

Article

Optimized Scheduling of an Integrated Energy System with an Electric Truck Battery Swapping Station

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Abstract: Currently, the focus of integrated energy system scheduling research is the multi-objective's optimized operational strategies that take into account the economic benefits, carbon emissions, and new energy consumption rates of such systems. The integration of electric trucks with battery charging and swapping capabilities, along with their corresponding battery swapping stations, into an integrated energy system can not only optimize system operation, but also reduce investment costs associated with building energy storage equipment. This study first constructs an operational model for the electric trucks, as well as an electric truck battery swapping station, of the flexible charging and discharging; then, an optimized scheduling model of an integrated energy system is proposed, including an electric truck battery swapping station and using stepped carbon trading. On the basis of meeting the charging and battery swapping needs of electric trucks and coordinating the system's electrical, thermal and cooling energies, the goal of the optimized scheduling model is to reduce the system's carbon emissions, improve its economics, and optimize its ability to absorb new energy. Finally, a simulation model of the integrated energy system including an electric truck battery swapping station is built on the MATLAB platform, and commercial software package CPLEX is used to solve the model. In the calculation example, compared to the integrated energy system of disorderly charging and battery swapping of electric trucks and electric truck battery swapping stations, the proposed optimized model of the integrated energy system with the flexible charging and discharging of electric trucks and electric truck battery swapping stations reduces the operating costs by CNY 819, reduces carbon emissions by 414 kg, improves the utilization rate of wind and solar power by 0.3%, and fully utilizes wind and photovoltaic power. Therefore, the rational dispatching of the electric trucks and their battery swapping stations with flexible charging and discharging mentioned in this article can effectively optimize system operations.

Keywords: electric trucks with battery charging and swapping capabilities; electric truck battery swapping station; flexibly adjust; step carbon trading; integrated energy system



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1. Introduction

Against the backdrop of fossil fuels depletion on Earth and the intensification of greenhouse effects, energy infrastructure urgently needs to be reformed. In the current energy system, vigorous development of new energy on the energy supply side has reduced the carbon emissions of thermal power plants; on the other hand, the uncertainty of new energy output has resulted in great difficulties in stabilizing the operation of power systems. At the same time, the energy demand side is also rapidly promoting the transformation of new energy and reducing the use of fossil fuels. However, the demands of energy-consuming equipment further affect the stable operation of power systems. The current effective measure to address this issue is to build an integrated energy system (IES) [1],

which can optimize the operation of itself through the coordinated conversion of multiple energies and further tapping the scheduling potential of the load side. A large number of scholars at home and abroad have conducted extensive studies on integrated energy systems. Current research focuses on building a more efficient IES structure [2], improving IES carbon trading strategies [3], further exploring the scheduling potential of IESs on the energy demand side [4–8], constructing IES optimization models that consider the uncertainty of new energy output and load [9–13] and constructing IES optimization models with multiple stakeholders [1,8,14], etc. Although the research of integrated energy systems has achieved many results, there are still many problems that need to be explored and solved.

In recent years, a large number of fuel vehicles have been replaced by electric vehicles (EVs), which effectively alleviates environmental problems caused by the use of fossil fuels. However, the energy demand for batteries that provide energy for EVs is very significant. If EVs undergo disorderly charging and battery swapping, this will have a significant negative impact on the safe and stable operation of IESs. At the same time, the batteries of EVs can be used as energy storage devices to participate in IES scheduling when EVs are not working, which can optimize the operation of IESs and reduce the investment costs of constructing energy storage equipment. Therefore, studying the charging and swapping behaviors of EVs is of great significance.

Currently, domestic and foreign scholars mainly focus on EV charging loads and battery swapping loads prediction, as well as optimizing the operations of charging stations and battery swapping stations. Currently, EV charging loads and battery swapping loads prediction is mostly made on the basis of historical data for charging and battery swapping loads [15–18], as well as probability distribution functions [19–24]. In addition, according to the operating characteristics of different model EVs, the charging loads and battery swapping loads can be predicted. For example, study [25] established an “electric taxi-battery-traffic-station” interconnected system based on the battery swapping mode and predicted the battery swapping demand based on the travel behavior of electric taxis and the battery swapping behavior in the station. Study [26] predicted the battery swapping demand according to bus number, task schedule, bus route, and other parameters. The authors of [27] calculated the battery charging and discharging demand by considering the two-day charging, unloading, and arrival and departure times of electric trucks in factories. However, there has been little research on electric truck (ET) charging and battery swapping behavior based on operating characteristics on fixed routes. Moreover, the EV power supply method is relatively simple, either charging or battery swapping, and few studies have combined considerations of the two modes.

Compared with charging mode, the battery swapping mode of EVs has the advantages of greater scheduling flexibility, fast power supply, easy centralized management, and low green energy losses [28]; thus, the application prospects are very good. However, the battery swapping load of the optimized operation model of the battery swapping station in the current study is generally not adjustable [20,25,26]. The charge and discharge behavior of batteries in the battery swapping station is generally regulated by a group [29,30]. Most batteries can only be swapped when they are fully charged and can only be charged and discharged continuously at constant power until they are full or drained [31–33]. In practice, on the basis of meeting the transportation tasks of ETs running on a fixed route, the battery swapping load of ETs can be adjusted to a certain extent; the charging and discharging behavior of each battery can be separately regulated by the battery swapping station; when the battery is swapped on an ET, it does not need to be fully charged; the charging and discharging power of the battery is variable; and the charging and discharging behavior of the battery can also be interrupted.

In view of the above research status and actual needs, firstly, the characteristics of ETs with battery charging and swapping capabilities running on fixed lines were analyzed, and the adjustable load model of ETs based on meeting transportation tasks was established. Furthermore, the operation model of the electric truck battery swapping station (ETBSS)

was constructed, in which the charging and discharging power of each battery is variable, the charging and discharging behavior of each battery can be interrupted, and the battery does not need to be fully charged during swapping. Combined with an ETBSS operating model, the IES model that contained an ETBSS was established using a gas turbine with an adjustable thermoelectric ratio, while a waste heat boiler of heat output was used for the cooling and heating adjustable ratio, taking into account various flexible loads. Based on the above model, an optimized scheduling model of the IES with an ETBSS was established to calculate the carbon emissions costs of the IES using a stepped carbon trading mechanism. Based on meeting the demands of ET charging and battery swapping and coordinating the electrical, thermal and cooling energies of the IES, the scheduling strategy optimizes IES operation with the goal of reducing carbon emissions and improving the economics and the ability to absorb new energy of IES. Finally, CPLEX software was used to solve the simulation examples, and a variety of cases were set for comparative analysis to verify the economics and the low-carbon and new energy consumption abilities of the proposed model.

