in the grid, and P_i^t is the power output of unit i in period t.

On the basis of the CDM transactions, the CO$_2$ emission cost C_c^t can be evaluated by comparing the CO$_2$ emission allowances and actual emissions, which is written by

$$C_c^t = K_{CDM} \Delta E_{CDM}^t + K_p \Delta E_p^t - K_{CDM} \Delta E_{CDM}^t{}' \tag{14}$$

$$\Delta E_{CDM}^t = \max\left\{0, \min\left(\left(E_c^t - E_d^t \right), E_{CDM,\max}^t \right)\right\} \tag{15}$$

$$\Delta E_p^t = \max\left\{0, E_c^t - E_d^t - \Delta E_{CDM}^t\right\} \tag{16}$$

$$\Delta E_{CDM}^t{}' = \max\left\{0, \min\left(\left(E_d^t - E_c^t \right), E_{CDM,\max}^t \right)\right\} \tag{17}$$

where, in each period t, ΔE_{CDM}^t, ΔE_p^t, and $\Delta E_{CDM}^t{}'$ represent the purchased emission allowances through CDM transactions, the emission allowances obtained by paying penalty, and the sold emission allowances through CDM transactions, respectively. K_{CDM} is the price of purchased and sold emission allowances through CDM transactions, K_p is the penalty paid for excessive CO_2 emission, and $E_{CDM,\max}^t$ is the upper limit of purchased and sold emission allowances through CDM transactions.

The two cases of C_c^t are as follows. When $E_c^t > E_d^t$, i.e., the amount of carbon emissions being more than the allocated emission allowances, the system has to purchase emission allowances via CDM transactions or pay a penalty for the exceeding emissions. In this case, it would increase the overall cost of the power system. Whereas when $E_d^t \geq E_c^t$, the system could sell the surplus allowances to make a profit. In such case, it would decrease the total cost of the power system accordingly.

Considering the allocated emission allowances and the development scale of the carbon trading market, constraints of the maximum CO_2 emissions and limit of CO_2 trading allowances by CDM transactions should be enforced

$$E_c^t + \Delta E_{CDM}^t{}' \leq E_d^t + \Delta E_{CDM}^t \quad \forall t \in T \tag{18}$$

$$\Delta E_{CDM}^t \leq E_{CDM,\max}^t \quad \forall t \in T \tag{19}$$

$$\Delta E_{CDM}^t{}' \leq E_{CDM,\max}^t \quad \forall t \in T \tag{20}$$

4. Unit Commitment Model of the Power System Including BSSs under a Low-Carbon Economy

4.1. Objective Function

As described in Section 2, BSSs can exchange power bi-directionally with the grid as load or generator depending on the Grid-to-Battery mode (G2B) and Battery-to-Grid mode (B2G), which makes the operation of the power system more flexible and a lower carbon emitter, but also more complicated. To solve this problem, a unit commitment model under a low-carbon economy with BSSs considered is proposed to coordinate the charging/discharging profile of BSSs with the production of generators. The objective of this model is to minimize the overall cost, which includes fuel costs and the start-up cost of generators, the CO_2 emission cost arising from a low-carbon economy, and battery wear cost due to discharging batteries to the grid. Therefore, the objective function is described as

$$\min C_{total} = \min \sum_{t \in T} \left(C_p^t + C_s^t + C_c^t + C_w^t \right) \tag{21}$$

$$C_p^t = \sum_{i \in I} \left(a_i \left(P_i^t \right)^2 + b_i P_i^t + c_i \right) \tag{22}$$

$$C_s^t = \sum_{i \in I} u_i^t \left(1 - u_i^{t-1} \right) ST_i \tag{23}$$

$$ST_i = \begin{cases} C_{HS,i}, & \text{when } T_{MD,i} \leq T_{off,i}^{t-1} \leq T_{MD,i} + T_{cold,i} \\ C_{CS,i}, & \text{when } T_{off,i}^{t-1} > T_{MD,i} + T_{cold,i} \end{cases} \tag{24}$$

$$C_w^t = \sum_{n \in N} \left(N_{discharge,n}^t \cdot \frac{C_{bat}}{L} \right) \tag{25}$$

where, C_p^t is the fuel cost in period t, C_s^t is the start-up cost in period t, a_i, b_i, and c_i are the fuel cost coefficients of unit i, ST_i is the start cost of unit i, and $C_{HS,i}$ and $C_{CS,i}$ are the hot-start and cold-start cost of unit i, respectively. $T_{off,i}^{t-1}$ represents the duration that unit i is continuously off. $T_{MD,i}$ and $T_{cold,i}$ are the minimum down-time and the cold-start time of unit i, respectively. N is the index set of BSSs in the grid, and $N_{discharge,n}^t$ is the number of chargers used for discharging in period t of BSS n.

