REAL TIME PREDICTION METHOD OF ENERGY CONSUMPTION OF GEOTHERMAL SYSTEM IN PUBLIC BUILDINGS BASED ON WAVELET NEURAL NETWORK

by

Yongguang LI[a]* and Shaocui GUO[b]

[a] Office of Educational Administration, Yantai Vocational College, Yantai, China
[b] Open Education College, Yantai Vocational College, Yantai, China

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Real time prediction of energy consumption is the basis of energy conservation and emission reduction. Aiming at the problems of large prediction error and poor effect, a real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network is proposed. Firstly, the energy consumption of geothermal system in public buildings is analyzed, the wavelet neural network is designed, the neural network is optimized and solved by genetic algorithm, and the necessity of constructing the real-time prediction model of energy consumption based on wavelet neural network is established. Then it introduces the basic principle of model establishment, wavelet analysis, and shows the role of wavelet analysis in prediction model. Finally, based on the distribution structure of public buildings, this paper analyzes the energy consumption system of geothermal system, constructs the energy consumption prediction method, analyzes the overall temperature regulation energy consumption prediction principle of building geothermal system, and realizes the real-time prediction of energy consumption of geothermal system of public buildings. The experimental results show that the energy consumption real-time prediction results of the designed method are basically similar to the actual prediction values, and the prediction efficiency is high, which can effectively reduce the energy consumption of the geothermal system of public buildings.

Key words: *wavelet neural network, public buildings, geothermal system, real time prediction method of energy consumption*

Introduction

Energy plays an important role in the development of today's society and the progress of science and technology. It is the basic guarantee for the change of human renewal era [1, 2]. For any country, energy is the lifeblood resource to promote rapid economic development and social stability [3, 4], and plays a vital role in improving the quality of life and comprehensive national strength of people in all countries. Therefore, the absolute control of energy is the key to the rapid development of a country [5, 6]. In 2016, China's building energy consumption accounted for 20.62% of the country's total energy consumption, of which public building energy consumption accounted for 38.53% of the total building energy consumption. Therefore, the research on energy conservation in the construction field and related technologies has become the focus of scholars' attention.

* Corresponding author, e-mail: yongguangli1978@163.com

Wang *et al*. [7] proposed an improved building energy consumption prediction model based on model integration. The model combines the advantages of various basic prediction algorithms and forms *meta features* to ensure that the final model can observe the data set from different spatial and structural perspectives. Two examples are given to illustrate the practical engineering application of the superposition model. Ahmed *et al*. [8] proposes the physical and hybrid modelling technology of ground to air heat exchanger to reduce building energy consumption, which is the first study to comprehensively prove the prospects and technical challenges caused by unmeasured interference, assumptions or uncertainties in the experimental and numerical work of developing the modelling technology of earth to air heat exchanger. However, this study found that hybrid modelling is more effective than physical model in accurate prediction. On the contrary, if the operating conditions and all key parameters of EAHE are considered in the model development process, the complexity of the hybrid model is high. With regard to generalization ability, the physical model provides improved performance, followed by the hybrid model. Developing physical models requires a minimum amount of training data, while hybrid models require a medium amount of training data. The results of this study also provide scientists and researchers with valuable information about physical and hybrid EAHE modelling technology, so as to adopt the EAHE modelling technology most suitable for their climate. Based on the aforementioned research, a real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network is proposed.

Real time prediction model of energy consumption based on wavelet neural network

Wavelet neural network

According to the energy consumption analysis of the geothermal system of public buildings, a wavelet neural network energy consumption real-time prediction model is designed [9]. The model cannot only predict the real-time energy consumption in the operation state of the geothermal system of public buildings, but also predict the energy consumption of each process in the geothermal system of public buildings. Compared with the traditional prediction model based on material flow and energy flow, the energy consumption prediction has high accuracy and efficiency.