2. IES with an ETBSS Structure and Model Building

The basic structure of an IES containing an ETBSS, which integrates electrical, thermal, and cooling loads, is shown in Figure 1. It mainly includes three parts: the energy supply side, the conversion side, and the demand side. The energy supply side involves the power distribution network, gas network, wind turbine (WT), and photovoltaic (PV); the energy conversion side contains the gas turbine (GT), waste heat boiler (WHB), absorption cooler (AC), heat pump (HP), and electric cooler (EC); the energy demand side comprises the electrical, thermal, and cooling loads containing various flexible loads.

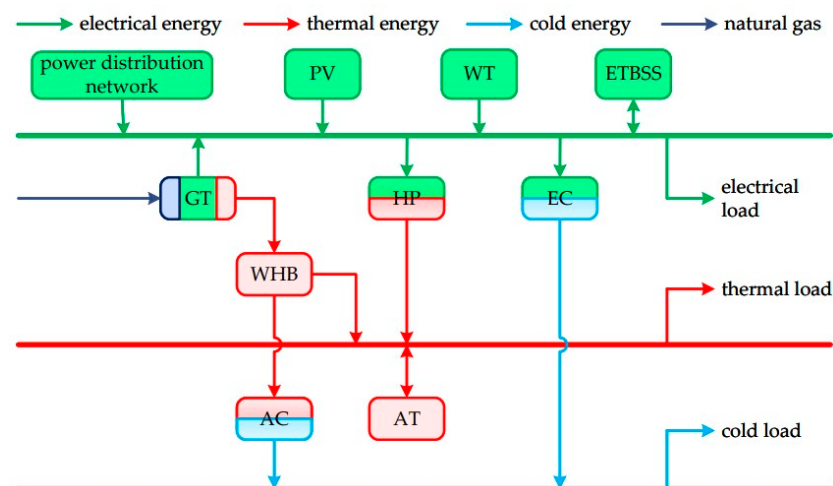


Figure 1. IES with an ETBSS architecture diagram.

In the IES, the electricity is mainly supplied by the WT and PV, and the insufficient part can be obtained from the ETBSS, the power distribution network, and the GT. Thermal energy is provided by the WHB, HP, and accumulator tank (AT); cooling energy is provided by the AC and EC.

2.1. ET and ETBSS Models

Currently, ETs are mainly used for freight transportation on fixed lines. ETs can use battery swapping mode to improve their efficiency during working hours; during non-working hours, ETs are connected to the ETBSS via charge and discharge equipment to participate in IES scheduling. This research explores the optimal ETBSS scheduling under the case that the ETBSS can complete two or more round-trip operations with a battery swap. On the premise of meeting the transportation task of ETs, the number of battery

swaps of ETs and the number of round-trip operations supported by each battery swap can be flexibly adjusted in order to adjust an ET's battery swapping load. The idea of constructing the ETBSS model is shown in Figure 2.

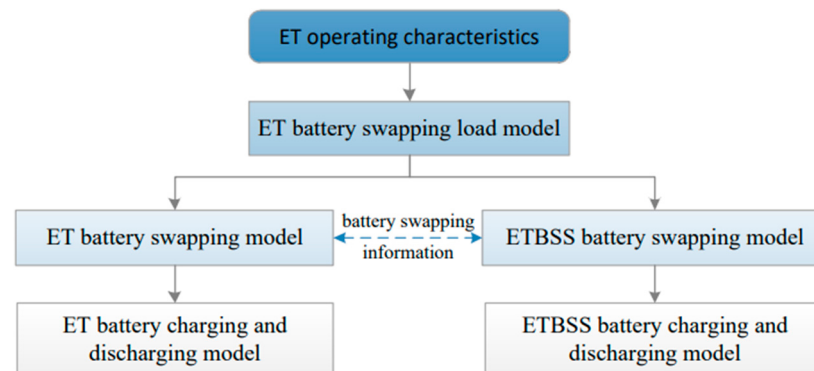


Figure 2. ETBSS model construction idea diagram.

In order to ensure the service life of an ET battery, undesirable charging and discharging behavior should be prevented. And in order to reserve a certain spare electrical energy for the ET, the state of charge (SOC) of the battery in this research was kept between 20% and 95% [26]. In order to simplify the calculation process and ensure that the simulation results did not deviate too much from actual situations, the following assumptions were made:

- (1) The ET battery is the same model as the battery in the ETBSS, and the ET can complete a round-trip operation and battery swap within a period of time.
- (2) The electricity of the ETBSS's batteries at the initial moment of the battery swapping period should meet the power demands of ET users during the period, and the batteries swapped by the ETs can only start charging and discharging in the next period; that is, the impact of ET arrival time on the ETBSS charge and discharge plan is not considered.
- (3) A charge and discharge chamber can only charge or discharge a battery in a certain period of time.
- (4) The number of battery storage locations in the ETBSS is the same as the number of batteries in the ETBSS.

2.1.1. Modeling of ET Battery Swapping Load

According to the total number of round-trip running of an ET, the number of round-trip running that the SOC of battery swapped to the ET needs to support in each period can be obtained. The SOC of battery that is swapped to the ET at each time period needs to meet the power demand of the ET, so the following constraints shown in Equation (1) must be met:

$$\begin{cases} \sum_{jj=N_{T,start}}^{N_{T,start}+N_{trans}-1} N_{b,jj}^i = N_{trans} - N_{run_start,i} \\ \sum_{jj=1}^{N_{T,start}+N_{run_start,i}-1} N_{b,jj}^i + \sum_{jj=N_{T,start}+N_{trans}}^{N_T} N_{b,jj}^i = 0 \end{cases} \quad (1)$$

where $N_{b,j}^i$ is the number of round-trip running that the SOC of battery swapped from the ETBSS to the i ET needs to support in the j time period (its value is 0, indicating that the battery of the ET is not swapped); N_{trans} is the total number of round-trip running of the ET; $N_{run_start,i}$ refers to the number of round-trip running that the battery power in the i ET can support when it starts running; $N_{T,start}$ is the period when the ET starts running; and N_T indicates the total number of time segments in a scheduling cycle.

Due to the battery capacity limitation, the battery on the ET can only support the ET for a limited number of round trips, so the value ranges of $N_{b,j}^i$ and $N_{run_start,i}$ are shown in Equation (2):

$$\begin{cases} 0 \leq N_{b,j}^i \leq N_{run} \\ 0 \leq N_{run_start,i} \leq N_{run} \end{cases} \quad (2)$$

where N_{run} is the maximum number of round-trip running that can be completed by a battery swap.

