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Dispatch of Low-carbon Campus Power System Considering Flexible Loads and Green Power

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ABSTRACT

In recent years, energy consumption in universities and colleges has accounted for about 10% of the total energy consumption of Chinese society. In order to achieve the goal of carbon peaking and carbon neutrality, it is a major trend to build a new, cleaner campus power system. At the same time, fully exploiting the flexibility of campus loads is also conducive to the accommodation of renewable energy. This paper provides an optimal dispatch approach to achieve low-carbon in a campus smart grid. Firstly, a green electricity trading mechanism based on power-load matching was proposed. Secondly, flexible load models in the campus for electric vehicles, air conditioners, energy storage, and other loads were established. Thirdly, a day-ahead renewable energy power prediction method based on weather forecast data for a campus wind-solar-storage combined operation power system is proposed. Finally, by means of load regulation measures, such as flexible class schedule, an optimal dispatch approach for the low-carbon campus power system was established. The case study shows that adopting load regulation measures can effectively promote the consumption of renewable energy sources and support the development of the low-carbon campus.

Keywords: renewable energy, low-carbon campus, optimal dispatch, smart grid, flexible load

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
RC	Resistor & Capacitor
EV	Electric Vehicle
SOC	State of Charge
RE	Renewable Energy
AC	Air Conditioner
Symbols	
$\hat{P}$	Forecast actual power
p_e	Wind power conversion efficiency
ρ	Air density
A	Swept area of the wind turbine blade
P_{Wrated}	Rated power of the wind turbine
P_{Srated}	Rated power of the PV module
$\hat{v}_t$	Forecast wind speed
$\hat{R}_t$	Forecast irradiance
v_{in}	Cut-in wind speed
v_{out}	Cut-out wind speed
v_{rated}	Rated wind speed
R_{rated}	Rated irradiance
R_e	Irradiance at maximum photoelectric conversion efficiency
λ^T	Penalty factor for exceeding the thermal comfort zone
$T^{\max}$	Upper limits of the thermal comfort zone
$T^{\min}$	Lower limits of the thermal comfort zone
T_t^{up}	Temperature exceeding the thermal comfort zone
T_t^{down}	Temperature below the thermal comfort zone
C	Cost
$\mathcal{N}_{w_i}$	The set of all of neighboring nodes to node
$\mathcal{N}_{r_i}$	The set of all of the neighboring nodes to room i
$u_{r_i,t}$	Binary indicator for course schedule
δ	Degradation factor of batteries in secondary utilization
k	Battery charge/discharge efficiency
λ_{in} & λ_{out}	SOC upon EV connection/departure

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1. INTRODUCTION

As the global climate continues to deteriorate, reducing carbon emissions and building a low-carbon society is the consensus of all countries in the world [1]. Since China announced its carbon peak and carbon neutral goals in 2020, the concept of a "low carbon" future has garnered attention across various domains [2]. Data show that the energy consumption of Chinese universities accounts for 10% of the total energy consumption of the society, and the per capita energy consumption of university students is four times of the per capita energy consumption of residents [3]. Therefore, colleges and universities are an important area for China's low-carbon construction, with huge energy-saving potential. And actively promoting the construction of "low-carbon campuses" in colleges and universities is an inevitable choice for realizing the dual-carbon goal.

Regarding energy use by type, campus energy consumption consists primarily of electricity, gasoline, and natural gas [4]. Campus energy consumption is dominated by building usage, and air conditioning related carbon emissions constitute a substantial proportion of total campus carbon emissions [5]. In the future, following the electrification of vehicles, on-board batteries can also play a constructive role in grid energy storage and peak load shaving [6].

An important approach to realize a low-carbon campus is to adopt RE sources for electricity supply and increase the share of electricity in energy consumption. This necessitates fully harnessing campus space for renewable generation facilities such as rooftop PVs and small wind turbines. However, such distributed renewable generation cannot fully satisfy the high load demand of modern campuses. Therefore, a feasible concept is to contract with centralized wind farms and solar plants to purchase green power through electricity market mechanisms. The primary challenge is maintaining the balance between renewable generation and load demand [7].

