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Load regulation application of university campus based on solar power generation forecasting

GUOZHENG HAN ✉, SHUJUAN TAN, ZIHAN ZHANG

School of Information and Automation Engineering
Qilu University of Technology (Shandong Academy of Sciences)
No. 3501, Daxue Road, Changqing District, Jinan 250353 Shandong Province, PR China
e-mail: ✉hgz@qlu.edu.cn

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Abstract: For a solar photovoltaic power system on a university campus, the electricity generated by the system meets the campus load, and the extra electricity is delivered to the grid. Generally, the price of the photovoltaic system is cheaper than that of the utility power system. The full use of solar electricity can reduce the electricity cost of the school. The deep belief network is used to predict solar photovoltaic generation and electricity load, and the gap is found. According to the gap, the power loads on the campus are adjusted to improve the utilization rate of solar power generation. Through the practical application of Changqing Campus of Qilu University of Technology in China, it is found that the utilization rate of solar photovoltaic power generation effectively improved from 91.24% in 2017 to 98.16% in 2019, and the annual electricity is saved by 68 610 yuan (in 2019).

Key words: load regulation, solar power generation forecast, photovoltaic generation

1. Introduction

At present, the energy demand of the university campus is increasing. The energy supply of the university campus is also relatively complex, including electricity, natural gas, solar energy, and so on. How to make full use of all kinds of energy supply is an important problem of comprehensive energy supply at present. Many scholars have carried out extensive and in-depth research on the modeling, analysis, planning, operation, and market of integrated energy service systems, involving various energy supply forms such as power-gas [1], power-heat [2], and power-gas-heat [3] and so on. Bando S., Asano H. and Sajima K. [4] analyze the energy utilization rate of electricity, cold, and heat combined power supply system and micro network system with the goal of economic, energy conservation, and environmental protection. Savic D.A., Bicik J. and Morley M.S. [5] study the planning of integrated energy services with the goal of economic and energy consumption levels. It can make full use of distributed energy on the basis of generation forecasting and load forecasting. Yang Y., Pei W. and Qi Z. [6] proposed an improved simulated annealing algorithm to optimize the model of the energy system on the basis of considering the uncertainty of load and renewable energy. In reference [7, 8], a combined method for wind power generation forecasting is proposed. A model of predictive direct power control for an energy storage quasi-Z-source inverter is proposed in reference [9].

Some photovoltaic systems have been installed on campus on-grid and off-grid systems in the last few years. Jongsung Lee, Byungik Chang, Can Aktas and Ravi Gorthala evaluated the economics of the campus photovoltaic system in New England [10]. Elieser Tarigan analyzes the rooftop photovoltaic system of the University of Surabaya, Indonesia [11]. J.H. Angelim and C.M. Affonso [12] introduced the method of optimizing the operation of photovoltaic – battery systems on existing university campuses in Brazil. The electricity generated by the photovoltaic system on the university campus meets all or part of the campus' electric load and the extra electricity is delivered to the grid and photovoltaic electricity price is generally cheaper than that of the public grid. Therefore, making full use of the electricity generated by the solar photovoltaic system can reduce the university's electricity bill. In addition, reducing the extra electricity delivered to the grid will also reduce the impact of distributed power on the public grid. Based on the photovoltaic power generation forecast and campus load forecast, this manuscript proposes a campus load adjustment strategy to improve the utilization rate of campus solar power generation to more than 98%.

2. Energy consumption analysis of university campus

2.1. Energy consumption composition

The energy demand of the university campus mainly includes electricity, natural gas, heating, and cooling. Compared with ordinary office buildings, the characteristics of energy consumption on campus are different.

The load components of office buildings mainly include electrical load, heating load in winter, cooling load in summer, and spring and autumn. The energy consumption characteristics of Chinese universities vary depending to their geographical location. Heating energy consumption of colleges and universities in northern China is close to that of electricity consumption. Due to their longer heating season, they mainly use coal and natural gas during the heating season. The main energy consumption of universities in South China is electric energy consumption. And its energy components include water, electricity, natural gas, etc., and its electric energy consumption is the most prominent.