In addition, the $N_{b,j}^i$ of the same ET in different time periods affect each other, so the $N_{b,j}^i$ of the same ET needs to meet the following constraints shown in Equation (3):

$$\begin{cases} N_{b,j+1}^i \geq 0 & (N_{b,j}^i = 0) \\ N_{b,j+1}^i \geq 1 & (N_{b,j}^i = 1) \\ \sum_{jj=j+1}^{j+N_{b,j}^i-1} N_{b,jj}^i = 0 \& N_{b,j+N_{b,j}^i}^i \geq 1 & (N_{b,j}^i \geq 2) \\ N_{b,j}^i \leq N_{T,start} + N_{trans} + 1 - j & (j > N_{T,start} + N_{trans} - N_{run} + 1) \end{cases} \quad (3)$$

In the equation, the value of $N_{b,j}^i$ of the same ET in the j time period will affect the value of $N_{b,j+}^i$ of the same ET in the time period after the j time period. In addition, the value of $N_{b,j}^i$ of the ET in the last few time periods is also constrained by the remaining number of round-trip running.

Due to limitations in the numbers of battery swapping equipment and the time to complete a battery swap, the ETBSS can provide a limited number of battery swaps in a period of time, so the total number of ET battery swaps in a period of time needs to meet the following constraints shown in Equation (4):

$$\sum_{i=1}^{N_{truck}} F_{b,j}^i \leq N_{swap,max} \quad (4)$$

where N_{truck} refers to the number of ETs, $F_{b,j}^i$ refers to the battery swapping status of the i ET during the j operating period (swapped with 1, not swapped with 0), and $N_{swap,max}$ refers to the maximum number of battery swaps that the ETBSS can provide within a period of time.

2.1.2. ET Battery Swapping Model

The ET battery swapping model shown in Equation (5) is obtained through the corresponding relationship between the batteries on ETs in each time period and the batteries at each position in the ETBSS, as follows:

$$\begin{cases} N_{p,j}^i = 0 & (N_{b,j}^i = 0) \\ 1 \leq N_{p,j}^i \leq N_{p,total} & (N_{b,j}^i \geq 1) \end{cases} \quad (5)$$

where $N_{p,j}^i$ is the storage location number in the ETBSS of the battery that was swapped from the ETBSS to the i ET during the j period (a value of 0 indicates that it is not swapped); $N_{p,total}$ is the total number of batteries (storage locations) in the ETBSS.

The storage location number in the ETBSS of the batteries that are swapped from the ETBSS to ETs during the same time period cannot be the same, so the $N_{p,j}^i$ in a time period must meet the constraints shown in Equation (6):

$$N_{p,j}^{n_m} \neq N_{p,j}^{n_k} \quad (N_{p,j}^{n_m} \geq 1, N_{p,j}^{n_k} \geq 1, n_m \neq n_k, n_m, n_k \in \{1, 2, \dots, N_t\}) \quad (6)$$

In the equation, $N_{p,j}^{n_m}$ and $N_{p,j}^{n_k}$ are the storage location numbers in the ETBSS of the batteries swapped from the ETBSS to the n_m ET and the n_k ET during the j time period, respectively; if $N_{p,j}^{n_m}$ and $N_{p,j}^{n_k}$ are not all 0, then $N_{p,j}^{n_m}$ and $N_{p,j}^{n_k}$ cannot be the same.

2.1.3. ETBSS Battery Swapping Model

Based on the swap correspondence between the batteries on the ET and the batteries in the ETBSS, the round-trip operation times supported by battery SOC at the initial moment of each time period for a battery participating in the swapping in the ETBSS can be obtained, as shown in Equation (7). The SOC of batteries swapped from a ET to the ETBSS in each time period constraint are shown in Equation (8). The minimum SOC constraints at the beginning of each time period for batteries at various locations in the ETBSS are shown in Equation (9), as follows:

$$\begin{cases} N_{s,j}^{N_{p,j}^i} = N_{b,j}^i (N_{p,j}^i \geq 1) \\ \sum_{i=1}^{N_{truck}} N_{b,j}^i = \sum_{i=1}^{N_{p,total}} N_{s,j}^i \end{cases} \quad (7)$$

$$\begin{cases} S_{s,N_{T,start}+N_{run,start,i}}^{N_{p,N_{T,start}+N_{run,start,i}}^i} = S_{b,N_{T,start}-1}^i - N_{run,start,i} \times S_{one} + (S_{bc,N_{T,start}-1}^i - S_{bd,N_{T,start}-1}^i) \times T \\ S_{s,j+N_{s,j}^i}^{N_{p,j+N_{s,j}^i}^i} = S_{s,j}^{N_{p,j}^i} + (S_{sc,j}^{N_{p,j}^i} - S_{sd,j}^{N_{p,j}^i}) \times T - N_{s,j}^{N_{p,j}^i} \times S_{one} (j > N_{T,start} + N_{run,start,i} \text{ and } N_{p,j}^i \geq 1) \end{cases} \quad (8)$$

$$S_{s,j-1}^m + (S_{sc,j-1}^m - S_{sd,j-1}^m) \times T \geq S_{low} + N_{s,j}^m \times S_{one} \quad (N_{s,j}^m \geq 1) \quad (9)$$

where $N_{s,j}^i$ is the number of round-trip running supported by the SOC at the initial moment of time period j for a battery to be swapped in the i storage position in the ETBSS (its value is 0, indicating that the battery is not replaced); $S_{sc,j}^m$ and $S_{sd,j}^m$ are the average charging SOC and average discharging SOC of batteries in the ETBSS at the m position in j time period, respectively. $S_{s,j}^m$ is the SOC of a battery in the ETBSS at the m position at the beginning of time period j ; $S_{bc,j}^m$ and $S_{bd,j}^m$ are the average charging SOC and average discharging SOC of the battery in the m ET in the j time period, respectively. $S_{b,j}^m$ is the SOC of the battery in the m ET at the beginning of time period j ; S_{one} is the SOC required for an ET to complete a round-trip operation; S_{low} is the minimum SOC for battery operation; and T indicates the duration of a period.

2.1.4. ETBSS Battery Charging and Discharging Model

Due to limitations in the charge and discharge power and capacity of battery in the ETBSS, $S_{s,j}^m$, $S_{sc,j}^m$ and $S_{sd,j}^m$ need to meet the following constraints shown in Equation (10):

$$\begin{cases} 0 \leq S_{sc,j}^m \leq \frac{P_{sc,max}}{S} \\ 0 \leq S_{sd,j}^m \leq \frac{P_{sd,max}}{S} \\ 20\% \leq S_{s,j}^m \leq 95\% \\ 20\% \leq S_{s,j}^m + (S_{sc,j}^m - S_{sd,j}^m) \times T \leq 95\% \end{cases} \quad (10)$$

where $P_{sc,max}$ and $P_{sd,max}$ are the maximum average charging power and maximum average discharging power of the battery within a period of time in the ETBSS, respectively. S indicates the capacity of the battery.