4.2. Constraints

1.　Electric power balance constraint of the whole system in each period t.

$$\sum_{i \in I} P_i^t - \sum_{n \in N} \left(N_{charge,n}^t - N_{discharge,n}^t \right) P_{rate}^{CH} = P_{LD}^t \quad \forall t \in T \tag{26}$$

where P_{LD}^t is the power demand of the traditional load during period t. $N_{charge,n}^t$ is the number of chargers used for charging in period t of BSS n.

2.　Minimum and maximum output constraints of generation units.

$$u_i^t P_{\min,i} \leq P_i^t \leq u_i^t P_{\max,i} \quad \forall t \in T \tag{27}$$

where $P_{\max,i}$ is the maximum generation output of unit i, $P_{\min,i}$ is the minimum generation output of unit i, and u_i^t is the on/off status of unit i during period t.

3.　Minimum on and off time constraints of generation units.

$$\begin{cases} \left(u_i^t - u_i^{t-1} \right) T_i^{on} + \sum_{j=t-T_i^{on}}^{t-1} u_i^j \geq 0 \quad \forall t \in T \\ \left(u_i^{t-1} - u_i^t \right) T_i^{off} + \sum_{j=t-T_i^{off}}^{t-1} \left(1 - u_i^j \right) \geq 0 \quad \forall t \in T \end{cases} \tag{28}$$

where T_i^{on} is the minimum on time intervals of unit i, and T_i^{off} is the minimum off time intervals of unit i.

4.　Up- and down-ramping rate constraints of generation units.

$$\begin{cases} P_i^t - P_i^{t-1} \leq R_{up,i} \quad \forall t \in T \\ P_i^{t-1} - P_i^t \leq R_{dn,i} \quad \forall t \in T \end{cases} \tag{29}$$

where $R_{up,i}$ is the ramp-up limit of unit i, and $R_{dn,i}$ is the ramp-down limit of unit i.

5.　Spinning reserve constraints

$$\sum_{i \in I} \min\left\{ u_i^t R_{up,i}, u_i^t P_{\max,i} - P_i^t \right\} \geq SR_{up}^t \quad \forall t \in T \tag{30}$$

$$\sum_{i \in I} \min\left\{ u_i^t R_{dn,i}, P_i^t - u_i^t P_{\min,i} \right\} \geq SR_{dn}^t \quad \forall t \in T \tag{31}$$

where SR_{up}^t is the up-spinning reserve requirement in period t, and SR_{dn}^t is the down-spinning reserve requirement in period t.

6.　Operation constraints of the BSS, i.e., Equations (7)–(11), should be satisfied.
7.　Constraints of the maximum CO_2 emissions and limit of CO_2 trading allowances by CDM transactions, i.e., Equations (18)–(20), should be satisfied.

5. Case Study

A simulation study of an independent system consisting of ten units with 1662 MW total installed capacity was carried out. The generation data of the ten units and the traditional load profile were obtained from Reference [19]. The estimated emission coefficients of the ten units were collected from Reference [20], and the unit parameters can be found in Table 1. Both up- and down-spinning reserve requirements were set to 10% of peak demand. It was assumed that there were 50 BSSs connected to the system and each of them provided a swapping service for 1000 EVs. Some important parameters of BSSs and EVs are shown in Table 2 [21,22]. Assuming that EVs would go to the BSS to complement energy when they finish their last trips, the statistical data of the end time of the last trip

from Reference [23] was used to generate the EVs battery swapping demand of each BSS, as shown in Figure 3.

Table 1. Relevant Parameters of 10-unit Test System.

Unit	P_{max} (MW)	P_{min} (MW)	a_i ($/MW^{2}h)	b_i ($/MWh)	c_i ($/h)	α_i (ton/MW^{2}h)	β_i (ton/MWh)	γ_i (ton/h)
1	455	150	0.00048	16.19	1000	0.00312	−0.24444	10.33908
2	455	150	0.00031	17.26	970	0.00312	−0.24444	10.33908
3	130	20	0.002	16.6	700	0.00509	−0.40695	30.03910
4	130	20	0.00211	16.5	680	0.00509	−0.40695	30.03910
5	162	25	0.00398	19.7	450	0.00344	−0.38132	32.00006
6	80	20	0.00712	22.26	370	0.00344	−0.38132	32.00006
7	85	25	0.0079	27.74	480	0.00465	−0.39023	33.00056
8	55	10	0.00413	25.92	660	0.00465	−0.39023	33.00056
9	55	10	0.00222	27.27	665	0.00465	−0.39524	35.00056
10	55	10	0.00173	27.79	670	0.0047	−0.39864	36.00012

Table 2. Relevant Parameters of BSS$_S$ and EV$_S$.