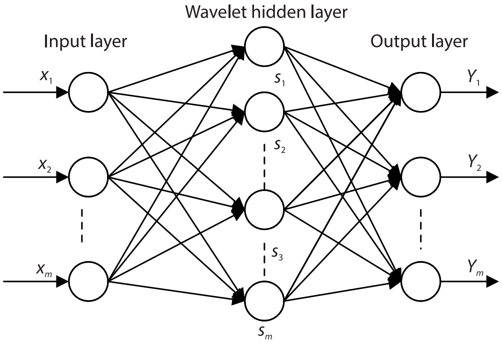

Figure 1. Wavelet neural network

The combination of traditional neural network and wavelet analysis makes up for the shortcomings of traditional neural network and improves the prediction accuracy. Figure 1 shows the structure of a typical wavelet neural network.

As can be seen from fig. 1, there are m training samples, S is the number of nodes in the input layer, X – the all sample sets of the input layer, and Y – the set of output prediction results. The definition of wavelet neural network can be described:

$$E_g^i = \sum_{ij=1}^{n} K_{ij} \left(\sum_{fh=1}^{p} K_{fh} x \right) \tag{1}$$

where E_g^i is the wavelet neural network is expressed as the output prediction value of the i neuron corresponding to the g input sample, n – the number of output layer nodes K_{ij} – the connection weight between the input layer node i and the hidden layer node j, and K_{fh} – the connection weight between the hidden layer node f and the output layer node h.

Compared with traditional neural network, the optimization point of wavelet neural network is to replace sigmoid function with tanmoid function, which avoids the problem that sigmoid function cannot find corresponding solutions or multiple corresponding solutions. In this prediction model, the propagation mode of wavelet neural network is forward propagation, so the solution of wavelet neural network energy consumption real-time prediction model is generally realized through the reverse derivation of error [10].

Firstly, determine the objective function of wavelet neural network, *i.e.*, mean square error (MSE):

$$\mathrm{MSE}=\frac{\sum_{g=1}^{g}\sum_{i=1}^{q}\left(E_g^i-L_g^i\right)^2}{2} \tag{2}$$

where q is the number of spatial dimensions and L^i_g – the actual value of output.

The prediction calculation of wavelet neural network is mainly to solve the uncertain parameter output layer weight, hidden layer weight, scaling factor and translation factor by gradient descent method [11]:

– Output layer weight

$$A=-\sum_{g=1}^{g}\left(L_g^i-E_g^i\right) \tag{3}$$

where A is the weight of the output layer.

– Hidden layer weight

$$B=\frac{-\sum_{g=1}^{g}\sum_{i=1}^{q}\left(L_g^i-E_g^i\right)k_{ij}}{a_j b_j} \tag{4}$$

where B is the weight of hidden layer, a_j – the expansion coefficient of hidden node j, and b_j – the translation coefficient of hidden node j.

– Expansion factor

$$C=\frac{-\sum_{g=1}^{g}\sum_{i=1}^{q}\left(L_g^i-E_g^i\right)k_{ij}}{a_j} \tag{5}$$

where C is the expansion factor.

– Translation factor

$$\alpha_{b_j}=\frac{-\sum_{g=1}^{g}\sum_{i=1}^{q}\left(L_g^i-E_g^i\right)k_{ij}}{b_j} \tag{6}$$

where D is the translation factor. According to the previous equation, the training process of wavelet neural network can be determined: the first step is to randomly select training samples, the second step is to adjust the learning rate, and the third step is to converge it by using MSE function. The prediction process of wavelet neural network energy consumption real-time prediction model is shown in fig. 2.

Wavelet neural network optimizes the shortcomings of traditional neural network, but in the actual prediction process, some hidden problems gradually emerge. For example, there is no