Thus, the charge and discharge model of the battery in the ETBSS, as shown in Equation (11), can be obtained as follows:

$$\begin{cases} S_{s,j}^m = S_{s,j-1}^m + (S_{sc,j-1}^m - S_{sd,j-1}^m) \times T & (N_{s,j}^i = 0) \\ S_{sc,j}^m = S_{sd,j}^m = 0 & (N_{s,j}^m \geq 1) \end{cases} \quad (11)$$

Since only a battery can be charged or discharged in the charging and discharging equipment within a period of time, the following constraints shown in Equation (12) must be met:

$$F_{sc,j}^m + F_{sd,j}^m \leq 1 \quad (12)$$

where $F_{sc,j}^m$ and $F_{sd,j}^m$ are the charging and discharging states of the battery in the ETBSS at the m position in the j time period; if $F_{sc,j}^m$ is 1, the battery in the ETBSS is in charge state, and if $F_{sc,j}^m$ is 0, the battery in the ETBSS is not in charge state; if $F_{sd,j}^m$ is 1, the battery in the ETBSS is in discharge state, and if $F_{sd,j}^m$ is 0, the battery in the ETBSS is not in discharge state.

Due to limitations in the number of charge and discharge equipment in the ETBSS, the number of batteries in the charged and discharged states at each time period should meet the following constraints shown in Equation (13):

$$\sum_{p=1}^{N_{p,\text{total}}} (F_{sc,j}^p + F_{sd,j}^p) \leq N_{cd} \quad (13)$$

where N_{cd} is the number of charge and discharge equipment.

2.1.5. ET Battery Charging and Discharging Model

Due to limitations in the charging and discharging power and capacity of battery in an ET, $S_{bc,j}^m$, $S_{bd,j}^m$, and $S_{b,j}^m$ should meet the following constraints shown in Equation (14):

$$\begin{cases} 0 \leq S_{bc,j}^m \leq \frac{P_{bc,\text{max}}}{S} \\ 0 \leq S_{bd,j}^m \leq \frac{P_{bd,\text{max}}}{S} \\ 20\% \leq S_{b,j}^m \leq 95\% \\ 20\% \leq S_{b,j}^m + (S_{bc,j}^m - S_{bd,j}^m) \times T \leq 95\% \end{cases} \quad (14)$$

where $P_{bc,\text{max}}$ and $P_{bd,\text{max}}$ are the maximum average charging power and maximum average discharging power of the battery within a period of time in an ET, respectively.

ETs use the battery swapping mode to improve work efficiency during working hours and are connected to the ETBSS through charging and discharging equipment during non-working hours. Therefore, the charge and discharge model of a battery on an ET is shown in Equation (15):

$$\begin{cases} S_{b,j}^i = S_{b,j-1}^i + (S_{bc,j-1}^i - S_{bd,j-1}^i) \times T & (N_{p,j}^i = 0) \\ S_{bc,j}^i = 0 \text{ and } S_{bd,j}^i = S_{\text{one}} & (N_{T,\text{start}} \leq j \leq N_{T,\text{start}} + N_{\text{trans}} - 1) \\ S_{b,N_{T,\text{start}}-1}^{N_{p,N_{T,\text{start}}-1}^i} + (S_{bc,N_{T,\text{start}}-1}^i - S_{bd,N_{T,\text{start}}-1}^i) \times T \geq N_{\text{run_start},i} \times S_{\text{one}} + S_{\text{low}} \\ S_{b,j}^i = S_{s,j-1}^{N_{p,j}^i} + (S_{sc,j-1}^{N_{p,j}^i} - S_{sd,j-1}^{N_{p,j}^i}) \times T & (N_{p,j}^i \geq 1) \end{cases} \quad (15)$$

In the equation, when the battery in the i ET does not participate in battery swapping during the j time period, the $S_{b,j}^i$ is obtained from the charging and discharging situation of the battery in the i ET in the previous time period. When the battery in the i ET participates

in battery swapping during the j time period, the $S_{b,j}^i$ is determined by the battery swapped from the ETBSS to the i ET during the j time period.

2.2. GT Model with Adjustable Thermoelectric Ratio

A GT with an adjustable thermoelectric ratio can change the ratio of electrical and thermal output for each time period, which can optimize IES operation. The working model is shown in Equation (16), as follows:

$$\begin{cases} P_{GT,t} = \eta_{GT} \cdot V_{GT,t} \cdot q_{lg} \\ P_{GT,t} = P_{GT,t}^e + P_{GT,t}^h \\ k_{GT}^{\min} \cdot P_{GT,t}^e \leq P_{GT,t}^h \leq k_{GT}^{\max} \cdot P_{GT,t}^e \end{cases} \quad (16)$$

where $P_{GT,t}$, $P_{GT,t}^e$, and $P_{GT,t}^h$ are the total average power, average generation electrical power, and average generation thermal power generated by the GT during t time period, respectively. η_{GT} is the efficiency of the GT; $V_{GT,t}$ is the average gas consumption rate of the GT during t period; q_{lg} is the calorific value of natural gas; and $k_{GT}^{\min}$ and $k_{GT}^{\max}$ are the minimum and maximum thermoelectric ratios of the GT, respectively.

2.3. WHB Running Model

The WHB heat output is used for heating and AC cooling, and adjusting the ratio of WHB heat generation to heating and AC cooling for each time period can optimize IES operation. The working model is shown in Equation (17), as follows:

$$\begin{cases} H_{WHB,t} = P_{GT,t}^h \cdot \eta_{WHB} \\ H_{WHB,t} = H_{WHB,t}^h + H_{WHB,t}^c \end{cases} \quad (17)$$

where $H_{WHB,t}$ is the average heating power of the WHB during t time period; η_{WHB} is the efficiency of the WHB; and $H_{WHB,t}^h$ and $H_{WHB,t}^c$ are parts of the average heating power of the WHB used for heating and for AC refrigeration in t period, respectively.

The device models of the WT and PV are referred to in study [34]. The device models of the AC and EC are referred to in study [35]. The equipment model of the HB can be found in study [36]. The AT adopts the general model under the generalized energy storage system [37]. According to its characteristics, flexible loads can be divided into three categories: transferable loads, translatable loads, and reducible loads. For the corresponding load models, refer to study [38].

