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Research Article

Coordinated Planning of Power Grids in Information Parks considering the Time-Space Transfer Characteristics of Data Center Loads

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With the development of green energy, the penetration rate of new energy in the power grid is rising rapidly. Incorporating a large amount of new energy into the power grid will affect the power supply balance of the power grid, and even in severe cases will affect the safe and stable operation of the power grid. The information park has various small and medium data centers. The adjustable load of the data center can be transferred in time and space through the optical fiber and other communication networks, which can enhance the controllability of the power grid to a certain extent and promote the consumption of new energy. This paper proposes a collaborative planning method for information parks that considers the temporal and spatial transfer characteristics of data center loads, builds a load transfer model for data centers and builds a park power grid expansion model with the goal of minimizing the total cost of construction and operation. In this paper, an example of a park is used to verify the calculation example, and it is compared with other schemes to verify the feasibility of the method in this paper.

1. Introduction

Under the carbon emission reduction target, China's new energy is developing rapidly, the energy industry is undergoing a green and low-carbon transformation, and a new power system with new energy as the main power supply is the trend of future power grid development [1]. With the rapid development of information technologies such as 5G and artificial intelligence, the integration of information technology and traditional industries has accelerated. As a physical carrier for the normal operation of information systems in various industries, data centers have become critical key infrastructure. The data center must fully meet the network load and be equipped with a sufficient number of servers that can be used to minimize network congestion. However, the ability to cope with network load peaks makes a large number of hardware facilities in the data center idle during non-network peak periods, so the hardware settings of the data center have high redundancy and equipment utilization is low. According to a research report by the National Resource Defense Council, the average utilization rate of servers in traditional data centers only accounts for 12% to 18% of their computing power [2]. The data center does not shut down idle servers for the sake of hot standby during network peaks. As data centers continue to grow in size, their power consumption also increases with the computing load. Unlike traditional adjustable loads such as air conditioners, which only have the characteristics of time transfer, data centers can have the potential for time and space transfer of loads through information transmission channels such as optical fibers [3]. The load of the data center includes real-time response load and delayable response load. Through reasonable and scientific scheduling management of the delayable load, the electricity demand can be effectively reduced during the peak load period, and the electricity consumption can be increased during the load trough period or the high generation period of new energy. It can effectively balance the unbalanced power supply and demand caused by the fluctuation of new energy, and improve the effective consumption rate of new energy.

Information smart park power grid refers to an industrial park with a high proportion of new energy access and mainly high-tech information technology industries [4], including multiple small and medium data centers. Therefore, when planning, a power grid planner can fully consider the characteristics of data center load time and space transfer to improve the economy of the planning scheme.

At present, many scholars have carried out research on considering the adjustable characteristics of data center load. Chen [3] comprehensively expounds on the role of the data center as a flexible and adjustable load on the demand side, puts forward the requirements of the future power grid for the adjustable load, and points out that the existing research does not fully consider the complex nonlinear relationship between computing power and electricity. Kwon [5] builds a single data center adjustable load energy consumption model and studies the time shift characteristics of data center load for new energy consumption. Li and Qi [6] study the influence of electricity price, new energy output, and randomness of data center load on the load regulation ability of data center. Cao et al. [7] model the energy consumption parts such as temperature, workload data volume, and the operating cost of the data center in the power grid on the basis of the traditional data center model, and expounds on the change of cost when the data network and the power network are mixed. Wen and Liu [8] consider the linkage of three new energy sources, wind, solar, and water on the source side, and the time-space transfer characteristics of the demand-side data center and propose a concurrent processing mode for the workload of the data center, and establish a multienergy complementary power generation end and load including wind, water, and light. The optimal scheduling model of the end data center. Wu [9] is based on the particle swarm algorithm, fully consider the economy, reliability, and flexibility of power grid planning, determines the weights of the three properties through the analytic hierarchy process, and introduces auxiliary populations to maintain the flexibility of the PSO algorithm to obtain the optimal Pareto solution set. Sun [10] proposed an improved ant colony algorithm to solve the task scheduling strategy of the data center, adding energy consumption constraints on the existing basis, and the solution time is basically the same as the standard ant colony algorithm, which reduces the system load and improves the system operating efficiency. Wu [11] comprehensively expounds the research on DC participation in power grid operation and planning with spatiotemporal transfer characteristics, conducts detailed modeling of DC servers, operating energy consumption, etc. and lists the specific forms of DC participation in demand response. The flexibility objective is added to the model, a model considering the load space transfer is established, and different planning schemes are obtained by using the improved particle swarm algorithm. Tang et al. [12] propose a demand response control method for small data centers, which uses data links and power networks to control the power load of data centers participating in demand response, which makes more than 50% of the total small and medium data centers participate in it. Demand response of the grid becomes possible. Guo et al. [13] use the Nash bargaining theory to model and analyze the interaction between the managed data center and users and motivates the rental customers to reduce the load used during the power shortage period, thereby reducing the power load reduction of the data center in emergency situations and realizing the operation. Wang et al. [14] study the impact of data center load redistribution on the power grid, and how the power grid can actively use the data center load distribution to achieve power load balance. Cheng et al. [15–17] conducted in-depth research on demand-side response management and proposed a market decision-making study based on artificial intelligence combined with the electricity market clearing mechanism.