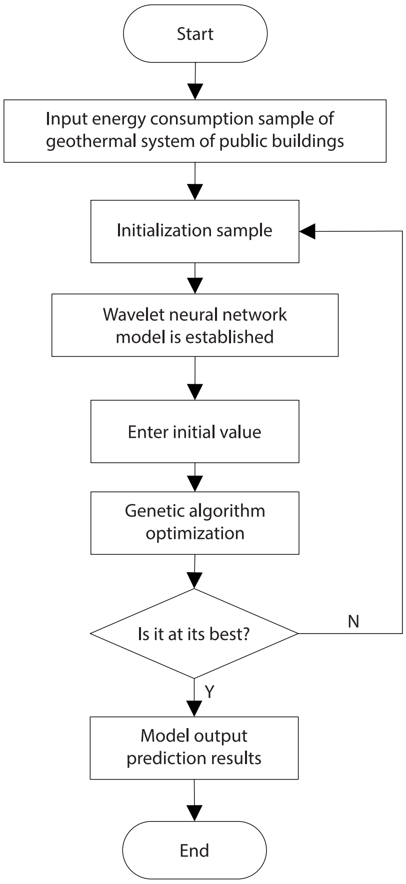

Figure 2. Prediction flow chart of wavelet neural network energy consumption real-time prediction model

scientific basis to guide people to choose which function is more suitable for the energy consumption prediction of specific public building geothermal system. The wavelet functions selected for the energy consumption prediction of different public building geothermal systems are different. Therefore, it is necessary to select the appropriate wavelet function according to the specific situation, that is, to obtain the optimal prediction result. Aiming at the energy consumption problem in the real-time prediction of energy consumption of geothermal system in public buildings, the wavelet neural network is optimized combined with genetic algorithm.

Genetic algorithm optimization and solution

Genetic algorithm is used to optimize the wavelet neural network. Its purpose is to select more accurate input value and threshold value, so as to make the output predicted value closer to the real value [12]. The optimal initial value of wavelet neural network is found through selection, crossover and mutation in genetic algorithm.

The biggest advantage of genetic algorithm is simple calculation, wide applicability and strong function. It has been widely used in various fields. Although all the operations of genetic algorithm in the real-time prediction of energy consumption of geothermal system of public buildings are not fixed, the search characteristics are not consistent, but the next generation optimal value can be predicted according to the existing information. Through continuous cyclic evolution, we will finally get an initial input value closest to the real situation, so as to get a predicted value closest to the real value of energy consumption. Genetic algorithm is used to optimize wavelet neural network, including initialization subgroup, chromosome coding, fitness calculation and genetic operation:

– Initialize subgroups

The diversity of subgroups affects the efficiency of real-time prediction of energy consumption of wavelet neural network. Therefore, the larger the subgroup base, the higher the prediction efficiency. But at the same time, the greater the amount of calculation. The initial subgroup is constructed. Firstly, the prediction operator is used to preliminarily predict the energy consumption of the geothermal system of public buildings, and then the obtained results are binarized. Finally, the binarized prediction results obtained previously are randomly sampled to obtain the initial subgroup, that is, multiple chromosomes, and each chromosome represents a prediction result.

– Chromosome code

Chromosome coding refers to coding the initial input value of wavelet neural network, and there are many coding methods, among which binary method and real number method are the most common. The real number method is encoded, that is, each chromosome has a corresponding edge configuration structure, and then it is represented by the 2-D Boolean matrix of *M*/*n*, so as to omit the decoding process of each chromosome, directly evaluate the cost value, and then calculate the fitness value.

In the process of chromosome coding, through the bit set class in C^{++} language, each chromosome in the subgroup is given a corresponding storage location, and eight storage bits form a byte, so as to reduce the occupation of storage space and improve the prediction efficiency of the model.

– Fitness calculation

Fitness can measure the viability of each chromosome in the subgroup. The higher the fitness of chromosome position, the stronger the viability. The wavelet neural network is trained according to the weight and threshold of each chromosome, and the fitness value of prediction error is selected for calculation:

$$T = z\left[\sum_{i=1}^{n}\left(E_i - O_i\right)\right] \tag{7}$$

where z is the coefficient, E_i – the expected output of the i neuron, and O_i – the predicted output of the i neuron.

– Genetic operation

Selection operation: the basic principle of genetic algorithm is the survival of the fittest and the survival of the fittest. Therefore, it is necessary to select individuals with high fitness value from existing subgroups according to certain standards to complete crossover and mutation operations. The better the individual fitness value, the greater the probability of being selected. The probability of the i individual being selected:

$$R_i = \frac{T_i}{\sum_{i=1}^{n} T_i} \tag{8}$$

where R_i is the probability that the i^{th} individual is selected, and T_i – the usage value of the i individual.