3. IES with an ETBSS Optimization Scheduling Model

3.1. Objective Function

Based on the IES with an ETBSS model, the IES with an ETBSS-optimized scheduling model is proposed, which converts carbon emissions, battery life decay, and new energy utilization into economic indicators and integrates them into the objective function. Therefore, its objective function includes the energy purchase cost C_{buy} , the equipment operation and maintenance cost C_{om} , the flexible load compensation cost C_{fl} , the battery life decay cost C_{loss} , the stepped carbon trading cost C_{co2} , and WT and PV abandonment penalty cost C_{pun} of the entire IES. The specific model is shown in the following Equations (18)–(22):

$$\min C = C_{buy} + C_{om} + C_{fl} + C_{loss} + C_{co2} + C_{pun} \quad (18)$$

$$C_{buy} = T \times \sum_{t=1}^{N_T} (c_{e_buy,t} \times P_{e_buy,t} + c_{g_buy} \times V_{G,t}) \quad (19)$$

$$C_{om} = T \times \sum_{t=1}^{N_T} \sum_{k=1}^9 w_k \times P_{k,t} + \sum_{k=1}^9 u_k \times Q_k \quad (20)$$

$$C_{\text{loss}} = \eta_{\text{c_loss}} \times S \times T \times \sum_{j=1}^{N_T} \left(\sum_{m=1}^{N_{\text{ba}}} S_{\text{sc},j}^m + \sum_{m=1}^{N_{\text{truck}}} S_{\text{bc},j}^m \right) + \eta_{\text{d_loss}} \times S \times T \times \sum_{j=1}^{N_T} \left(\sum_{m=1}^{N_{\text{ba}}} S_{\text{sd},j}^m + \sum_{m=1}^{N_{\text{truck}}} S_{\text{bd},j}^m \right) \quad (21)$$

$$C_{\text{pun}} = \varepsilon \times T \times \sum_{t=1}^{N_T} \left(P_{\text{pre},t}^{\text{pv}} - P_{\text{act},t}^{\text{pv}} + P_{\text{pre},t}^{\text{wt}} - P_{\text{act},t}^{\text{wt}} \right) \quad (22)$$

where $c_{\text{e_buy},t}$ is the time-of-use electricity prices; $c_{\text{g_buy}}$ is the price of natural gas of per unit volume; $P_{\text{e_buy},t}$ is the average electrical power purchased during the time period t ; w_k is the unit power operating cost factor of device k ; u_k is the daily maintenance cost of per unit power capacity of device k ; $P_{k,t}$ is the average output power of device k during time period t ; Q_k is the capacity of device k (k is 1, 2...8, and 9, representing the PV, WT, ETBSS, GT, WHB, AC, EC, HP, and AT, respectively); and $\eta_{\text{c_loss}}$ and $\eta_{\text{d_loss}}$ are the loss costs of charging and discharging 1 kW · h electrical energy of a battery, respectively. ε is the unit penalty cost of abandoned WT and PV; and $P_{\text{pre},t}^{\text{pv}}$ and $P_{\text{pre},t}^{\text{wt}}$ are the predicted output of the PV and WT during time period t , respectively. $P_{\text{act},t}^{\text{pv}}$ and $P_{\text{act},t}^{\text{wt}}$ are the actual consumptions of the PV and WT during time period t , respectively.

The cost calculation method of flexible load compensation is referred to in study [38]. The calculation method of carbon transaction cost of ladder type is described in study [3], and the method of carbon quota is free quota [39].

3.2. Constraints

3.2.1. Energy Balance Constraints

IES energy flow in this research includes electrical energy flow, thermal energy flow, and cooling energy flow, all of which must meet the following energy balance constraints shown in Equation (23):

$$\left\{ \begin{array}{l} P_{\text{act},t}^{\text{pv}} + P_{\text{act},t}^{\text{wt}} + P_{\text{GT},t}^{\text{e}} + \frac{\eta_{\text{d}} \times S}{100} \times \left(\sum_{m=1}^{N_{\text{ba}}} S_{\text{sd},j}^m + \sum_{m=1}^{N_{\text{truck}}} S_{\text{bd},j}^m \right) + P_{\text{buy},t}^{\text{e}} = P_{\text{HP},t}^{\text{e}} + P_{\text{EC},t}^{\text{e}} + \frac{S}{100\eta_{\text{c}}} \times \left(\sum_{m=1}^{N_{\text{ba}}} S_{\text{sc},j}^m + \sum_{m=1}^{N_{\text{truck}}} S_{\text{bc},j}^m \right) \\ \quad + P_{\text{fix},t}^{\text{e}} + P_{\text{shift},t}^{\text{e}} + P_{\text{tran_max},t}^{\text{e}} - P_{\text{tran_act},t}^{\text{e}} + P_{\text{tran},t}^{\text{e}} + P_{\text{cut_max},t}^{\text{e}} - P_{\text{cut},t}^{\text{e}} \quad (j \leq N_{\text{T,start}} - 1 \text{ or } j \geq N_{\text{T,start}} + N_{\text{trans}}) \\ P_{\text{act},t}^{\text{pv}} + P_{\text{act},t}^{\text{wt}} + P_{\text{GT},t}^{\text{e}} + \frac{\eta_{\text{d}} \times S}{100} \times \sum_{m=1}^{N_{\text{ba}}} S_{\text{sd},j}^m + P_{\text{buy},t}^{\text{e}} = P_{\text{HP},t}^{\text{e}} + P_{\text{EC},t}^{\text{e}} + \frac{S}{100\eta_{\text{c}}} \times \sum_{m=1}^{N_{\text{ba}}} S_{\text{sc},j}^m + P_{\text{fix},t}^{\text{e}} \\ \quad + P_{\text{shift},t}^{\text{e}} + P_{\text{tran_max},t}^{\text{e}} - P_{\text{tran_act},t}^{\text{e}} + P_{\text{tran},t}^{\text{e}} + P_{\text{cut_max},t}^{\text{e}} - P_{\text{cut},t}^{\text{e}} \quad (N_{\text{T,start}} \leq j \leq N_{\text{T,start}} + N_{\text{trans}} - 1) \\ H_{\text{WHB},t}^{\text{h}} + H_{\text{HP},t}^{\text{h}} + H_{\text{AT_d},t}^{\text{h}} = H_{\text{AT_c},t}^{\text{h}} + H_{\text{fix},t}^{\text{h}} + H_{\text{shift},t}^{\text{h}} + H_{\text{cut_max},t}^{\text{h}} - H_{\text{cut},t}^{\text{h}} \\ C_{\text{AC},t}^{\text{c}} + C_{\text{EC},t}^{\text{c}} = C_{\text{fix},t}^{\text{c}} + C_{\text{shift},t}^{\text{c}} + C_{\text{cut_max},t}^{\text{c}} - C_{\text{cut},t}^{\text{c}} \end{array} \right. \quad (23)$$