At present, most of the research studies focus on analyzing the operation scheduling scheme using the load transfer characteristics of data centers and the corresponding demand-side mode of participating in the market, and less research on the impact of data center load transfer characteristics on power system construction in the planning stage. This paper proposes a coordinated planning of the information smart park power grid considering the time-space transfer characteristics of data center loads. Through the research and modeling of the time-space transfer characteristics of the data center's adjustable load, with the economy as the goal, finally, the actual park power grid example is used to test the model's performance. The validity is tested, and the planning scheme of the line and energy storage as well as the operation data of the power grid under typical scenarios are obtained.

The rest of this article is arranged as follows: Section 2 summarizes the coplanning process of the information smart park grid. Section 3 gives the mathematical model of an adjustable load of data centers. Section 4 builds the coplanning model of the information smart park grid. Section 5 is a case verification. Section 6 is the conclusion.

2. The Framework for Collaborative Planning of Power Grids in Information Smart Parks

The research object of this paper is the information smart park power grid including small and medium data centers. The power supply of the information smart park power grid is mainly distributed to new energy and the upper-level power grid. The main electricity load of the information intelligence park studied in this paper includes the data center load, the electricity load of each R&D center, and the electricity consumption of other facilities. Due to the uncertainty of load and new energy, under the penetration of a high proportion of new energy, the power grid of the information park needs to give full play to the demand-side response of the load to realize the internal adjustment of the power grid and solve the problem of supply and demand imbalance caused by the fluctuation of new energy. Therefore, the operating characteristics and adjustable potential of adjustable loads should be fully considered in the planning. The information park power grid should be equipped with appropriate energy storage to provide sufficient flexibility margin and flexibility. According to the geographical location and capacity information of the load, the expansion of the grid is carried out to ensure the safe and stable operation of the power grid. The framework of this paper is as Figure 1.

3. Modelling of the Spatiotemporal Transfer Characteristics of Data Center Loads

Data centers include servers, cooling equipment, lighting equipment, and other supporting equipment. At present, many literature have carried out research on the equivalent modeling of server energy consumption in data centers, including linear models considering server load conditions, dynamic voltage, and frequency adjustment CPU consumption [11]. The complex energy consumption model is more accurate, but its nonlinearity brings huge difficulties to the solution of the problem. It is suitable for the energy management scheduling control strategy of the data center. The single server energy consumption linear model is used in the planning scene of the present invention [11], which is

$$P_{\text{server},t}^{\text{single}} = P_n + \eta_t\left(P_{\text{peak}} - P_n\right). \quad (1)$$

Here, $P_{\text{server}}^{\text{single}}$ is the power consumption of a single server, P_n and P_{peak} represent the rated power consumption and peak load power consumption of a single server, respectively, and η represent the utilization rate of the server.

In addition to the power consumption of servers in the data center, there are also the power consumption of cooling equipment and other equipment such as lighting. Therefore, the energy consumption model of the data center can be expressed as follows [11]:

$$P_{dc\ ,n,t} = P_{\text{server},t} + P_{\text{others},t}. \quad (2)$$

Here, $P_{dc,n,t}$ represents the total energy consumption of the nth data center at the moment t, $P_{\text{server},t}$ is the total energy consumption of the data center server at the moment t, which is the sum of the power consumption of all single servers, and $P_{\text{others},t}$ represents the other energy consumption of the data center at the moment.

The cooling energy consumption and lighting energy consumption of the data center account for a small proportion of the total energy consumption of the data center. Generally speaking, the adjustable load of the data center mainly refers to the adjustable load of the server. The load of the server includes real-time response load and delayable response load. The real-time response load includes real-time dialogue, commercial transactions, and other user needs that need to be responded to immediately; the delayable response load includes large-scale data processing and medical image processing. Therefore, the load of the data center with the potential of time and space transfer is the load that can delay response. Different types of loads require a different number of servers and server processing time, and different types of loads have different latency tolerances. Therefore, the energy consumption model of the data center can be expressed as follows:

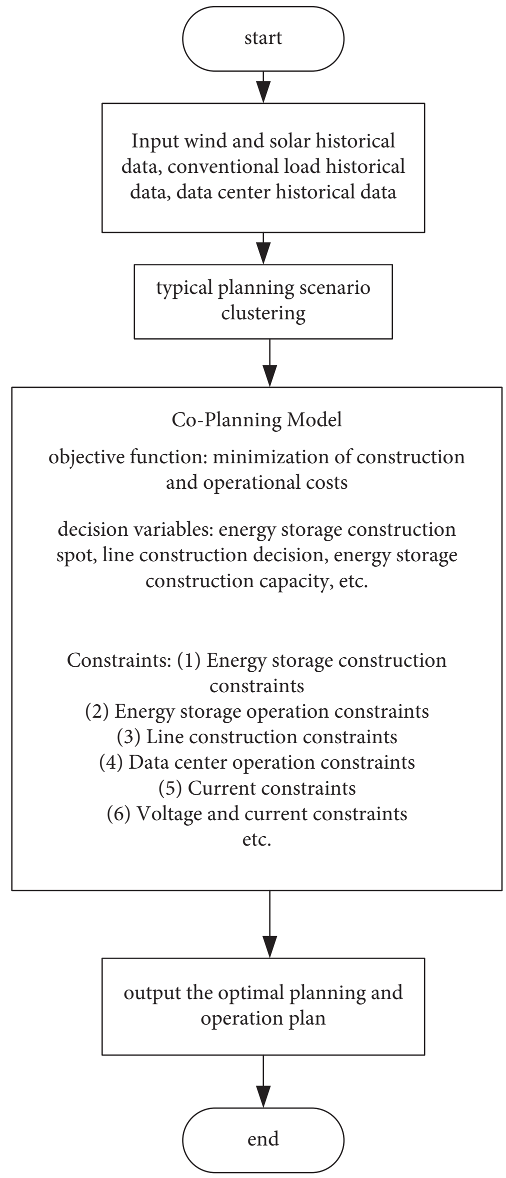

Figure 1: Flowchart of the paper.