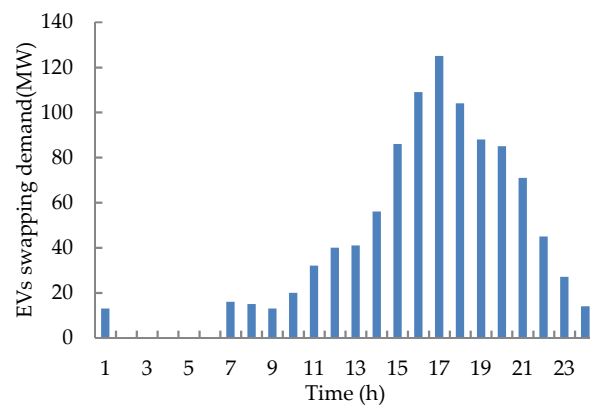| Parameters	Values
Battery capacity (KWh)	24.0
Battery lifetime in cycles for shallow DoD	6000
Battery capital cost ($)	9890
Average state of charge of EVs	0.5
Number of chargers in each BSS	500
Number of batteries in each BSS	600
Charging/discharging efficiency	0.9
Rated charging/discharging power (KW)	6.6
Minimal state of charge	0.2

Figure 3. Battery swapping demand of EVs in each BSS.

In this case study, the CO_2 emissions were assumed to be measured simply through the CDM transactions. The price of the purchased or sold emission allowances under the CDM was set to be $20/tCO_2$. The benchmarking emission factor of the grid was 0.55 tCO$_2$/MWh. The optimization period was one day from 6:00 to the next day 6:00 in order to ensure all batteries fully charged at the last time interval. The time interval Δt used for all the simulations was 1h. The proposed model was a Mixed Integer Quadratic Programming (MIQP) problem, which was solved by using CPLEX solver under MATLAB.

5.1. Results Analysis

The charging/discharging process of the BSSs, the original load, and the formed total load with BSSs are shown in Figure 4a. As shown, the charging of batteries was mainly focused on the off-peak periods, while the B2G injections were primarily in the peak periods. The charging process from 15:00 to 18:00 was to ensure that BSSs were able to meet the energy requirement of battery swapping in peak periods. Note also that the BSSs charged again from 22:00 to 4:00 because they needed the same energy state as the one they had at the beginning of the optimization horizon. The B2G injections (11:00–13:00 and 19:00–20:00) could replace the output of units in a part, which decreased the burden of units and increased their flexibility to achieve a more optimal operating condition. Due to the B2G/G2B process of BSSs, the difference of peak load and off-peak load was reduced from 800 MW to 632.1 MW, which implied a more effective utilization of all units in the system.

The optimization results of the commitment status and production of each generating unit are shown in Figure 4b. As can be seen, the initial states of units 1–5 were synchronized while the others are offline. All the generators were operating from hours 8:00 to 13:00, during which the load demands were greater than that of the other periods. Additionally, the units with small capacities were operating at the maximum output state as far as possible, if they were online. Under the low-carbon economy, the generation outputs of units with large capacities, which were with lower fuel consumption and higher CO_2 emissions, were reduced to some extent so as to achieve the optimum of economic benefit and environmental benefit.
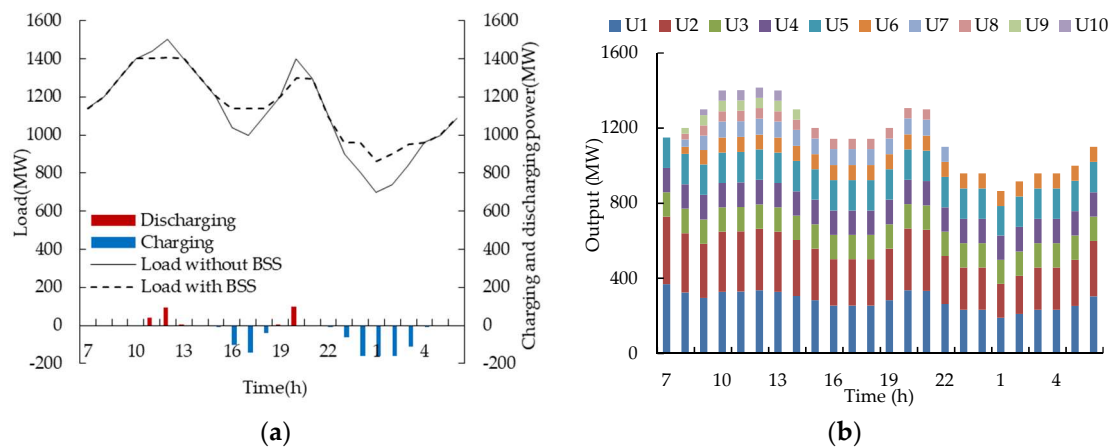

Figure 4. The optimization results of UC model: (**a**) The charging/discharging profile of BSSs; (**b**) The output of each unit in each period.