In the equation, $P_{\text{HP},t}^{\text{e}}$ and $P_{\text{EC},t}^{\text{e}}$ are the average electrical power of the HB and EC in t time period, respectively. $P_{\text{fix},t}^{\text{e}}$ is the average electrical power of the basic electric load in time period t ; $P_{\text{tran_max},t}^{\text{e}}$ is the maximum average electrical power of the transferable electrical load in time period t before optimization; $P_{\text{tran_act},t}^{\text{e}}$ is the average electrical power that is transferred of the transferable electric load in t time period after optimization; $P_{\text{tran},t}^{\text{e}}$ is the average electrical power of the transferable electric load optimized for transfer to time period t ; $P_{\text{shift},t}^{\text{e}}$ is the average electrical power of the translatable electric load after optimization in t time period; $P_{\text{cut_max},t}^{\text{e}}$ is the maximum average electrical power of the reducible electric load during a period of t before optimization; $P_{\text{cut},t}^{\text{e}}$ is the average electrical power that is curtailed of the reducible electric load after optimization in t time period; η_{c} and η_{d} are the charging and discharging efficiency of the battery, respectively; and $H_{\text{HP},t}^{\text{h}}$ is the average thermal power of the HP during t period. $H_{\text{AT_c},t}^{\text{h}}$ and $H_{\text{AT_d},t}^{\text{h}}$ are the average thermal power stored and released from the AT during t period, respectively. $H_{\text{fix},t}^{\text{h}}$ and $H_{\text{shift},t}^{\text{h}}$ are the average thermal power of the basic heat load and the translatable heat load after optimization during t period, respectively. $H_{\text{cut_max},t}^{\text{h}}$ is the maximum average thermal power of the reducible heat load during t period before optimization. $H_{\text{cut},t}^{\text{h}}$ is the

average thermal power that be curtailed of the reducible thermal load after optimization during t period. $C_{AC,t}^c$ and $C_{EC,t}^c$ are the average cooling powers of the AC and EC in t time period, respectively. $C_{fix,t}^c$ and $C_{shift,t}^c$ are average cooling powers of the basic cooling load and the translatable cooling load after optimization during t period, respectively. $C_{cut_max,t}^c$ is the maximum average cooling power of the reducible cooling load during t period before optimization. $C_{cut,t}^c$ is the average cooling power that be curtailed of the reducible cooling load after optimization during t period.

3.2.2. Power Constraints of Energy Conversion Equipment

Due to limitations in the capacity and power output change rate, the output power of various energy conversion devices needs to satisfy the relevant constraints, as shown in Equation (24):

$$\begin{cases} P_k^{\min} \leq P_{k,t} \leq P_k^{\max} \\ |P_{k,t+1} - P_{k,t}| \leq \Delta P_k^{\max} \end{cases} \quad (24)$$

where $P_{k,t}$ is the average output power of device k during t time period; $P_k^{\max}$ and $P_k^{\min}$ are the maximum and minimum average output powers of device k in a period of time, respectively; and $\Delta P_k^{\max}$ is the upper limit of climbing power of device k (the values of k are 1, 2...5, and 6, which stand for the GT, WHB, AC, EC, HP, and AT, respectively).

3.2.3. Energy Trading Constraints

Due to power flow constraints of the power system and the capacity constraints of GT, the energy purchased from the power distribution network and the natural gas purchased from the gas network by the IES during each time period need to meet the following constraints of Equation (25):

$$\begin{cases} 0 \leq P_{buy,t}^e \leq P_{buy,max}^e \\ 0 \leq V_{GT,t} \leq V_{GT,max} \end{cases} \quad (25)$$

where $P_{buy,max}^e$ is the maximum average electrical power purchased for the IES in a time period; and $V_{GT,max}$ indicates the maximum value of the IES's average natural gas consumption rate in a time period.

For the PV and WP output constraints, refer to study [40].

3.3. Model Solving

Based on the mathematical model for optimizing scheduling of the IES with an ETBSS, a simulation model for optimizing their scheduling was built on MATLAB platform. Optimizing the scheduling model of the IES with an ETBSS in this research belongs to a type of mixed-integer linear programming problem. Therefore, the simulation model in this research uses MATLAB platform to call the CPLEX solver for a solution to this problem.

4. Analysis of Simulation Example

4.1. Basic Data

A community IES was selected as the research object, and its scheduling cycle was 24 h, with 1 h as the unit scheduling period. In order to reduce the operation time of the optimization model and achieve the expected results, the parameters selected in the example are small; alternately, a larger parameter can be selected, but more running time is required. The various equipment parameters are shown in Table 1 below; the relevant parameters of carbon trading are shown in Table 2; the relevant parameters of energy trading are shown in Table 3; and the electricity price adopts the time-of-use prices shown in Table 4. The fixed price of natural gas is 2.55 CNY/m³, and the calorific value of natural gas is 9.87 [41]. The predicted outputs of the WP and PV are shown in Figure 3. The compo-

nents of each flexible part of the electrical, thermal and cooling loads before optimization are shown in Figure 4a–c, and the corresponding parameters are shown in Table 5.

Table 1. Device parameters of IES.

Device Type	Parameter	Numerical Value
ET	ET quantity	3
	Run time (h)	8:00~12:00
	Number of round trips (times)	4
	A round trip consumes the battery SOC	32%
	Maximum average charging power (kW)	240
	Maximum average discharge power (kW)	240
ETBSS	Number of batteries	3
	Number of charge and discharge equipment	3
	Maximum number of batteries swapped in a period	3
	Maximum average charging power (kW)	240
	Maximum average discharge power (kW)	240
	Battery charging efficiency	0.97
	Battery discharging efficiency	0.95
	Operating cost (CNY/(kW · h))	0.06
	Maintenance cost ((CNY/kW)	0.49
Battery	Battery capacity (kW · h)	281.92
	Battery charge and discharge loss cost (CNY/(kW · h))	0.135
AT	AT capacity (kW · h)	1000
	Initial thermal energy (kW · h)	200
	Maximum average power of charging and releasing heat (kW)	300
	Thermal energy storage efficiency	0.95
	Thermal energy release efficiency	0.9
	Coefficient of thermal energy loss	0.01
	Utilization range of thermal energy (kW · h)	200~950
	Operating cost (CNY/(kW · h))	0.016
	Maintenance cost (CNY/kW)	0.6
GT	GT capacity (kW · h)	8000
	Efficiency	0.8
	Upper limit of climbing power (kW)	4000
	Operating cost (CNY/(kW · h))	0.04
	Maintenance cost (CNY/kW)	0.72
	Thermoelectric ratio range	1.22~2.33
WHB	WHB capacity (kW · h)	5000
	Efficiency	0.8
	Upper limit of climbing power (kW)	2500
	Operating cost (CNY/(kW · h))	0.04
	Maintenance cost (CNY/kW)	0.72
AC	AC capacity (kW · h)	6000
	COP	1.1
	Upper limit of climbing power (kW)	3000
	Operating cost (CNY/(kW · h))	0.05
	Maintenance cost (CNY/kW)	0.8
HP	HP capacity (kW · h)	5200
	COP	4.2
	Upper limit of climbing power (kW)	2600
	Operating cost (CNY/(kW · h))	0.035
	Maintenance cost (CNY/kW)	0.72

Table 1. *Cont.*

Device Type	Parameter	Numerical Value
EC	EC capacity (kW · h)	5200
	COP	3.5
	Upper limit of climbing power (kW)	2600
	Operating cost (CNY/(kW · h))	0.04
	Maintenance cost (CNY/kW)	0.72
WT	Operating cost (CNY/(kW · h))	0.07
	Maintenance cost (CNY/kW)	0.48
	Abandoning wind energy penalty costs (CNY/(kW · h))	0.2
PV	Operating cost (CNY/(kW · h))	0.039
	Maintenance cost (CNY/kW)	0.5
	Abandoning light energy penalty costs (CNY/(kW · h))	0.2

Table 2. Parameters related to carbon trading.