$$P_{dc,n,t}^{ctrl} = \rho_{n,t} P_{\text{server}}. \quad (3)$$

Substitute into formula (2) to obtain the following equation:

$$P_{dc,n,t} = \rho_{n,t} P_{\text{server},t} + \left(1 - \rho_{n,t}\right) P_{\text{server},t} + P_{\text{others},t}. \quad (4)$$

Here, $P_{dc,n,t}^{ctrl}$ represents the adjustable load at the time t of the nth data center, and $\rho_{n,t}$ represents the adjustable proportion of the server load at the time t of the nth data center.

Other energy consumption in the data center is random and nonadjustable like other regular loads, so typical scenario generation is required to deal with its uncertainty.

Considering the information transmission of data centers located in different geographical locations, the delayable response load can realize the spatial transfer of the load through the information transmission function of the data center. The spatiotemporal transfer characteristics of the adjustable load in the data center can be expressed by the load transfer matrix as follows:

$$T_s^x = \begin{bmatrix} p_{s,11}^x & p_{s,12}^x & \dots & p_{s,1j}^x & \cdots & p_{s,1T}^x \\ 0 & p_{s,22}^x & \dots & p_{s,2j}^x & \cdots & p_{s,2T}^x \\ \dots & \dots \ddots & \cdots \dots & \dots & \cdots & \dots \\ 0 & \dots & p_{s,ii}^x & p_{s,ij}^x & \cdots & \dots \\ \dots & \dots & \dots & \dots & \ddots & \dots \\ 0 & 0 & \dots & p_{s,nj}^x & \cdots & p_{s,nT}^x \end{bmatrix} \quad x \in N_{dc}, \tag{5}$$

$$p_{s,ij}^a = p_{s,ij}^b = \dots = p_{s,ij}^x = 0 \quad j - i \geq T_{\text{tolarate}}^k or\ j - i \leq 0, \tag{6}$$

$$P_{dc,s,t}^{ctrl} = \sum_{x=1}^{N_{dc}} \sum_{j=1}^{T} p_{s,ij}^x. \tag{7}$$

Here, N_{dc} is the set of data center nodes, $p_{s,ij}^x$ represents the adjustable load is transferred from the moment i to the power at the moment j at the s-th typical scenario of the data center of the node x; T represents the total optimization time. T_{tolarate}^k indicates the delay tolerance time for delayable response loads of type k. $P_{dc,s,t}^{ctrl}$ is the total power consumption of the adjustable load generated for the s-th typical scenario at time t.

In this paper, it is assumed that the power grid dispatching center of the park can optimally dispatch the adjustable load of the data center according to the current situation of the power flow, reasonably allocate the power consumption time and power consumption nodes of the adjustable load within the tolerable time range of the adjustable load, and realize the time-space transfer of the load in order to alleviate the problem of line congestion and promote the consumption of new energy.

4. Construction of Collaborative Planning Model for Power Grid

The power grid of the information smart park is composed of data centers, other loads, new energy, energy storage, lines, and the contact point of the upper-level power grid. When planning, it is necessary to take into account the cost of planning and operation and to optimize the overall construction and operation economy.

The decision variables of this model are the number and nodes of energy storage construction, the location of line construction, the energy storage dispatch signal, the data center's adjustable load time and air conditioning signal, and the transmission power of the upper-level power grid tie line.

4.1. Objective Function. The planning of the power grid of the information smart park needs to consider the economics of power grid construction and the safe and stable operation of the power grid. The goal is to minimize the total construction and operation costs of planning typical scenarios, which can be expressed as follows:

$$C_{\text{total}} = C_{\text{inv}} + C_{\text{loss}} + C_{\text{grid}}. \tag{8}$$

Here, C_{inv} is the equivalent annual construction cost of energy storage and line, C_{loss} represents the operating loss cost of the power grid, including the operating loss of energy storage and line loss, and C_{grid} represents the electricity purchase cost from the upper-level power grid. The formulas for calculating the various fees are as follows:

$$\alpha_m = \frac{r(1+r)^{\gamma_m}}{(1+r)^{\gamma_m} - 1}, \tag{9}$$

$$C_{\text{inv}} = \sum_{n \in N_{ess}} a_m x_{ess,n} c_{ess} E_{ess,n} + \sum_{b \in N_{\text{line}}} a_m x_{\text{line},b} c_{\text{line}}, \tag{10}$$

$$\begin{aligned} C_{\text{loss}} &= c_{\text{loss}} \sum_{s \in S} \sigma_s \sum_{t \in T} \sum_{ij \in B} I_{ij,s,t}^2 r_{ij} \\ &\quad + c_{\text{eloss}} \sum_{s \in S} \sigma_s \sum_{t \in T} \sum_{n \in N_{ess}} P_{ess,n,s,t}, \end{aligned} \tag{11}$$

$$C_{\text{grid}} = \sum_{s \in S} \sigma_s \sum_{t \in T} c_{\text{grid},s,t} P_{\text{grid},s,t}. \tag{12}$$