Take a comprehensive university in North China as an example. The campus has a total construction area of 573 229 square meters, including public teaching buildings, public laboratory buildings, a teaching area canteen, dormitory area canteen, student apartments, an engineering training center, office building, liberal arts teaching building, library, art, and sports center, etc. The main energy consumption of the campus is electricity, gas, heating, and cooling, supplemented by other energy consumption.

Specific energy consumption is as follows:

1) **Natural gas**

Natural gas is purchased through the natural gas pipeline and used by the boiler room and restaurant. The steam generated from the boiler is exchanged through the heat exchange station to provide winter heating for the student apartments, teaching buildings, and staff dormitories on the campus and provide steam for life.

2) **Electricity**

Electricity is purchased by the social network and supplemented by photovoltaic solar power generation, which is distributed to various buildings of the college through the power distribution room. Electricity is mainly used in teaching buildings, water stations, canteen, faculty dormitories, student apartments, and other units.

3) **Heating**

The heating system of the campus is not related to the municipal heating system, so the heating of the campus is mainly provided by burning natural gas in its boiler room, and heat is distributed through air-conditioning and other heating measures.

4) **Air conditioning**

Student apartments are cooled by rental air conditioning, which now covers nearly 90% of student apartments. Public teaching buildings are equipped with central air conditioning. The schematic diagram of the campus energy system is illustrated in Fig. 1.

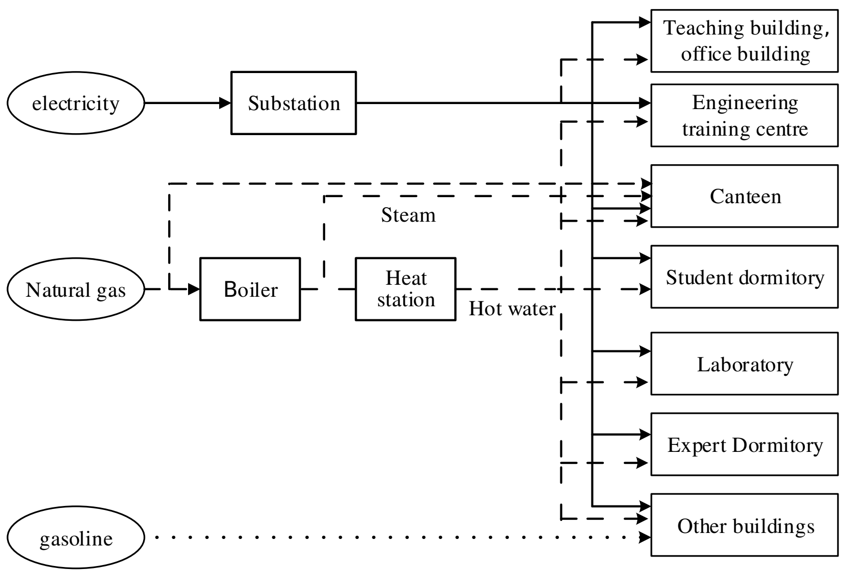

Fig. 1. Energy supply system for university campus

2.2. Energy consumption characteristic

1) **Obvious seasonal variation**

The load of the university campus mainly includes the annual power load, heat load for heating in winter, cooling load in summer, and domestic hot water load. As the university campus is an important part of the education system, its load character is closely related to the activities of teachers, students, and staff on campus. And it has an obvious rule for winter and summer vacations.

2) **Significant differences between buildings**

The building types of university campuses include teaching buildings, dormitories, and venues. The difference in energy consumption among different building types is also very obvious. The change in campus load is closely related to the activity rules of teachers, students, and staff on campus. For example, the electricity load on weekdays is significantly higher than that on holidays. At the same time, because the winter and summer vacations are the peak periods of various extreme weather, the load levels are significantly different due to different building types.

Teaching buildings

As the main place for teaching activities, the use of load in teaching buildings is closely related to the arrangement of school teaching courses. The specific performance is that the use of load varies significantly day and night, and the use of load on working days is significantly higher than that on weekends.

Dormitory buildings

A dormitory is a place for students to rest, and students spend most of their time in the dormitory in the evening. Therefore, the load usage of dormitory buildings in the evening increases significantly, and there is often a small peak between 17:00 and 20:00.