In recent years, various techniques have been proposed to balance electricity supply and demand with high RE penetrations. Among the most crucial methods is the rational utilization of energy storage to smooth the inherent variability of renewable generation [8]. For instance, Makarov et al. examined the energy storage capacities required to balance electricity production and consumption from renewable sources [9]. Another salient topic is demand-side flexibility, i.e., adapting load demand to accommodate the intermittency of renewables [10]. For example, industrial loads [11] and building loads [12,13] can participate in grid demand-side response. Nevertheless, existing studies have seldom discussed the load shaping potential of campuses. Determining how to enable flexible electricity utilization on campuses such that load follows renewable generation in order to balance supply and demand is pivotal to realizing low-carbon campuses. In this context, this paper proposes an optimal dispatch approach for low-carbon campus power systems considering green power trading and flexible loads. The core methodology utilizes load reshaping measures, such as adjusting student class times and controlling energy storage and EV charging/discharging, to achieve flexible variation in campus load.

2. METHODOLOGY

This study investigates the optimal dispatch of campus power system under the scenario of fully supplying electricity from RE sources. The problem can be formulated as determining how to balance power generation and consumption through rational dispatch solutions when the future campus power supply is entirely from green energy. The main approach is firstly to forecast renewable power generation capacity for the next day. Based on the prediction, the load curve of the next day is shaped to match the renewable generation profile by adjusting three types of load management techniques - students' class schedules, EV charging time, and energy storage charging/discharging time. This problem can be modeled as an optimization problem with the objective of minimizing costs and constraints on the operational limits of the campus power system.

2.1 Green power purchase agreement

Assuming that the campus enters into special green power purchase agreements with centralized PV stations and wind farms. The special green power purchase agreement stipulates that the campus's daily power consumption curve is to be matched with the RE supply curve. That is, the balance between the campus demand and the RE supply must be met.

$$\widehat{P}_{wind,t} + \widehat{P}_{solar,t} = \widehat{P}_{load,t} \tag{1}$$

2.2 Day-ahead renewable power forecasting

Day-ahead forecasts of wind and PV generation are derived using physical mapping models based on weather forecast data for the campus location from an external meteorological service. The wind power forecasting applies the wind speed-wind power mapping model delineated in Equation (1). The PV forecasting employs the irradiance-PV power mapping model delineated in Equation (2).

$$\hat{P}_{wind,t} = \begin{cases} 0 & if: \hat{v}_t < v_{in} \\ \frac{1}{2} p_e \rho A \hat{v}_t^{\,3} & if: v_{in} \le \hat{v}_t < v_{rated} \\ P_{Wrated} & if: v_{rated} \le \hat{v}_t < v_{out} \\ 0 & if: \hat{v}_t \ge v_{out} \end{cases} \tag{2}$$

$$\hat{P}_{solar,t} = \begin{cases} P_{Srated} \frac{\hat{R}_t}{R_e} \cdot \frac{\hat{R}_t}{R_{rated}} & if: \hat{R}_t < R_e \\ P_{Srated} \frac{\hat{R}_t}{R_{rated}} & if: R_e \le \hat{R}_t < R_{rated} \\ P_{Srated} & if: \hat{R}_t \ge R_{rated} \end{cases} \tag{3}$$

2.3 Optimal dispatch model of low-carbon campus power system considering load flexibility

The objective function of proposed model is shown in Equation (4).

$$\min F = \lambda^T \sum_{t=1}^{24} \left(T_t^{up} + T_t^{down} \right) + C^{storage} \sum_{t=1}^{24} \left| P_t^{storage} \right| + C^{car} \sum_{t=1}^{24} \left| P_t^{car} \right| \tag{4}$$

The loads of the campus are divided into rigid and flexible loads. Cafeteria, library, office and other loads are rigid loads with certain regularity that must ensure the supply of electricity, and this part of the load can be obtained from historical data statistics. And the teaching building, EV charging pile, energy storage system and so on are flexible loads.

$$\hat{P}_{load,t} = P_{ac,t} + P_{ev,t} + P_{storage,t} + P_{base,t} \tag{5}$$

The teaching building load is primarily from AC for cooling/heating, which can be flexibly adapted by adjusting class times. For instance, during periods when renewable generation is forecast to be low, classes can be cancelled by releasing the schedule day-ahead. AC is not required during these times, reducing building load. Moreover, as buildings possess thermal mass, they can be regarded as virtual thermal storage. When classes are cancelled but renewable generation is high, AC can be pre-cooled/heated, maintaining indoor conditions for a period. Even with lower renewable output, comfortable temperatures can then be maintained for classes.