Here, S, T, B, N_{ess} represents the set of typical scenarios, the calculation period, the set of all lines, the set of energy storage nodes, r is the discount rate, γ_m is the investment period, c_{ess} is the investment cost of energy storage unit capacity, c_{line} is the line investment cost, c_{loss} is the unit network loss electricity cost, c_{eloss} is energy storage conversion unit power charge and discharge loss cost, $c_{grid,s,t}$ represents the power purchase price of the upper power grid at time t in the typical scenario s, $x_{ess,n}, x_{line,b}$ represents the decision variable for energy storage construction of n nodes and the construction decision variable of line b respectively, σ_s represents the probability of the typical scenario, $I_{ij,s,t}$ is the current of the line between nodes i and j at time t in the typical scenario s. r_{ij} is the resistance of the line between nodes i and j, $P_{ess,n,s,t}$ represents the charging and discharging power of the energy storage at node n at time t in the typical scenario s, and $P_{gri\,d,s,t}$ represents the power transmitted by the upper power grid at time t in the typical scenario s.

4.2. Operational Constraints

4.2.1. Energy Storage Operation Constraints. Taking a typical electrochemical energy storage battery as an example, its operating constraints are as follows: (set the charging power of the energy storage battery to be positive and the discharge power to be negative)

$$P_{ess,n,\min} \le P_{ess,n,s,t} \le P_{ess,n,\max}, \tag{13}$$

$$Q_{ess,n,\min} \le Q_{ess,n,s,t} \le Q_{ess,n,\max}, \tag{14}$$

$$e_{ess,n,s,t+1} - e_{ess,n,s,t} = \eta P_{ess,n,s,t+1}\Delta t, \tag{15}$$

$$\text{SOC}_{n,s,t} = \frac{e_{ess,n,s,t}}{E_{ess,n}}, \tag{16}$$

$$\text{SOC}_{n,\min} \le \text{SOC}_{n,s,t} \le \text{SOC}_{n,\max}, \tag{17}$$

$$\text{SOC}_{n,s,0} = \text{SOC}_{n,s,T}. \tag{18}$$

where $P_{ess,n,\max}$ and $P_{ess,n,\min}$ are the upper limit and lower limit of active power of the nth energy storage, respectively, $Q_{ess,n,\max}$ and $Q_{ess,n,\min}$ are the upper limit and lower limit of reactive power of the nth energy storage, respectively, $\text{SOC}_{n,\min}$ and $\text{SOC}_{n,\max}$ are the lower and upper limits of the state of charge of the energy storage system, η is the efficiency of the battery, Δt is the time step, $e_{ess,n,s,t}$ and $\text{SOC}_{n,s,t}$ is the remaining battery capacity and state of charge of the nth ESS in the s-th typical scene at time t, respectively.

4.2.2. Electric Active Power Balance

$$\sum_{n\in N_{ess}} P_{ess,n,s,t} + P_{grid,s,t} + \sum_{i\in N}\left(P_{\text{wind},i,s,t} + P_{pv,i,s,t}\right) = \sum_{i\in N} P_{\text{load},i,s,t} + \sum_{i\in N} P_{dc,i,s,t}. \tag{19}$$

where $P_{wind,i,s,t}, P_{pv,i,s,t}, P_{load,i,s,t}$, $Q_{wind,i,s,t}, Q_{pv,i,s,t}, Q_{load,i,s,t}$, respectively, represent the active power and reactive power of typical curves of wind power, photovoltaics, and other loads on the node n at time t in the typical scenario s; $P_{grid,s,t}$ and $Q_{grid,s,t}$ represent the active power and reactive power transmitted by the upper power grid at time t in the typical scenario s; $P_{dc,i,s,t}$ and $Q_{dc,i,s,t}$ represent the active power and reactive power of the data center on the node n at time t in the typical scenario s, respectively.

4.2.3. Flow Constraints. The traditional AC power flow constraint is a nonconvex nonlinear constraint, which brings great challenges to the solution of the problem. Therefore, this paper adopts linear AC power flow for power flow calculation:

$$k_{ij\_1} = \frac{r_{ij}x_{ij}}{r_{ij}^2 + x_{ij}^2}, k_{ij\_2} = \frac{x_{ij}^2}{r_{ij}^2 + x_{ij}^2}, \tag{20}$$

$$P_{ij,s,t} = k_{ij\_1} \cdot \frac{U_{i,s,t} - U_{j,s,t}}{x_{ij}} + k_{ij\_2} \cdot \frac{\delta_{i,s,t} - \delta_{j,s,t}}{x_{ij}}, \tag{21}$$

$$Q_{ij,s,t} = -k_{ij\_1} \cdot \frac{\delta_{i,s,t} - \delta_{j,s,t}}{x_{ij}} + k_{ij\_2} \cdot \frac{U_{i,s,t} - U_{j,s,t}}{x_{ij}}, \tag{22}$$

$$\begin{aligned} P_{i,s,t} &= \sum_{j=1,j\ne i}^{N} \frac{k_{ij\_2}}{x_{ij}}\left(\delta_{i,s,t} - \delta_{j,s,t}\right) + \frac{k_{ij\_1}}{x_{ij}}\left(U_{i,s,t} - U_{j,s,t}\right) \\ &= P_{ess,i,s,t} + P_{\text{wind},i,s,t} + P_{pv,i,s,t} + P_{\text{grid},s,t} - P_{\text{load},i,s,t} - P_{dc,i,s,t}, \end{aligned} \tag{23}$$