5.2. Optimization Results with and without B2G

The BSS may not be willing to discharge to the grid when needed, considering the battery degradation, because of B2G injections [24]. Therefore, case 2, in which the discharging of batteries was not allowed, was employed to analyze how the optimization results changed without B2G. Figure 5 shows the total load curves of the two cases. It indicates that the valley in the load curve could be filled in both cases, while the peak of the load curve was only decreased in case 1. Also, from 15:00 to 18:00, batteries of case 1 were scheduled to charge more energy than that of case 2. The reason is that the additional energy was not only used to compensate the consumption energy of B2G from 11:00 to 13:00, but also as reserves to deploy scheduled discharging during 19:00–20:00.
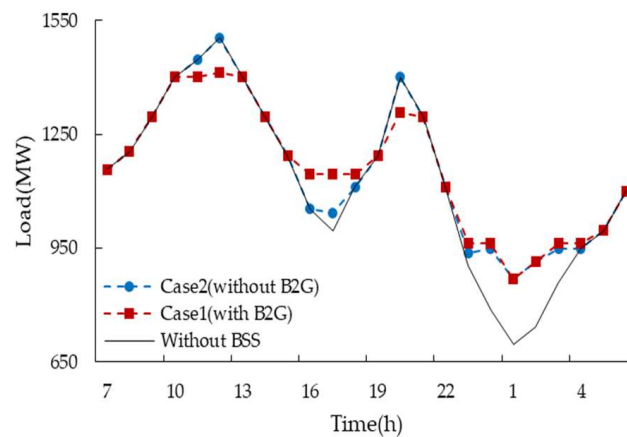
Figure 5. Total load curves formed in case 1 and case 2.

The costs and CO_2 emissions of the two cases are shown in Table 3. It can be seen that the battery wear cost only occurred in case 1 because the B2G process and fuel cost in case 1 was more than that of case 2, while both start-up cost and CO_2 emission costs were less than that of case 2. It was the loss resulting from the flow of electricity from the system to batteries and then from batteries back to the system that required more power production from generators in case 1, thereby increasing the fuel cost. However, the B2G injections were available for peak load shaving, which allowed generators to operate more flexibly and reduce startup and output with higher CO_2 emission intensity, thus the start-up cost and CO_2 emission cost of case 1 was decreased compared to case 2. Therefore, the overall cost was reduced and the total CO_2 emissions were decreased by 243 tons when the B2G mode was implemented.

Table 3. Costs and CO_2 Emissions in Different Cases.

Cost	Case 1 (With B2G)	Case 2 (Without B2G)	Case 3 (Without EVs)
Fuel cost (10^4\$)	64.316	63.966	62.803
Start-up cost (\$)	610	670	670
Emission cost (10^4\$)	0.819	1.341	0.161
Battery wear cost (\$)	1236	–	–
Overall cost (10^4\$)	65.320	65.374	63.031
Total CO_2 emissions (tons)	15,332.6	15,575.2	14,985.4

5.3. Low Carbon Analysis of EVs

EVs with zero-emission of CO_2 are regarded as the clean alternatives of traditional vehicles. However, charging the EVs will increase the load of the power system, which in return increases the CO_2 emissions from power plants. Thus, it is worthwhile to analyze whether EVs can reduce emissions or not, as emissions will be shifted from the transportation sector to the power system.

As shown in Table 2, the average daily mileage of each EV is 33.9 miles. If so, the total daily mileage of the 50,000 EVs in the system is 1,695,000 miles. Then, the total CO_2 emission from CVs is 927.3 tons, if they cover the same mileage with EVs (the average CO_2 emission from CVs is 1.2 lb/mi). As shown in Table 3, the CO_2 emissions of case 3 without EVs are 14,985.4 tons. Compared with that of case 1, the excess emission from power plants to supply energy for the EVs is 328.5 tons, which is regarded as the CO_2 emissions of EVs. Thus, 50,000 EVs reduce the CO_2 emissions by 598.8 tons compared to CVs. Even in case 2, EVs can also reduce a total of 337.5 tons CO_2 emissions. It can be seen that the application of EVs are effective to achieve carbon emission reduction, although it increases CO_2 emissions of the power system to some extent.