Cross operation: select two individuals from the subgroup, and then change the chromosomes of the two individuals, that is, select any position for cross exchange, and finally produce a new excellent individual. The cross operation is shown in fig. 3.

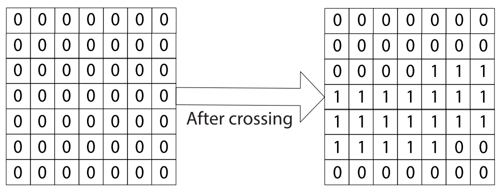

Figure 3. Cross operation diagram

Mutation operation: randomly select an individual from the subgroup, and then randomly mutate a point in its chromosome to obtain a better individual. The j chromosome of individual i was mutated:

$$M_{ij} = \begin{cases} W_{ij} + \left(W_{ij} - W_{max}\right) \times s(\theta) \\ W_{ij} + \left(W_{\min} - W_{ij}\right) \times s(\theta) \end{cases} \tag{9}$$

where W_{ij} is the variation value of j chromosome of i individual, $W_{\max}$ – the upper bound of chromosome W_{ij}, $W_{\min}$ – the lower bound of chromosome W_{ij}, and $s(\theta)$ – the random number.

The flow of BP neural network optimized by genetic algorithm is shown in fig. 4.

As can be seen from fig. 4, first input the model sample, then initialize it, and construct the initialization subgroup [13]. After initialization, chromosome coding is performed

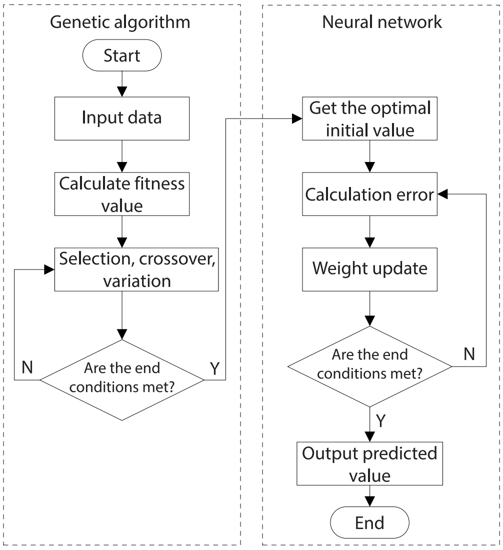

Figure 4. Genetic algorithm optimization BP neural network process

for each individual in the subgroup, and then the fitness value is calculated. Finally, genetic operation is carried out, and genetic operation includes three operations: selection, crossover, and mutation. After the aforementioned operations, determine whether the input value is the optimal input value. If yes, wavelet neural network is used for function prediction. If not, perform genetic operation on the input value again until the condition is met. When the conditions are met, the prediction process of wavelet neural network: first, input the optimal initial value in wavelet neural network, then calculate the error and update the weight at the same time, and finally determine whether the result meets the end conditions. If so, the result is the optimal prediction result, otherwise it will return to the error link until the conditions are met.

Realize real-time prediction of energy consumption of geothermal system in public buildings

Analysis of energy consumption system of geothermal system in public buildings

Firstly, the energy consumption system is analyzed according to the power consumption of public buildings. Generally speaking, the energy consumption of geothermal system of public buildings is related to the building distribution of the park. Therefore, firstly, the 3-D building structure model corresponding to geothermal system of public buildings is constructed. Under the corresponding structure, the number of rooms in public buildings, the number of air conditioners, the number of corridors, the number of rows, the room area and other parameter indicators are analyzed to obtain the energy consumption system of the geothermal system of public buildings, as shown in fig. 5.