$$\begin{aligned} Q_{i,s,t} &= \sum_{j=1,j\ne i}^{N} -\frac{k_{ij\_1}}{x_{ij}}\left(\delta_{i,s,t} - \delta_{j,s,t}\right) + \frac{k_{ij\_2}}{x_{ij}}\left(U_{i,s,t} - U_{j,s,t}\right) \\ &= Q_{ess,i,s,t} + Q_{\text{wind},i,s,t} + Q_{pv,i,s,t} + Q_{\text{grid},s,t} - Q_{\text{load},i,s,t} \\ &\quad - Q_{dc,i,s,t}, \end{aligned} \tag{24}$$

where N represents the nodes in the power grid; $U_{i,s,t}, \delta_{i,s,t}$ are the voltage amplitudes and phase angles of the nodes i at the time t of the typical scenario s, respectively; r_{ij}, x_{ij} represent the resistance and reactance between the nodes i and j, respectively; $P_{ij,s,t}$ and represent the power transmitted on the line ij at the time t of the typical scenario s; $P_{i,s,t}$ and $Q_{i,s,t}$ represent the active power and reactive power injected on the node n at the moment t of the typical scenario s, respectively.

4.2.4. Operating Voltage Constraints

$$U_{i\min} \le U_{i,s,t} \le U_{i\max} \quad i = 1, 2, \ldots, N. \tag{25}$$

Here, $U_{i\max}$ and $U_{i\min}$ are the upper and lower limits of the node voltage amplitude, respectively.

4.2.5. Branch Current Constraints

$$I_{ij,s,t}^2 = \frac{P_{ij,s,t}}{r_{ij}}, \tag{26}$$

$$I_{ij,\min}^2 \le I_{ij,s,t}^2 \le I_{ij,\max}^2. \tag{27}$$

Here, $I_{ij,s,t}$ is the current amplitude flowing through the branch between node i and node j at the time t of the typical scenario s; $I_{ij,\min}$ and $I_{ij\max}$ are the lower limit and upper limit of the current amplitude of the branch, respectively.

4.2.6. Data Center Adjustable Load Constraints and Operating Constraints

$$P_{dc,x,s,t} = P_{dc,x,s,t}^{\text{normal}} + \sum_{i=t}^{T} p_{s,it}^{x}, \tag{28}$$

$$0 \le P_{dc,x,s,t} \le P_{dc,x,\max}, \tag{29}$$

$$Q_{dc,x,s,t} = \mu_{x,s,t} P_{dc,x,s,t}. \tag{30}$$

Equation (5)-Equation (7)

Here, $P_{dc,x,s,t}^{\text{normal}}$ is the normal load output data center at node x at the time t of the s-th typical scenario, $p_{s,t't}^{x}$ represents the adjustable load of the node's data center's s-th typical scenario at the time of transferring to the power at the time, and $P_{dc,x,\max}$ represents the maximum power of the node's data center. $\mu_{x,s,t}$ represents the reactive power parameter at time t in the s-th typical scenario of the data center at node x.

4.2.7. Line Radial Constraints

$$\sum_{b\in L} L_{\text{line},b} = N - 1. \tag{31}$$

Here, L is the set of all lines, $L_{\text{line},b}$ represents the state of line construction, 0 means not built, 1 means built.

5. Case Verification

5.1. Case Information. The power grid of a park in Guangdong Province is selected as a calculation example, as shown in Figure 2. The calculation example originally has 4 nodes, 3 lines, 1 wind farm, 1 photovoltaic power generation, and 1 data center. In the future planning period, 6 nodes, 2 data centers, 2 wind farms, 3 photovoltaic power generation, some energy storage, and some lines are to be constructed to meet the demand of the economic and social development. The rated voltage of this example is 115 kV, node 1 is the contact point of the upper-level power grid, which is maintained at the rated voltage value. NaS batteries are used for energy storage, and the parameters are shown in Table 1. The load data of each node are shown in Table 2. The parameters of wind power and photovoltaic are in Table 3. The parameters of lines and data center are shown in Tables 4 and 5. The data of the Time-of-Use Tariff used is shown in Table 6. The system time-of-use tariff scheme is shown in the table. The set of energy storage candidate nodes is {2, 3, 10}. In this example, the time step is 15 minutes. There are 96 power flow sections in a typical daily curve. The current, voltage, line transmission power, and energy storage power of each power flow section are calculated, and the scheduling decision of the adjustable load of the data center in order to meet the safety of the power grid and stable operation constraints. Timing coupling constraints are considered. Details of the data used in the case can be found in the supplement.

5.2. Calculation Result. All the examples in this paper use a desktop computer with a CPU of i7 (10700F) and a memory of 16 GB, written in python3.8, and solved by the commercial software Gurobi. The total scheduling period is set to 24 h, unit time period 15 min. The calculation example sets 3 typical curves of solar, wind power, and load as shown in Figure 3.

The model circuit and energy storage planning of this paper are shown in Figure 4.