5.4. Sensitivity Analysis of CDM Transactions Price

Under the low-carbon economy, the price of the CDM transactions plays an important role in the UC optimization problem. The CO_2 emission intensity at different CDM prices are shown in Figure 6a. Observe that an increase in the CDM price led to the decrease of the CO_2 emission intensity. This is because more units with lower CO_2 emission intensity were scheduled to increase production with higher CDM price, reducing the total CO_2 emissions. Additionally, the emission intensities were decreased slightly, and were almost the same when the price was higher than $30/tCO_2$, since the units with lower emissions intensity have been used as far as possible. Thus, it was tough to reduce the CO_2 emissions further.

Figure 6b presents how the different costs change with the CDM price. As shown, with an increase of the CDM price, the generation cost, including the fuel and start-up costs, tended to increase continuously, while the CO_2 emission cost increased at first and then decreased. Consequently, the overall cost was increased first and had the maximum value when the CDM price was $24/tCO_2$, and then decreased. The reasons are as follows. As the CDM price increased, the units with a lower emission intensity as well as higher fuel consumption were scheduled to increase power output, which reduced the CO_2 emissions, which increased the generation cost correspondingly. Besides, given the emission allowances through CDM transactions increased with higher CDM price, the total CO_2 emission cost depended on the trade-off between the increase of the CDM price and the decrease of CO_2 emissions. Therefore, if the effect of the CDM price dominated over the effect of CO_2 emissions, the CO_2 emission cost was increased. Otherwise, it tended to decrease.
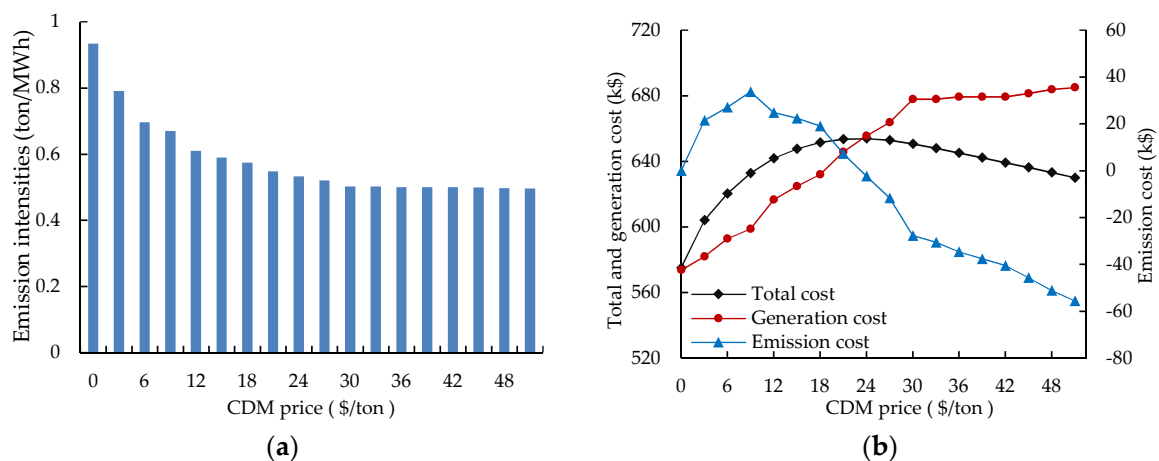

Figure 6. The generation scheduling results under different CDM prices: (**a**) CO_2 emission intensities; (**b**) Generation cost, CO_2 emission cost, and total cost.

6. Conclusions

A model for optimizing the unit commitment and the charging/discharging profile of BSSs under a low-carbon economy has been proposed in this paper, which aimed to minimize the overall cost of the power system. By taking the relevant constraints of BSSs and a carbon trading mechanism into account, the model could better evaluate the generation scheduling of a power system with BSSs, in the condition of a low-carbon economy. In addition, an explicit model of the operation characteristics of BSSs was also described.

An implementation of case studies based on a 10-unit test system showed that BSSs were scheduled to charge during off-peak periods, while being discharged in peak periods, so as to achieve the optimum of economic benefit and environmental benefit. A comparison of UC with and without B2G revealed that B2G injections were effective for CO_2 emission reduction. It was also shown that EVs

shifting less CO_2 emissions to the power system was promising to be the alternative to the traditional vehicles. Moreover, the results of UC optimization were sensitive to the CDM transaction price.

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