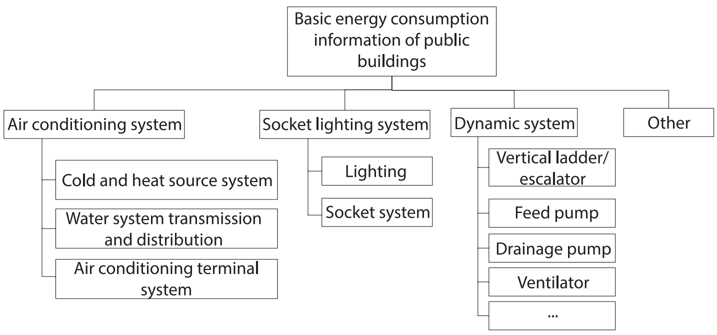

Figure 5. Block diagram of energy consumption system of public buildings

As can be seen from fig. 5, the basic energy consumption units of public buildings include air conditioning, lighting, production power and other aspects. When using wavelet neural network to search historical energy consumption data, it can be carried out according to the category of public building energy consumption system to ensure the integrity of search data results.

Prediction principle of overall temperature regulation energy consumption of geothermal system in public buildings

In the process of predicting the overall temperature regulation energy consumption of public buildings, give the input time series samples of monthly energy consumption data of buildings, predict the monthly energy consumption of buildings, give the periodic oscillation index of monthly energy consumption, obtain the distance between all monthly temperature regulation energy consumption prediction samples and the clustering center, and calculate the overall energy consumption variable set of public buildings, Thus, the overall temperature regulation energy consumption prediction of public buildings is realized. The specific steps are detailed.

Assuming that E_s represents the characteristic parameters of public buildings, r_d represents the minimum value of original data, A_d represents the maximum value of original data, and s_d represents the energy consumption data of original buildings, the input time series sample of monthly energy consumption data of public buildings is given [14]:

$$A_d = \frac{E_s \times A_a}{r_d \times s_d} + F_{dr} \times d_{kp} \tag{10}$$

where F'_{wsdr} is the indoor characteristic quantity and d''_{zxkp} – the energy consumption parameters of geothermal system.

Assuming that ε_{er} represents indoor environmental parameters, ε_{er} represents air conditioning operation mode, and m_{hj} represents energy consumption modelling sample data, the monthly energy consumption of buildings is predicted:

$$A_s = \frac{m_{hj} + \varepsilon_{er}}{\sigma_{po}} + d_{kp} + \mu_{kp} \tag{11}$$

where d_{kp} is the principal variable in the monthly energy consumption characteristic space of buildings and μ_{kp} – the meteorological factor.

Assuming that p_{ko} is the output vector of the whole neural network and s_{fh} represents the original cumulative sequence weight of building monthly energy consumption, the overall temperature regulation energy consumption prediction of public buildings is realized:

$$\eta_{sf} = \frac{A_d \times A_s}{p_{ko} \times s_{fh}} \tag{12}$$

To sum up, it is the principle of energy consumption prediction in the process of overall temperature regulation of public buildings, which is used to predict the energy consumption of overall temperature regulation of public buildings.

Realize real-time prediction of energy consumption of geothermal system in public buildings

The energy consumption prediction of geothermal system of public buildings is to design the corresponding energy consumption model based on the existing historical data [15], and on this basis, accurately evaluate the possible energy consumption in the future. In this process, the establishment of the corresponding model needs to follow the following principles, including the principle of continuity, the principle of analogy Correlation principle, probability inference principle and feedback principle. Follow the construction principles and prediction principles of