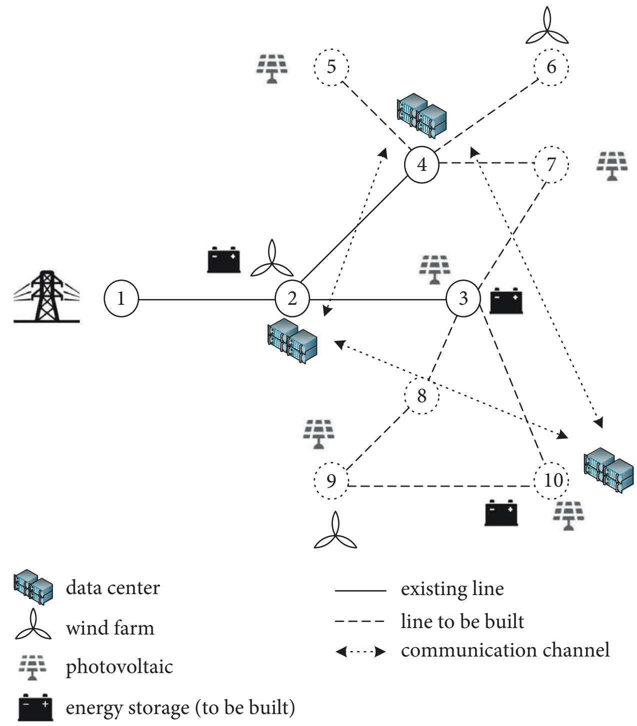

Figure 2: Schematic diagram of the power grid in the case.

Table 1: Related parameters of NaS battery.

Parameters	NaS
Investment cost per unit capacity ($/kW)	247
Operation and maintenance cost per unit of power generation ($/kWh)	0.067
Charge and discharge efficiency	0.95
Use period (year)	20

Table 2: Node load related parameters.

Node	Active power (MW)	Reactive power (MW)
1	0.85	0.30
2	2.93	0.81
3	0.86	0.29
4	1.81	0.72
5	0.90	0.13
6	0.98	0.10
7	1.20	0.80
8	1.25	0.20
9	0.76	0.12
10	1.45	0.63

The energy storage operation data is in Figure 5 (taking the typical curve of the first type of wind and solar as an example).

It can be seen that within the 24 hours dispatch period, the charging and discharging power of the energy storage is basically the same as the fluctuation of the electricity price. During the peak period of the high electricity price, the energy storage is mostly discharged,

Table 3: Wind power and photovoltaic related parameters.

Node	Type	Capacity (MW)
2	WT	1.5
6	WT	2.5
9	WT	1.0
3	PV	1.0
5	PV	1.5
7	PV	0.5
10	PV	1.5

Table 4: Parameters of lines.

Branch head and end node	Branch length (km)	Line resistance per kilometer (Ω)	Maximum current (kA)
1–2	13	10.3	2
2–3	15	10.3	2
2–4	14	10.3	2
4–5	13	10.3	2
4–6	8	10.3	2
4–7	9	10.3	2
3–8	20	10.3	2
8–9	17	10.3	2
9–10	6	10.3	2
3–10	9	10.3	2

Table 5: Parameters of data center

Node	Number of servers	Server power rating (MW)	Server maximum power (MW)	Typical values of other load (MW)
2	3	1.0	1.5	0.97
4	5	1.0	1.5	0.88
10	4	1.0	1.5	1.01

Table 6: Data of time-of-use tariff.

Period type	Period	Time-of-use tariff ($/kWh)
Peak period	08 : 00–12 : 00 16 : 00–23 : 00	0.2
Normal period	06 : 00–08 : 00 12 : 00–16 : 00 23 : 00–24 : 00	0.13
Valley period	00 : 00–06 : 00	0.07

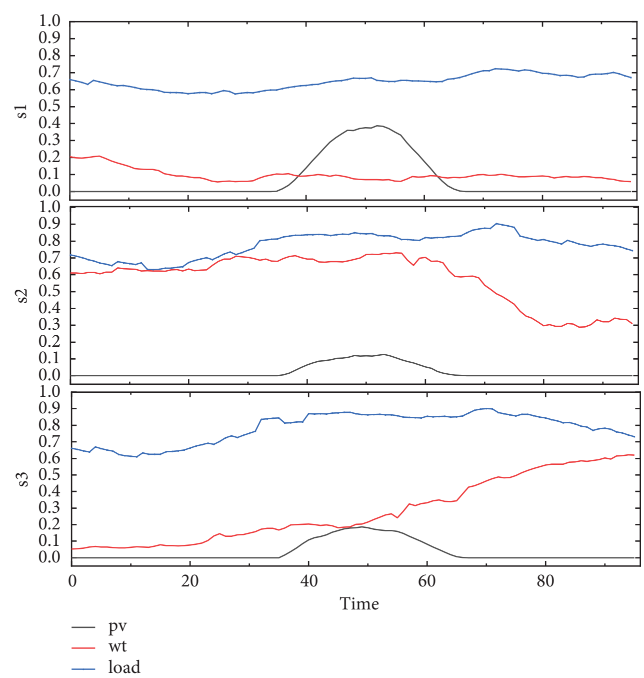

Figure 3: Typical curves of solar, wind power, and load.

except for some periods of time, which is charged for system power balance, while charging is performed during normal and valley periods when electricity prices are low.

Figure 6 shows the output curve of the delayable load and the normal load after the data center adopts the delayable load adjustment strategy. It can be seen that there are two obvious periods of load adjustment, one is the period 16–30, and the data center of node 10 performs The load space is shifted to the data centers of node 2 and node 4. The other is the 32–66 period, the load of the 32–50 period is transferred to 50–66, and the time transfer of the load is carried out.