Venue buildings

The load usage of venue buildings is different from that of the above two types of buildings. The load usage is random, mainly related to the opening hours of the venues. The load usage of the venues has increased significantly during the opening hours.

2.3. Solar photovoltaic

As clean energy, solar energy has been widely used. It is renewable, pollution-free, and easy to obtain. Solar photovoltaic is a power generation method that uses the photovoltaic effect of solar cells (a semiconductor device similar to crystal diodes) to convert solar radiation energy into electrical energy directly. The process of solar photovoltaic power generation is simple, without mechanical rotating parts and noise. It does not consume fuel, emits any substances, including greenhouse gases, and is pollution-free. The actual output power of photovoltaic power generation systems is mainly affected by solar irradiance. However, the energy density per unit area of solar radiation is low, and it has large discontinuity and instability in time, so it is difficult to calculate its output power accurately. It is not only affected by seasonal and geographical factors, but also closely related to the atmospheric transparency, moisture content, aerosol, cloud amount, cloud shape, and the relative position of clouds and the sun at that time.

The instantaneous power (DC) output by photovoltaic modules is:

$$P_{\mathrm{dc}}(t) = \eta_s A G(t), \tag{1}$$

where: $P_{\mathrm{dc}}(t)$ is the output power of the photovoltaic system (W), η_s is the efficiency of photoelectric conversion, A is the module area (m^2), and $G(t)$ is solar global irradiance values (W/m^2). η_s is usually related to temperature, radiation, and air quality.

The daily AC power generation of the photovoltaic system E_{ac} is

$$E_{ac} = \eta E_{dc} = \eta \int_{t1}^{t2} P_{dc}(t)\,dt, \tag{2}$$

where: η is inverter efficiency, $t1$ is the sunrise time, $t2$ is the sunset time. η is related to temperature, radiation and air quality.

If the total solar radiation on the horizontal plane is given, the power generation of a whole year can also be estimated according to (3).

$$E_{ac} = \eta \frac{P_{inst}}{Es} \times H, \tag{3}$$

where: η is inverter efficiency, Es is the irradiance under standard conditions (AM1.5, 1 kW/m^2) [13], H is the total solar radiation on the horizontal plane (kWh/m^2, peak hours).

Take the photovoltaic solar power station in Changqing campus of Qilu University of Technology as an example. The exact location of Changqing campus is 116.81° East and 36.56° North. The campus has installed a 5 MW photovoltaic power plant. Based on government subsidies, electricity price subsidies, and other preferential policies, 19 610 photovoltaic modules (255 Wp each module) are installed on the roofs of student apartments, teaching buildings, libraries, office buildings, canteens, and other buildings on the campus, with a total installed capacity of 5 MW. The site is located at 36.56° North, with good lighting conditions, and the annual average radiation can reach 1423.81 kWh/m^2. The total conversion efficiency η is 0.79. According to (3), it can be calculated that the annual power generation of this project is:

$$E_{ac} = \eta \frac{P_{inst}}{Es} \times H = 0.79 \times \frac{5}{1000} \times 1423 = 5.6\ \mathrm{M\,kWh}. \tag{4}$$

The design power generation load of the project is 5.6 million kWh, and the measured annual power generation is 4.95 million kWh (2019.1.1~2019.12.31) after the project is put into operation.

The electricity generated by the photovoltaic power station first meets the needs of the university campus load, and the excess electricity is delivered to the grid. The electricity charge of the campus in China is mainly composed of two parts: one is 0.52 yuan/kWh based on the normal civil electricity charge, and the other is the solar photovoltaic charge price, which is 0.32 yuan/kWh for the school electricity sales. So, one million yuan (0.2 yuan/kWh × 4.95 million kWh) of electricity cost can be saved every year. The project has been running well since it was put into operation, saving part of the school's electricity expenditure.

To further reduce the electricity expenditure of the school, it is also necessary to improve the utilization rate of photovoltaic power. Although solar photovoltaic power generation has saved part of the school's electricity expenditure, the utilization rate of its photovoltaic power generation needs to be further improved. As shown in Fig. 2, the output power of the photovoltaic system on the campus from 12:00 to 15:00 in summer is greater than the power load of the whole school. By adjusting part of the electricity load on the campus, we can make use of this part of the surplus as much as possible in the time with more surplus and improve the overall utilization efficiency of photovoltaic solar energy on the campus.