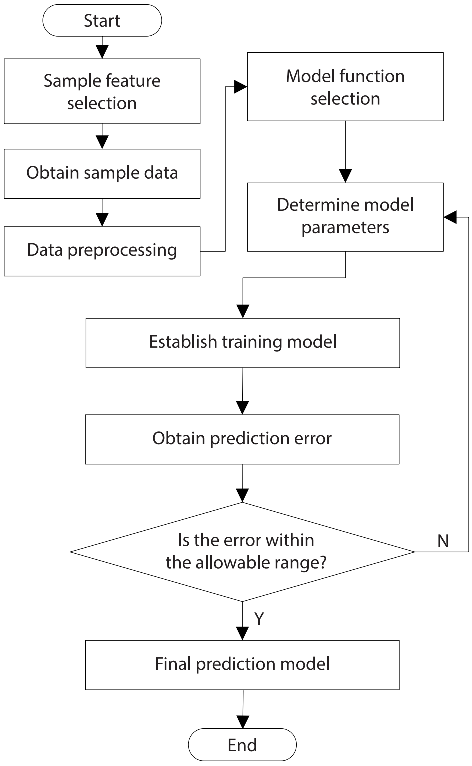

Figure 6. Flow chart of real-time prediction of energy consumption

the aforementioned model to realize the real-time prediction of energy consumption of geothermal system of public buildings, as shown in fig. 6.

In order to improve the real-time prediction performance, the wavelet neural network is introduced. The function of the network is to search and study the historical energy consumption data of the geothermal system of public buildings, and provide data support for the real-time prediction of the energy consumption of the geothermal system of public buildings at present and in the future, so as to complete the research on the real-time prediction method of the energy consumption of the geothermal system of public buildings based on the wavelet neural network.

Figure 7. Outline structure diagram of public building

Experimental results and analysis

In order to better verify the effect and feasibility of the real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network, experimental analysis is carried out. The data used for construction comes from a public building in a certain place, and its shape is shown in fig. 7.

The main building of the public building has 6 floors above the ground and 1 floor underground, with a total building area of 987 m^2, an above ground building area of 873 m^2 and an external window size of 2.5 m × 2.0 m. The experimental parameters are described in tab. 1.

Table 1. Experimental parameter setting

Experimental parameter name	Parameter setting
Solar radiation	0.346
Outdoor humidity	6.72
Operation mode of air conditioning system	4.33
Indoor humidity	5.32
Fresh air index per capita	6.30
Heat transfer coefficient of inner wall	1.53

The experimental environment is WINDOWS8 operating system with 256G memory. The goodness of fit between the actual temperature regulation energy consumption and the predicted temperature regulation energy consumption is used as the evaluation index to test the prediction accuracy of the proposed real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network.

It is assumed that Y is the prediction sequence of overall building temperature regulation energy consumption, $Y(x_i)$ – the x_i predicted value, and $Y(y_j)$ – the y_i actual value. The goodness of fit is given:

$$R = \frac{Y(x_i)\times Y(y_j)}{n}\times 100\% \tag{13}$$

where n is the dependence between the actual predicted value and the predicted value. From eq. (13), it can be seen that the higher the R value, the higher the goodness of fit. According to eq. (13), calculate the goodness of fit result, as shown in fig. 8.

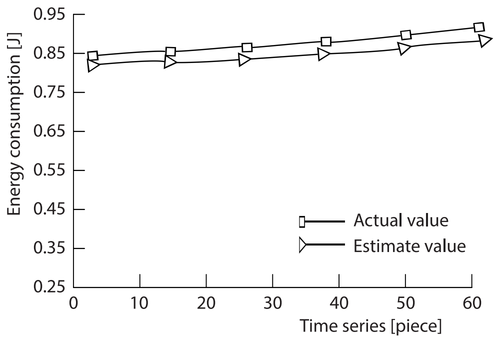

Figure 8. Goodness of fit experiment of the proposed method

According to the analysis of fig. 8, the proposed real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network can effectively calculate the correlation between building temperature regulation energy consumption data when predicting temperature regulation energy consumption. The results of real-time prediction of energy consumption are basically similar to the actual predicted values, which can be fully explained. When the proposed method is used to predict the overall temperature regulation energy consumption of public buildings, the prediction accuracy is high.

The calculation equation of real-time prediction efficiency [%]:

$$\theta = \frac{P(U_U)\times P(Y_Y)\times C_K}{Q_{BA}}\times 100\% \tag{14}$$

where $P(U_U)$ is the prediction function, $P(Y_Y)$ – the corresponding weight value, C_K – the deviation, and Q_{BA} – the effect between the actual predicted value and the predicted value. The prediction efficiency is calculated according to eq. (14). The comparison results of real-time prediction efficiency of energy consumption of geothermal system of public buildings under different methods are shown in tab. 2.

