International Journal of Mechatronics and Applied Mechanics
2026, Issue 24, Vol. I

ENERGY-SAVING RECONSTRUCTION SCHEME OF BUILDINGS BASED ON ENERGY CONSUMPTION DATA

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Abstract - The energy consumption level of urban public buildings is increasing continuously in the operation stage, and building energy-saving management has become an integral part of the energy management system. Twenty public buildings were selected as samples, and hourly energy consumption data, meteorological data and building operation information from 2021 to 2023 were collected, and the characteristics of building energy consumption were systematically analyzed. A multiple linear regression model is constructed to quantitatively describe the relationship between building area, outdoor temperature, air humidity and building energy consumption, and an energy-saving renovation scheme is designed based on the model analysis results. The transformation measures include the replacement of high-efficiency water chillers, the renewal of LED lighting system and the optimization of external wall insulation structure. The experimental results show that the annual energy consumption per unit area of the sample building is reduced from 153 kWh/m year to 127 kWh/m year, with an average reduction of 26 kWh/m year, and the energy saving rate is maintained in the range of 16%-19%. The results of economic analysis show that the electricity saving of buildings is about 31,000-61,000 kWh/year, and the investment recovery period is about 4-5 years. The research results show that the energy consumption data analysis method provides quantitative basis for building energy-saving renovation scheme and technical reference for energy management of public buildings.

Keywords: Building energy saving; Energy consumption data; Energy consumption forecasting model; Energy-saving transformation.

1. Introduction

The construction sector has long occupied an important proportion of urban energy consumption. Statistics released by the National Energy Administration and the International Energy Agency show (as shown in Figure 1) that the energy consumption of urban buildings in the operation stage accounts for about 35%-40% of the total terminal energy consumption, of which public buildings account for about 22%. Office buildings, commercial complexes and medical buildings occupy a major position in the annual energy consumption structure. The energy consumption of building operation mainly comes from air conditioning system, lighting system, elevator equipment and hot water system. Taking a typical office building as an example, the cooling load in summer accounts for 42%-48% of the annual energy consumption, the lighting system accounts for about 18%-22%, and the office equipment accounts for about 12%-16%. Building energy-saving transformation has become an important topic of urban energy management. The number of existing buildings is increasing, and some buildings are not included in the high-efficiency and energy-saving standards in the design stage, so the energy utilization efficiency is low. Traditional energy-saving management methods rely on empirical judgment, and the utilization of energy consumption data is low. The building energy management system continuously accumulates operation data, which records the building operation state, meteorological conditions and equipment load changes. After the data analysis method entered the research field of building energy efficiency, building energy consumption evaluation and energy-saving strategy formulation entered the quantitative analysis stage. There is a stable relationship between energy consumption data and building operation characteristics. The results of data model analysis can reveal the waste of building energy and provide a basis for energy-saving transformation. If the

dx.doi.org/10.17683/ijomam/issue24.25

building energy-saving renovation scheme is based on the analysis of historical operation data, the evaluation of renovation effect is more quantifiable and the prediction of energy-saving benefits is more reliable. Research on building energy consumption data has become the research direction of building energy-saving technology.

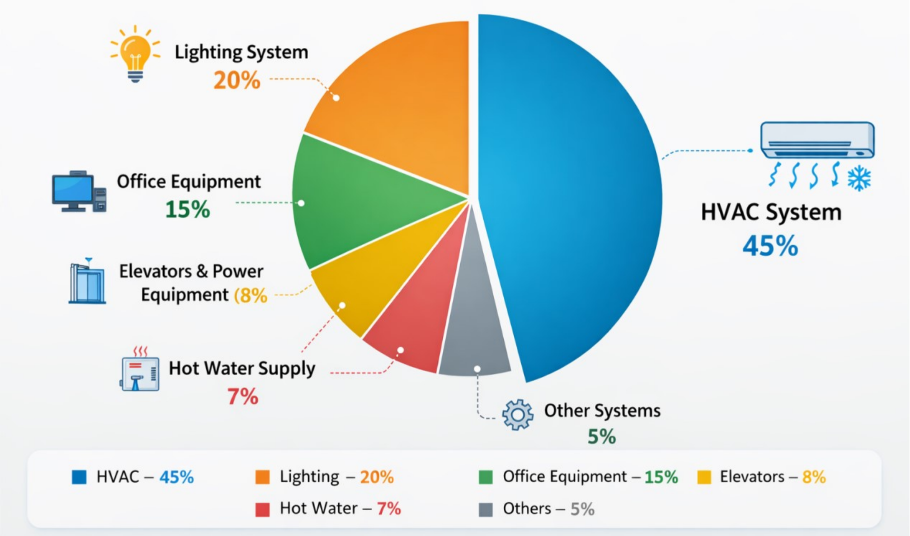

Figure 1: Schematic diagram of energy consumption structure of urban buildings

The research on building energy efficiency has shifted from single technology optimization to data-driven and systematic design. Shi et al. (2025) constructed the life cycle system dynamics model of prefabricated building envelope, and analyzed the changing rules of energy consumption and carbon emission of energy-saving design schemes, and concluded that the envelope design scheme has a continuous impact on the energy consumption level of the whole life cycle of the building [1]. Aziz et al. (2025) compared the application effects of ECBC-2023 and IECC-2021 in residential buildings in different climatic zones, and pointed out that differences in climatic conditions will change the control ability of building energy efficiency standards on energy consumption [2]. Cao (2025) proposed an energy-saving design method for residential buildings based on particle swarm optimization algorithm, and optimized the energy-saving parameters of buildings in cold and hot climates. It was considered that the optimization algorithm could obtain a lower energy consumption scheme in the energy-saving design stage of buildings [3]. Liao (2025) used BIM technology to establish a monitoring method for building energy consumption with near zero energy consumption, and the research pointed out that the combination of building information model and energy consumption data can realize energy consumption monitoring in operation stage [4].