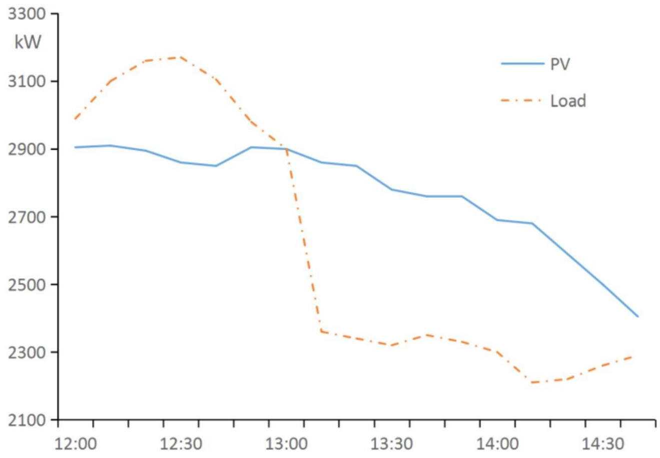

Fig. 2. Photovoltaic power generation vs. campus load

3. Solar photovoltaic power generation forecast

3.1. Factors of solar photovoltaic power generation

In order to improve the utilization rate of solar photovoltaic power generation, it is necessary to forecast solar photovoltaic power generation. The generation power of the solar photovoltaic system is characterized by uncertainty, random fluctuation, and intermittency. There are many factors as Formula (2) that need to be considered for power generation forecasting, including the parameters of the system itself and some factors of the external environment as shown in Fig. 3. However, due to the known and fixed physical characteristics of photovoltaic modules and inverters of the solar photovoltaic system on campus, we can ignore the impact of potential factors such as the conversion efficiency that will be affected by the photovoltaic modules themselves when predicting the short-term power generation of the system. Therefore, in the actual prediction, the influence of meteorological factors (such as irradiance, wind speed, temperature, etc.) is mainly

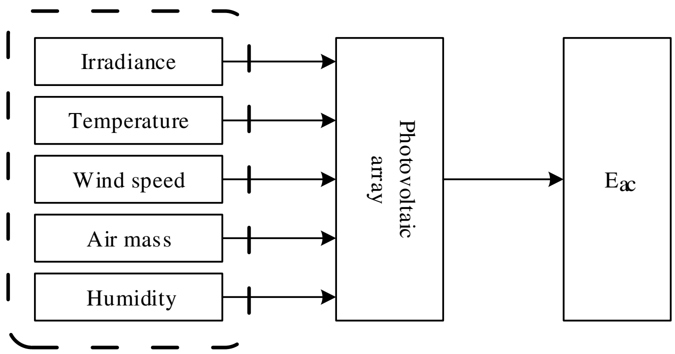

Fig. 3. Environmental factors affecting photovoltaic power generation

considered. When making predictions, it is necessary to fully consider meteorological factors and combine historical data for prediction analysis.

3.2. Forecast method of photovoltaic generation

The PV power generation forecast needs to collect the historical data of the system installation site, establish a scientific and accurate forecast model, adopt effective algorithms, conduct careful research based on historical data, summarize the experience, and constantly revise the model and algorithm [14]. There are many forecasting methods for photovoltaic power generation, which can be divided into ultra-short-term forecasting, short-term forecasting, medium and long-term forecasting according to the time scale. According to the research process, it can be divided into direct prediction and indirect prediction. The direct prediction method is based on (1). The prediction effect mainly depends on the accuracy of the photoelectric conversion efficiency model, inversion efficiency model, and radiation prediction. Reference [15] adopts a constant coefficient efficiency model, $\eta s$is provided by the battery manufacturer and is related to efficiency and materials. Reference [16] uses a single negative temperature coefficient efficiency model to calculate the ηs_o Reference [17] adopts the two-element model of temperature and total solar radiation. Reference [18] further increased air quality and formed a three-element model. For a multi-access point building photovoltaic grid-connected power generation system, the installation location and service time of the volt array vary greatly, so it will be very difficult to model the photoelectric conversion link of the principle prediction method [19]. Indirect prediction methods mainly include mathematical statistics prediction methods and artificial intelligence prediction methods. Grey theory forecasting method, multiple linear regression forecasting methods, and time series forecasting method all belong to the mathematical statistical forecasting method. Although the mathematical statistical prediction method can achieve the prediction effect in photovoltaic power generation forecasting, the accuracy of the prediction results is sometimes low. In the short-term forecast, the PV power generation is affected by environmental factors with strong timeliness, and the correlation of historical data is reduced, which will lead to slow changes in the forecast results and low prediction accuracy [20].