Table 2. Comparison results of prediction efficiency of different methods

Number of predicted data points [ten thousand]	Method prediction efficiency [%], [7]	Method prediction efficiency [%], [8]	Paper method prediction efficiency [%]
100	86.3	87.1	91.8
200	85.5	82.6	87.2
300	74.6	79.5	86.7
400	70.3	72.1	77.4
500	69.4	70.6	81.3

According to the analysis of tab. 2, comparing the methods of [7, 8], the real-time prediction efficiency of energy consumption of geothermal system of public buildings under this method is high. Because this method uses genetic algorithm to optimize the wavelet neural network, so that the output prediction value is closer to the real value, which is conducive to improve the prediction efficiency to a certain extent.

In order to further verify the feasibility of the prediction method in this paper, the application performance is compared with the methods in [7, 8]. Based on the prediction results, observe whether there are abnormal conditions, and use the same control method to control the energy consumption, so as to achieve the purpose of energy conservation. Through the application of the three methods, the actual energy consumption of the geothermal system of public buildings can be obtained, as shown in tab. 3.

Table 3. Application performance comparison results

Energy consumption period of geothermal system in public buildings	This method [kW per hour]	Method in [7] [kW per hour]	Method in [8] [kW per hour]
January	684	764	863
February	632	952	995
March	622	948	924
April	704	856	895
May	718	848	824
June	678	967	931
July	646	927	956
August	721	985	985
September	695	952	972
October	681	967	996
November	724	1052	1004
December	731	1072	1021
Total	8236	11290	11366

It can be seen from tab. 3 that after calculating the prediction data of the three methods, the actual energy consumption of the geothermal system of public buildings is 3054 kW per hour different from that of the prediction method in [7]. Compared with the real-time prediction method of energy consumption of the geothermal system of public buildings based on wavelet neural network, the total energy consumption of the real-time prediction method of energy consumption of public buildings in this paper is reduced by 27.1%, which proves that the application energy-saving performance of the designed real-time prediction method is improved by 27.1%. Compared with the prediction method in [8], the actual energy consumption of geothermal system in public buildings is 3130 kW per hour, and the application energy-saving performance of this method is improved by 27.5%. From the statistical data of electric energy consumption in the geothermal system of public buildings, it can be seen that the application of the designed real-time prediction method of energy consumption of the geothermal system of public buildings can effectively reduce the energy consumption of the geothermal system of public buildings. The reason is that this method carries out the prediction of lighting energy consumption, air conditioning energy consumption and power energy consumption during the experiment, to a certain extent, it is conducive to the accuracy of real-time prediction of energy consumption of geothermal system in public buildings and realize the scientific of energy consumption prediction.

Conclusions

- The real-time prediction method of energy consumption of geothermal system of public buildings based on wavelet neural network can effectively calculate the correlation between building temperature regulation energy consumption data, and the results of real-time prediction of energy consumption are basically similar to the actual predicted values.
- The real-time prediction efficiency of energy consumption of geothermal system in public buildings under the design method is high.
- Through the application of the designed real-time prediction method of energy consumption of geothermal system in public buildings, the energy consumption of geothermal system in public buildings can be effectively reduced.

Prospects

During the research period, due to the limitations of research time and personal level, there are still many problems to be solved in this paper. The contents that can be studied in the future are as follows.

- The follow-up research can further explore the real-time prediction data of energy consumption of public buildings, and pay attention the relationship between internal logic, meteorological factors and public building types.
- In the follow-up research, the prediction accuracy can be further improved by enriching the types of sub models of the combined model and screening more relevant variables, so as to better provide basis for management decision-making.
- Considering that the factors affecting the change of energy consumption are not comprehensive enough, other influencing factors can be further analyzed, such as room opening information of public buildings (including the number of open rooms, opening time*, etc.*), equipment start and stop cycle*, etc.*, which can be deeply studied in the future.

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