To characterize indoor temperature response to AC power, this paper refers to the RC network thermal model from [14], representing building heat transfer through electrical equivalents of thermal resistances and heat capacities. With n total nodes, m are rooms and n-m are walls. The temperature of wall node i is:

$$\frac{dT_{w_i}}{dt} = \frac{1}{C_{w_i}} \left[\sum_{j \in \mathcal{N}_{w_i}} \frac{T_j - T_{w_i}}{R'_{ij}} + r_i \alpha_i A_i q''_{\mathrm{rad}_i} \right] \tag{6}$$

The temperature of the i-th room is governed by the following equation:

$$\frac{dT_{r_i}}{dt} = \frac{1}{C_{r_i}} \left[\sum_{j \in \mathcal{N}_{r_i}} \frac{T_j - T_{r_i}}{R'_{ij}} + \dot{m}_{r_i} c_p \left(T_{s_i} - T_{r_i} \right) + \right. \\ \left. + w_i \tau_{\mathrm{win}_i} A_{\mathrm{win}_i} q''_{\mathrm{rad}_i} + \dot{q}_{\mathrm{int}} \right] \tag{7}$$

Unlike fixed scheduling, this method requires flexible day-ahead class scheduling based on renewable forecasting to reshape building loads. Temperature control is only needed during class times and should remain as close as possible to the comfort range:

$$T_{r_i,t} \le T^{\max} + (1 - u_{r_i,t}) \cdot M + T_t^{up} \tag{8}$$

$$T^{\min} - (1 - u_{r_i,t}) \cdot M - T_t^{down} \le T_{r_i,t} \tag{9}$$

The energy storage batteries equipped on campus are similar to traditional energy storage batteries. Generally, the charging capacity of power batteries considered for secondary utilization can only reach about 80% of the rated capacity.

$$-P_{STrated} \le P_{storage,t} \le P_{STrated} \tag{10}$$

$$0 \le E_{storage,t} \le \delta E_{STrated} \tag{11}$$

$$E_{storage,t+1} = E_{storage,t} + k P_{storage,t} \tag{12}$$

EV chargers use intelligent control, communicating with the campus control center for coordinated charging and discharging. EVs can thus provide flexibility as virtual storage with constraints similar to physical storage. Key differences are:

$$E_{t\_in}^{car} = \lambda_{in} E_{rated}^{car} \tag{13}$$

$$E_{t\_out}^{car} = \lambda_{out} E_{rated}^{car} \tag{14}$$

3. CASE STUDY

A university in the South of China has been chosen as a case study. Figure 1 illustrates the RE generation profile and campus load profile for a normal summer day.

The green line in Fig. 1 indicates the renewable generation curve, while the red line shows the load without flexible class scheduling. As observed, supply and demand are highly mismatched throughout the day absent load management. Before 5am, insufficient wind and PV cannot meet school loads. Shortfalls also occur during daytime when AC and EV charging produce large demands, while nighttime wind generation exceeds the reduced school load, causing renewable curtailment and waste.

Based on the day-ahead wind/PV power prediction information, the courses are rescheduled using the optimization method described in the paper to obtain Fig. 2. In the figure black squares indicate that a course is scheduled at that college during that time period and blanks indicate that no classes are held at that college during that time period. It can be seen that some daytime classes are scheduled in the evening due to cooler temperatures and the availability of renewable energy generation.