Intelligent prediction methods include the neural network method, support vector machine method, etc. In reference [21], a support vector machine (GASVM) model based on a genetic algorithm was proposed for short-term power prediction of a residential-scale PV system. In reference [22], a mathematical prediction model was proposed to optimize the short-term photovoltaic power output prediction of a photovoltaic system located at Deakin University in Victoria, Australia, using differential evolution and particle swarm optimization techniques. In recent years, with the research progress of deep learning, the prediction of photovoltaic power generation can also be completed by using the deep learning method.

It can be seen from the analysis in Section 3.1 that photovoltaic power generation is affected by multiple factors, which affect each other and have a complex relationship. A deep belief network (DBN) can map the nonlinear relationship between multiple factors and power generation, so it can be applied to short-term power generation prediction of photovoltaic power plants. DBN is a probability generation model, which is composed of a series of restricted Boltzmann machine (RBM) units. It can save the state of the original data, and analyze the relationship between different input, to effectively extract the feature information contained in the input information.

DBN is usually composed of two parts: the bottom part is feature extraction of DBN sample data by RBM, and the top part is fitting prediction by back propagation (BP) neural network. The whole prediction process can summarize the data characteristics obtained by the bottom layer DBN as the input of the top layer BP neural network, to output the prediction results. In the process of prediction, the BP algorithm is used to slightly adjust the parameters, which can achieve better prediction results.

Taking the campus photovoltaic power station as the research object, the operating state parameters of photovoltaic panels in the photovoltaic power station are collected as historical data, including the temperature of the solar panel backplane, the three-phase voltage, current, and power of the photovoltaic array composed of them. And the micrometeorological collection device is used to collect solar irradiance (W/m^2), ambient temperature (°C) and humidity (%), wind speed (m/s), wind direction, etc. as meteorological data. Solar irradiance is the most important factor affecting the output of the photovoltaic power generation system. In addition, atmospheric temperature, wind speed and ambient temperature are also the main factors affecting the output of the photovoltaic power generation system. The output of the photovoltaic system is positively correlated with atmospheric temperature and wind speed, and negatively correlated with relative humidity. In general, the computation of deep learning is relatively large. The key question is how to reduce computation. Therefore, a dual prediction model combining offline training and online prediction is adopted, which can effectively reduce the amount of calculation, as shown in Fig. 4. To ensure the timeliness of training parameters, samples and models need to be updated regularly.