Parameter	Numerical Value
GT carbon quota (kg/(kW · h))	0.102
Carbon quota for purchasing electrical energy (kg/(kW · h))	0.68
Conversion coefficient for carbon quota for electricity generation and carbon quota for heat generation of GT	1.67
Carbon trading base price (CNY/kg)	0.06
Length of carbon emission interval (kg)	2000
Price growth rate	0.5
Carbon emissions from natural gas combustion (kg/m ³)	1.964
The actual carbon emissions of electrical energy purchased (kg/(kW · h))	1.08

Table 3. Parameters related to energy trading.

Parameter	Numerical Value
Average purchasing electrical power range (kW)	0~5000
Average rate of natural gas consumption (m ³ /h)	0~1000

Table 4. Time-of-use electricity prices.

IES Power Load Status	Time (h)	Electricity Price (CNY/(kW · h))
Valley load	23:00~8:00	0.38
Plain valley load	8:00~12:00; 15:00~19:00	0.68
Peak load	12:00~15:00; 19:00~23:00	1.2

Table 5. Load parameters can be shifted before optimization.

Load Type	Parameter	Numerical Value
Translatable electrical load	Time of duration (h)	3
	Translatable time period	5:00~21:00
	Offset cost (CNY/(kW · h))	0.2
Translatable heat load	Time of duration (h)	3
	Translatable time period	5:00~21:00
	Offset cost (CNY/(kW · h))	0.1
Translatable cooling load	Time of duration (h)	3
	Translatable period	5:00~21:00
	Offset cost (CNY/(kW · h))	0.1

Table 5. Cont.

Load Type	Parameter	Numerical Value
Transferable electrical load	Minimum duration (h)	2
	Range of transferable load power (percentage of total transferable load power)	20%~100%
	Transferable time period	4:00~22:00
	Offset cost (CNY/(kW · h))	0.3
Reducible electrical load	Duration range (h)	2~5
	Maximum number of cuts (1 time period means 1 time)	8
	Reducible period	5:00~22:00
	Offset cost (CNY/(kW · h))	0.4
Reducible heat load	Duration range (h)	2~5
	Maximum number of cuts (1 time period means 1 time)	8
	Reducible period	6:00~22:00
	Offset cost (CNY/(kW · h))	0.2
Reducible cooling load	Duration range (h)	2~5
	Maximum number of cuts (1 time period means 1 time)	8
	Reducible period	11:00~19:00
	Offset cost (CNY/(kW · h))	0.2

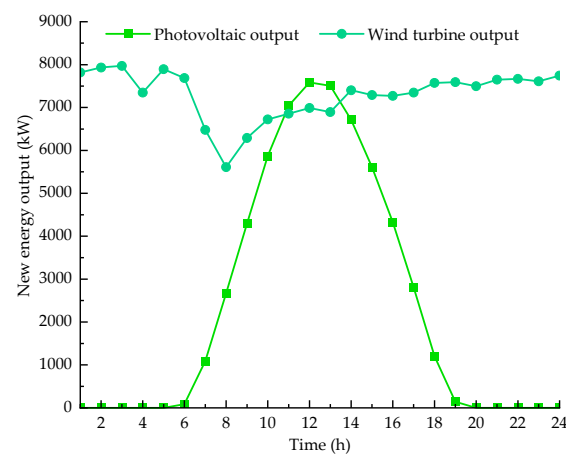


Figure 3. Chart of maximum output (forecast output) of new energy.

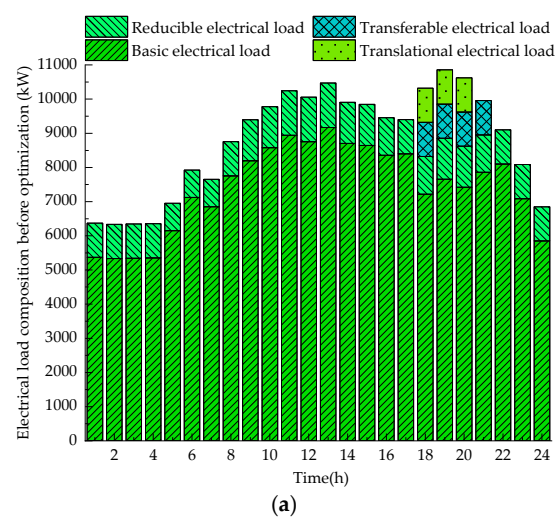


Figure 4. Cont.

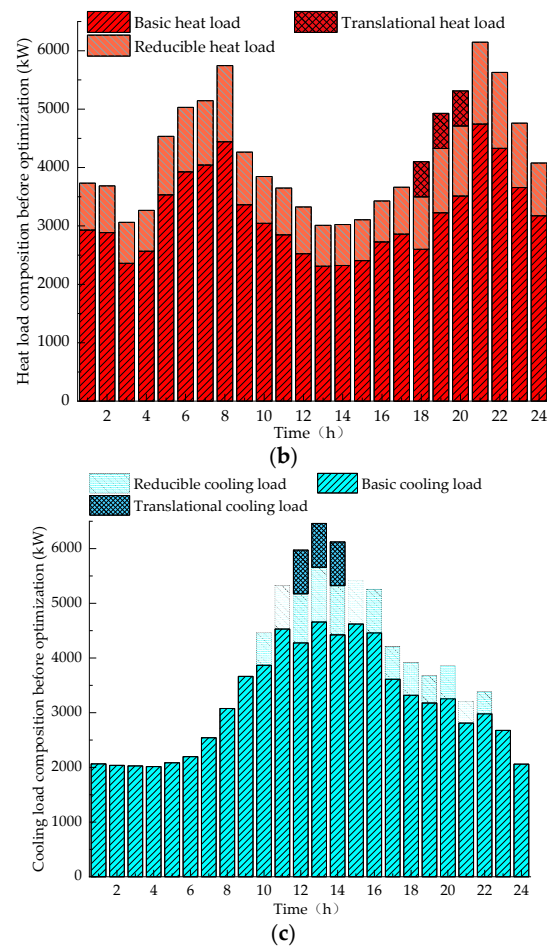


Figure 4. (a) Electrical load composition before optimization. (b) Heating load composition before optimization. (c) Cooling load composition before optimization.