5.3. Comparison of Different Plans. The following planning schemes and models are designed to analyze and compare the effectiveness of the methods proposed in this paper:

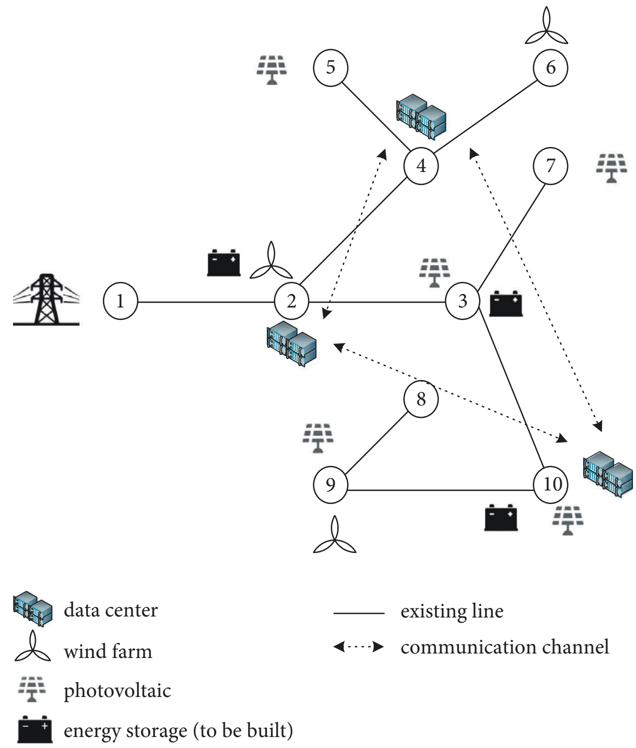

Figure 4: Planning result.

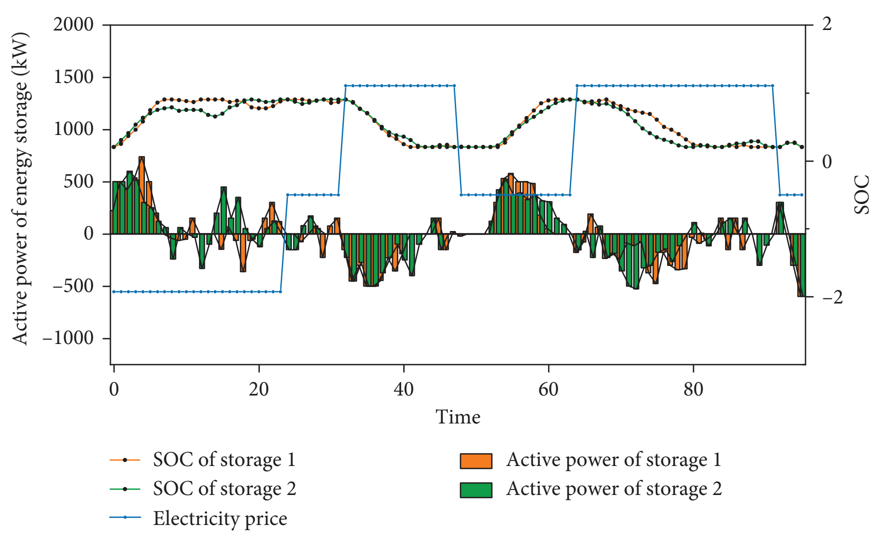

Figure 5: Energy storage operation.

(1) Scheme 1: collaborative planning considering the adjustable load of the data center
(2) Scheme 2: collaborative planning without considering the adjustable load of the data center
(3) Scheme 3: grid planning without energy storage
(4) Scheme 4: grid planning without energy storage and data center adjustable load

The planning result of different schemes is in Table 7.

It can be seen that compared with scheme 2, the construction cost of the method in this paper is significantly reduced. Compared with schemes 3 and 4 without energy storage, the network loss and electricity purchase cost are significantly reduced in schemes 1 and 2 with energy storage. Because energy storage can be managed through charge and discharge, it can be charged when the price of electricity is