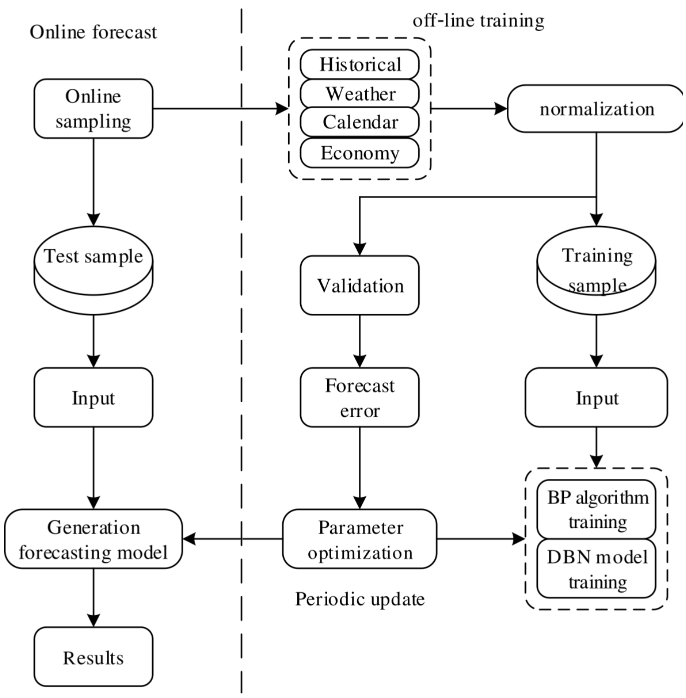

Fig. 4. Prediction algorithm of solar photovoltaic power generation

3.3. Forecast result analysis

We select the prediction results of a sunny day and a rainy day in June, to better analyze the prediction of the selected model for the output power of photovoltaic solar photovoltaic power generation system. The comparison between the predicted results of a sunny day and a rainy day and the actual output is shown in Fig. 5.

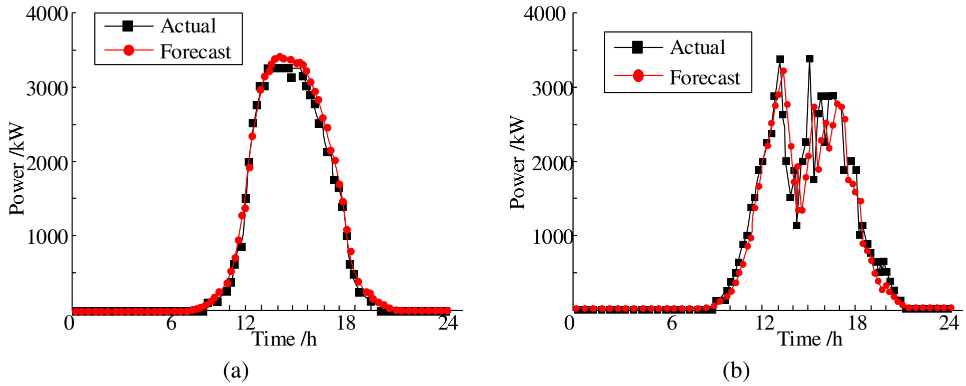

Fig. 5. Solar photovoltaic generation forecasting: sunny day (a); rainy day (b)

From Fig. 5(a) we can see that the deep learning algorithm can well predict the output power of the solar photovoltaic power generation system on a sunny day. The PV output can be well-fitted in the rising period, the maximum period and the falling period, and the error between the predicted value and the actual value is small. It can be seen from Fig. 5(b) that the randomness of the output power of the photovoltaic power generation system on a rainy day increases compared with on a sunny day. Even so, the deep learning algorithm can better predict the trend of its output, but the processing of details is not in place, and the error is greater than that on a sunny day.

4. Load adjustment strategy

4.1. Power load forecast

The method of deep learning can also be used to predict the short-term power load of a university campus. The load data of a university campus is used as the data source, and the data of the university campus before December 2017 is used as the training set to predict the load in 2018. We divide the data into three different seasons, namely winter, summer, and transition season. The corresponding days of each season are 92, 93 and 180, respectively. Use the deep learning toolkit in MATLAB to build the deep confidence network and model. The learning rate is 0.1, the adjustment factor is 0.05, the number of training times is 600, the number of hidden layer layers is 4, and the number of hidden layer nodes is 256. Through the analysis of the prediction results, the average absolute percentage error of power load prediction is 4.5%, which can meet the requirements of load adjustment.

4.2. Load adjustment

The power load of a university campus mainly includes two parts, adjustable load and fixed load. For lighting and some large experimental equipment (requiring 24-hour uninterrupted power supply), this kind of load cannot be adjusted and is a fixed load. Other loads are adjustable loads. The distinction of adjustable load shall be based on the actual situation of the school. Because of the low utilization rate of solar energy load during the 13:30–15:00 period, it is necessary to increase the adjustable load to this period as much as possible.

For this specific period, it is the normal class time for students, and the following adjustments should be made:

1. The experimental classes of some instruments and equipment with large power consumption can be adjusted to this time (it is necessary to coordinate with the Academic Affairs Office, the Experimental Center, and other departments to ensure normal teaching);
2. For each unit and part (especially some laboratories with large power demand), reasonably adjust the power consumption plan according to their actual power consumption and actual situation, and try to focus on the above time (it is necessary to coordinate with each unit and department with large power consumption to ensure their normal operation);
3. Implement comprehensive treatment of power quality for experimental buildings with prominent power quality problems, and install active power filter equipment in parallel in substation transformers for real-time control, to improve the quality of each building on campus.