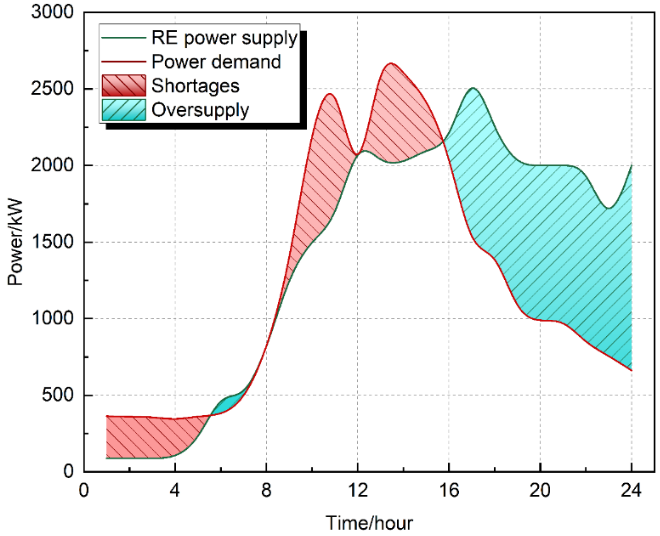

Fig. 1. The RE generation profile and campus load profile

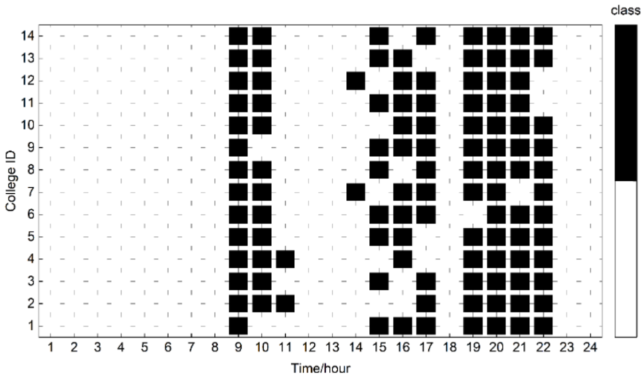

Fig. 2. One day-ahead course schedule

The power scenarios after implementing load reshaping are showed in Figs. 3 and 4. For supply, renewable generation was unrestricted with early morning shortfalls covered by storage discharge. For load, 5:00-8:00 AC pre-cools classrooms utilizing the wind power peak in preparation for morning classes. AC loads are more evenly distributed between daytime and evening classes, unlike the concentrated daytime peak without adjustment. EV charging is also sporadically spread from 7:00-18:00 rather than concentrated at morning entry times. Lastly, energy storage charges overnight when wind generation peaks, absorbing surplus RE and preventing curtailment. Notably, AC operates during 22:00-24:00 because energy storage reaches capacity while ample wind remains. At this point, excess wind can only be consumed by operating AC, balancing generation and load. As buildings have thermal mass, this energy is not completely wasted.

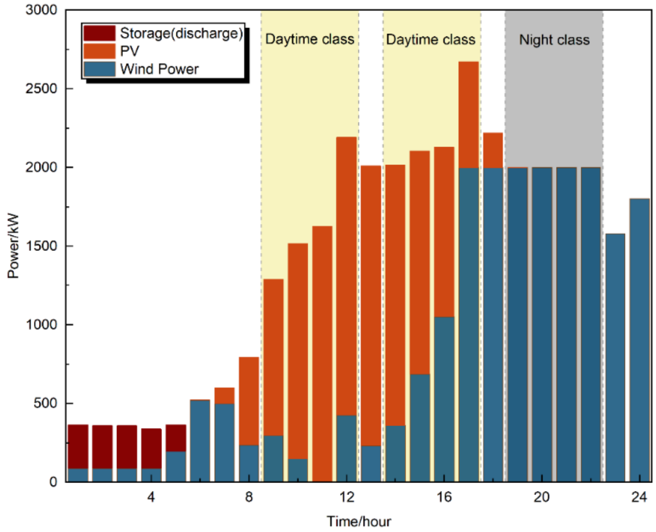

Fig. 3. One day-ahead Power supply

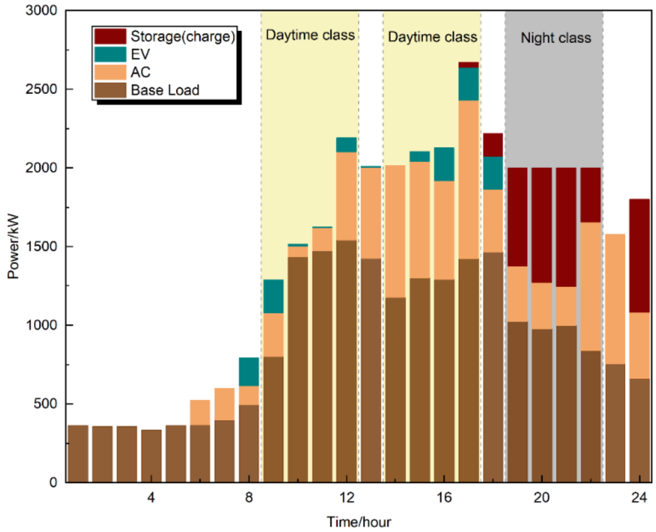

Fig. 4. One day-ahead Power demand

4. CONCLUSION

Against the backdrop of carbon peak and carbon neutrality goals, constructing low carbon campuses can not only generate substantial cost and environmental benefits, but also further energy conservation and carbon reduction education. This paper develops an optimization approach for low-carbon campus power systems considering green power trading and load flexibility. Case studies demonstrate that the proposed method can fully exploit the demand-side regulation potential of campuses based on the characteristics of renewable energy generation forecast and campus load demand. It can effectively improve the accommodation rate of renewable energy, providing support for the low-carbonization or even zero-carbonization of campus power systems.

The current study only demonstrates load management of the teaching buildings for student classes, while other campus facilities including the library, dormitories, and laboratories can further participate in regulation. For future work, scheduling holidays could be investigated to address the considerable mismatch between the seasonal fluctuations of renewable generation and shifting campus power demands. Moreover, human behaviors will impact load variability, so incorporating this randomness is also a worthwhile research direction.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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