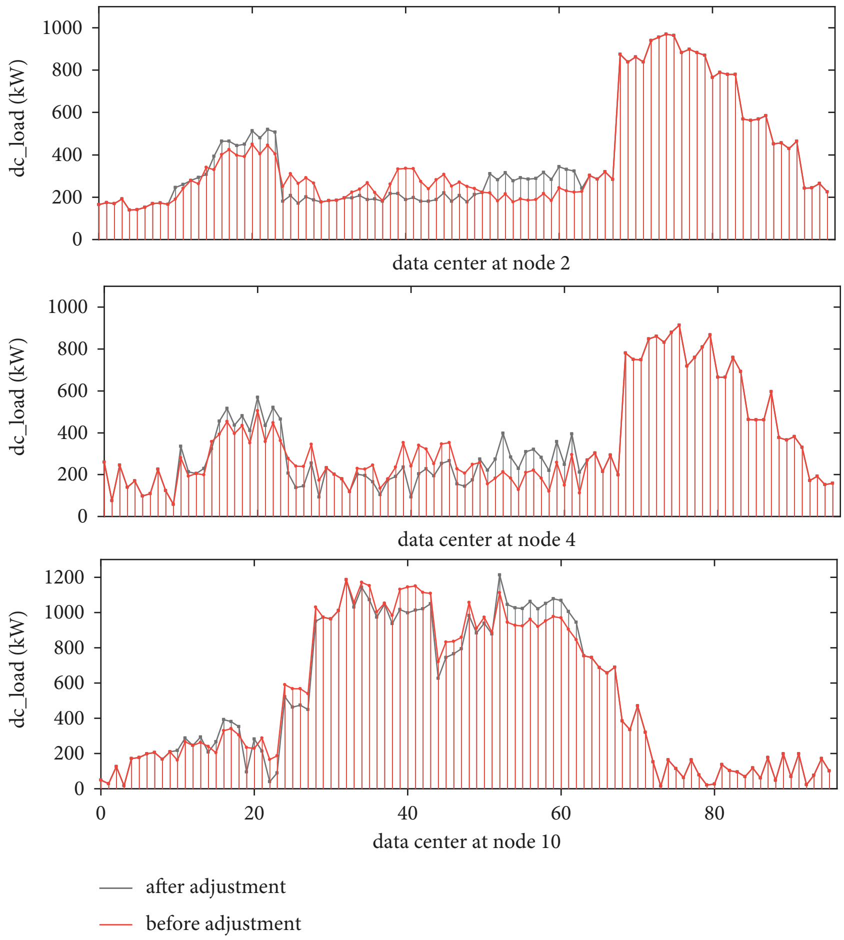

Figure 6: Load curves of data centers.

Table 7: Planning result of different schemes.

Scheme	Energy storage construction scheme	Line construction result	Construction and operation cost ($)			
			C_{inv}	C_{loss}	C_{grid}	Sum
1	2 (136 kW), 10 (311 kW)	4–5,4–6,3–7,8–9,3–10,9–10	7975.1	685.3	48958.7	57619.0
2	2 (368 kW), 10 (440 kW)	4–5,4–6,3–7,8–9,3–10,9–10	14328.7	806.9	49145.5	64281.2
3	None	4–5,4–6,3–7,8–9,3–10,9–10	91.7	8600.9	246634.3	255326.9
4	None	1–2,2–3,2–4,4–5,4–6,3–7,8–9,3–10,9-–10	91.7	8665.9	248485.7	257243.3

low and discharged when the price of electricity is high, reducing electricity purchase costs. Through the power flow optimization of energy storage, network losses can be reduced. As can be seen from the table, considering the load shifting characteristics of the data center can reduce the cost of the planning scheme, because the data center can perform energy management and play a role equivalent to energy storage, making the operation of the power system more economical.

Figure 7 shows the comparison of the electricity purchased by the contact point of the main network under different schemes. It can be seen that the peak-to-valley difference of the electricity purchase curve of scheme 1 is smaller, indicating that the external characteristics of the

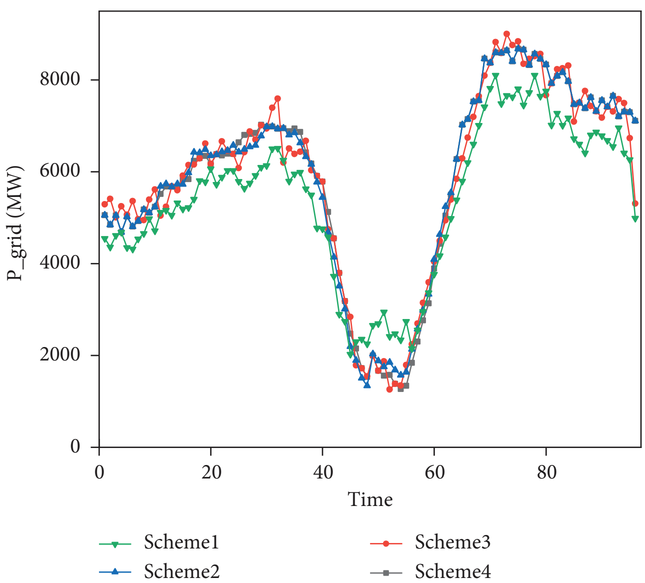

Figure 7: Electricity purchased by the contact point.

power grid are better. At the same time, it can be seen that scheme 1 can effectively reduce the Electricity purchase cost.

6. Conclusions

In this paper, the time-space transfer characteristics of the adjustable load of the data center are considered, aiming at the comprehensive cost of construction and operation cost, the coordinated planning of energy storage and lines in the distribution network of the park is carried out, and the following work is completed:

(1) The data center load transfer matrix is constructed to describe the load time and space transfer characteristics, and by optimizing the scheduling arrangement of the data center's delayable load, the power flow structure of the power grid is optimized, the consumption of new energy is improved, and the line loss is reduced.

(2) Construct a power grid planning model that considers the time-space transfer characteristics of the adjustable load of the data center, plan the lines and energy storage configuration of the power grid, and verify with an example to prove that considering the time-space transfer characteristics of the adjustable load of the data center can greatly reduce the construction and operation cost of the system, which provides a feasible solution for the distribution network of the information park containing the data center.

Data Availability

The data used to support the study are included in the paper. For more detailed data, please contact the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Author Tianlin Wang is employed by New Energy Service Center of Guangdong Power Grid CO.LTD. Authors Peidong Chen, Huazhen Cao, Chong Gao are employed by Power Grid Planning Center of Guangdong Power Grid CO.LTD. Authors Yu Liang, Yi Cao are employed by Energy Development Research Institute of China Southern Power Grid.

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Tianlin Wang proposed the framework and innovation of the paper. Peidong Chen is the corresponding author, responsible for submission and liaison, and completed the preface of the paper. Huazhen Cao completed the third part. Chong Gao and Yu Liang completed the verification part of the manuscript and the conclusion part. Yi Cao was responsible for the integration of various parts of the manuscript, text polishing, and translation.

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