4.3. Application result

In 2019, the above load adjustment strategies were applied on a university campus. The data of 2017 (without adjustment strategy) and 2019 (with load adjustment strategy) are selected for comparison, as shown in Table 1. It can be seen from the data in Table 1 that although the utilization rate of photovoltaic solar energy after the adjustment has not reached 100%, the overall utilization rate has been greatly improved. After energy consumption control, the utilization of photovoltaic power generation has been greatly improved. In many months, the utilization rate of photovoltaic power generation has exceeded 99%. Due to the curriculum of each academic year and other reasons, there are still some months that cannot fully absorb photovoltaic power generation, and further adjustments can be made in the future. Through control measures, the carbon emissions of school energy use have been effectively reduced, and the electricity expenditure has been reduced.

We can see from Table 1, the self-use rate of photovoltaic power generation in 2017 was 91.24%. After the load adjustment strategy was adopted, the self-use rate of photovoltaic power generation in 2019 increased to 98.16%. The campus's electricity savings in 2019 is 68 610 yuan:

$$\text{Cost}_{\text{saved}} = 4957340 \times (98.16\% - 91.24\%) \times (0.52 - 0.32) = 68609.59 \text{ yuan}.$$

4.4. Discussion

Loads of the university campus include adjustable loads and non-adjustable loads. For load adjustment, only the adjustable load can be adjusted. Although the load of some experimental equipment is adjustable, it is mainly affected by the progress of scientific research and teaching.

Table 1. PV power generation and campus load

	2017				2019			
	Load (kWh)	**Output (kWh)**	**Generation (kWh)**	**Ratio**	**Load (kWh)**	**Output (kWh)**	**Generation (kWh)**	**Ratio**
Jan	153 220	4 620	157 840	97.07%	244 640	0	244 640	100.00%
Feb	194 160	66 240	260 400	74.56%	224 720	1 280	226 000	99.43%
Mar	393 520	12 000	405 520	97.04%	237 280	480	237 760	99.80%
Apr	460 640	38 400	499 040	92.31%	340 560	0	340 560	100.00%
May	473 040	118 800	591 840	79.93%	490 640	31 840	522 480	93.91%
Jun	548 080	72 000	620 080	88.39%	706 480	0	706 480	100.00%
Jul	547 280	21 600	568 880	96.20%	529 680	50	529 730	99.99%
Aug	485 760	58 800	544 560	89.20%	615 680	500	616 180	99.92%
Sep	450 000	23 280	473 280	95.08%	477 280	0	477 280	100.00%
Oct	309 360	24 000	333 360	92.80%	401 600	32 060	433 660	92.61%
Nov	312 880	6 000	318 880	98.12%	340 080	25 050	365 130	93.14%
Dec	314 000	0	314 000	100.00%	257 440	0	257 440	100.00%
Sum	4 641 940	445 740	5 087 680	91.24%	4 866 080	91 260	4 957 340	98.16%

Therefore, excessive adjustment may have a negative impact on scientific research and teaching. The proportion of campus load adjustment is relatively limited. In addition, it can be seen from Table 1 that the extra electricity delivered to the grid in May, October and November is more than that in other months. In these months, the temperature is neither high nor low. There is no cooling load or heating load, and the overall load of the campus is less than the power generation of the photovoltaic system, so there is more electricity delivered to the grid.

5. Conclusions

Photovoltaic electricity prices on campus are generally cheaper than those from the power grid. Making full use of photovoltaic electricity on campus can save university electricity bills. To improve the utilization rate of solar photovoltaic power generation on the university campus, we used the method of deep belief network (DBN) to predict the solar photovoltaic power generation and the power load in the university campus, find out the gap and adjust the load. By adjusting the power load of the university campus, the utilization rate of solar photovoltaic power generation is improved, and the electricity cost of the school is saved. This method was applied to Changqing Campus of Qilu University of Technology in 2019. The utilization rate of solar power increased from 91.24% in 2017 to 98.16% in 2019. In 2019, the university saved 68 610 yuan in electricity costs.

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