4.2. Influence of ETBSS-Optimized Scheduling on IES Operation

In order to verify the rationality of the model proposed in this study, five optimization models for IESs in different cases were constructed for comparative analysis. The relevant parameters of the optimization models for each case are shown in Table 6, and the solution results of the optimization simulation models for each case are shown in Table 7.

Table 6. Different case parameters.

Case	ET Operating Mode	ETBSS Running Mode
Case 1	Integrated charging and battery swapping	Ordered charge and discharge
Case 2	Battery swapping	Ordered charge and discharge
Case 3	Battery swapping	Ordered charging
Case 4	Battery swapping	Unordered charging
Case 5	Battery swapping	Use spare batteries and charge overnight

Table 7. Scheduling results in different cases.

Case	Total Cost (CNY)	Amount of Carbon Emissions	Wind Electricity and Photovoltaic Utilization Rate
Case 1	105,294	6178	100%
Case 2	105,900	6489	99.87%
Case 3	106,059	6592	99.70%
Case 4	106,113	6592	99.70%
Case 5	106,497	6700	99.43%

Compared with case 1, the optimal scheduling of cases 2 and 3 does not play an electrical energy storage role for the ET; the ETBSS in case 4 and case 5 does not participate in scheduling. The ETBSS output of each case is shown in Figure 5 (positive value indicates ETBSS discharge, and negative value indicates ETBSS charging).

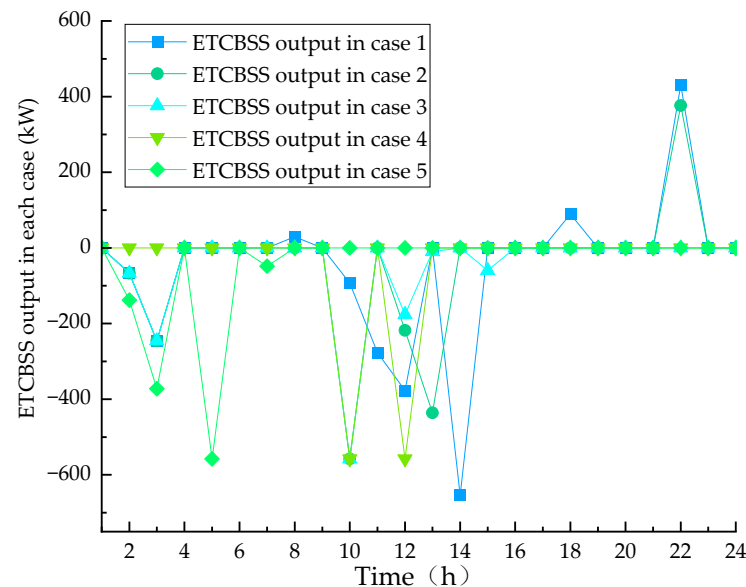


Figure 5. ETBSS output in each case.

As can be seen from Figure 5, the batteries in cases 1 and 2 replenish electrical energy when the load of the IES is low and release electrical energy when the load of the IES is high. The electrical energy storage capacity in case 1 is provided by batteries in the ETBSS and ETs, which is larger than that provided only by the batteries in the ETBSS in case 2, so it is better optimized for the IES. In case 3, the ETBSS can only supplement the power when the load of the IES is low and cannot release the power when the load of the IES is high. In case 4, the ETBSS can only supplement the power when the load is high. In case 5, all of the batteries in the ETBSS replenish electrical energy at night and cannot absorb photovoltaic power during the day. Combined with Table 7, it can be seen that the energy storage function of ETs and the ETBSS can play a better role in filling peaks and valleys and can more efficiently reduce the operating costs and carbon emissions and improve the utilization rate of new energy of the IES.

5. Conclusions

The differences between the operational models of ETs and ETBSSs with flexible charging and discharging and other charging and discharging station models for EVs are shown in Table 8.

Table 8. The differences between the operational model proposed in this paper and other EV charging and battery swapping station models.

The Operational Model of ETs and ETBSSs with Flexible Charging and Discharging	Other EV Charging and Battery Swapping Station Models
Each battery is managed individually.	Most batteries are classified and then managed in clusters.
The energy demands of ETs can be obtained according to the running characteristics of ETs; on the premise of meeting the transportation demands of ETs, the load can be adjusted to some extent according to the demand on the IES.	The energy supply requirements of the most EVs are predicted based on the EV operation law, and almost all of them are not adjustable.

Table 8. *Cont.*

The Operational Model of ETs and ETBSSs with Flexible Charging and Discharging	Other EV Charging and Battery Swapping Station Models
The battery does not need to be fully charged when the battery is swapped.	The battery does not take part in a battery swapping until it is fully charged.
The charging and discharging behavior of the battery can be interrupted.	The charging and discharging behavior of the battery cannot be interrupted.
The charging and discharging power of the battery is variable.	Most batteries are charged and discharged at constant power.
When an ET is working, the battery swapping mode is adopted to improve the working efficiency of the ET. When an ET is idle, the ET accesses the ETBSS to participate in IES scheduling and improve the electrical energy storage capacity of the IES.	Most EVs use a single means for energy supply, charging, or battery swapping.
Calculations of the optimization model are substantial, and the optimization model takes a long time to solve.	Calculations of the optimization model are small, and the optimized operation scheme can be obtained quickly.

According to the contents in Table 8, combined with the above IES simulation example that includes the ETBSS, the following conclusions can be drawn:

1. Under the premise of meeting the transportation tasks of ETs, the energy demands of ETs with integrated charging and battery swapping running on a fixed line can be adjusted within a certain range.
2. Combined with the above simulation examples, it can be seen that an IES that adopts integrated charging and battery swapping in ETs and orderly charging and discharging operation modes in the ETBSS can better play an energy storage role for the ETBSS and ET batteries on the basis of meeting the energy supply requirements of ETs, as well as coordinate the electrical, thermal and cooling energies of the IES; this makes the economics of the IES better, as well as the abilities to absorb new energy and reduce carbon emissions. In the above simulation example, compared with the IES that adopts the battery swapping mode in ETs and the unordered charge mode in the ETBSS, the IES that adopts the integrated charge and battery swapping mode in ETs and the orderly charge and discharge modes in the ETBSS reduces the operating costs by CNY 819, reduces carbon emissions by 414 kg, improves the utilization rate of WP and PV by 0.3%, and fully utilizes WT and PV.

The optimized IES with an ETBSS scheduling scheme proposed in this paper takes the ETBSS and IES as a whole; however, in practice, the ETBSS and IES may have different interest demands. Moreover, the next-day new energy output and load in the IES optimization model cannot obtain accurate values in advance; only inaccurate predicted values can be obtained. However, the optimized operation scheme in this research is based on the predicted values of new energy output and load, so the operation scheme may be different from actual situations. In the future, we can further study the optimal scheduling method of energy supply systems with ETBSSs and IESs as different subjects of interest, considering the uncertainty of loads and new energy outputs.

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