In the aspect of energy consumption analysis of building operation, Sinakovics et al. (2024) made a statistical analysis on the data of heating energy consumption of school buildings, and it was concluded that the thermal performance of building envelope and the efficiency of heating system have obvious influence on winter energy consumption [5]. Li (2024) put forward the design method of green energy-saving transformation based on the monitoring data of building energy consumption, and pointed out that building operation data can provide decision-making basis for energy-saving transformation scheme [6]. Sharma et al. (2024) took an educational building in India as a case to carry out energy-saving renovation research, and the energy consumption level of the building decreased obviously after the air conditioning system and lighting system were updated [7]. Cao et al. (2024) put forward a laboratory energy consumption control model based on deep reinforcement learning, and the research pointed out that the intelligent control model has high adjustment ability in energy dispatching management [8]. Zhu et al. (2024) established a forecasting model of energy consumption and combined with various quantitative characteristics analysis, and it is considered that the multivariate forecasting model can describe the changing trend of energy consumption [9]. Data-driven method has become the research direction of building energy consumption. Cao et al. (2023) put forward a short-term energy consumption prediction model for educational buildings, and the research pointed out that the model integration method can improve the accuracy of energy consumption prediction [10]. Deng et al. (2023) evaluated the effect of energy-saving renovation project of rural buildings in Beijing, and thought that large-scale energy-saving renovation had a role in reducing building energy consumption [11]. Liu et al. (2023) systematically summarized the data-driven building energy consumption forecasting methods, and pointed out that machine learning model has formed a relatively mature research system in the field of building energy consumption forecasting [12].

The research focuses on building energy consumption data, and the research object is 20 public buildings in a city. Building types cover office buildings, commercial complexes, medical buildings and teaching buildings. The research contents include building energy data collection, data preprocessing, energy consumption prediction model construction and energy-saving transformation scheme evaluation. The research content includes four aspects. The first part is the data collation and data quality processing of building energy. The data sources include building energy monitoring system, property energy management system and meteorological database. The data processing process involves abnormal data identification, missing data processing and data standardization. The second part is the construction of building energy consumption prediction model, and the multiple linear regression model is used to analyze the influence of building area, meteorological temperature and humidity on building energy consumption. The third part is the evaluation of building energy efficiency, and the energy consumption index per unit area is used to measure the level of building energy utilization. The fourth part is the evaluation of energy-saving transformation effect, and the energy-saving rate index is used to evaluate the economic and energy benefits of energy-saving transformation measures. Quantitative analysis of the relationship between building operation data and building energy consumption, and identification of high energy consumption links. The energy-saving renovation scheme of buildings is based on data analysis, and the renovation measures are consistent with the operation characteristics of buildings. The evaluation of energy-saving renovation scheme is analyzed by quantitative indicators, and the energy-saving benefits and renovation costs form a comparable index system.

The research process revolves around building energy consumption data. The research sample comes from the energy consumption monitoring system of urban public buildings. In the data processing stage, data cleaning and data standardization are completed, and the data quality meets the requirements of model analysis. The prediction model of building energy consumption is used to analyze the influence of building area, meteorological temperature and humidity on building energy consumption. Energy efficiency evaluation adopts energy consumption index per unit area. The evaluation of energy-saving transformation potential combines building operation data and energy-saving rate index. The design of energy-saving transformation scheme is based on the results of model analysis. The research technical route (as shown in Figure 2) covers five stages: data collection, data processing, model construction, energy saving evaluation and scheme design. The research process begins with building energy data collection, and then enters the model analysis stage after data cleaning and data processing. The model results evaluate the potential of energy-saving transformation, and finally form a building energy-saving transformation scheme.

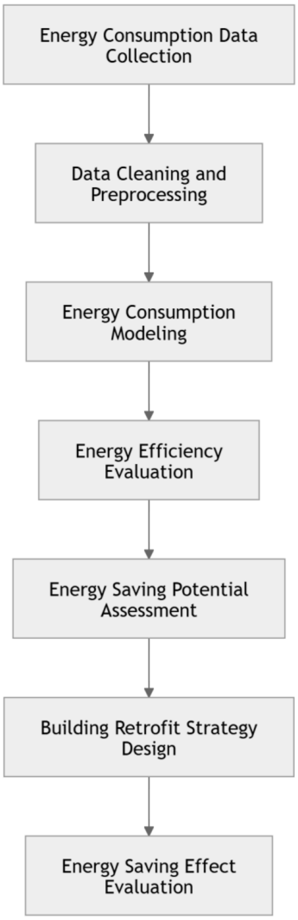

Figure 2: Research technical route

2. Materials and Methods

2.1 Data collection and Sample Selection

2.1.1 Data Sources and Collection Methods

The research data sources cover the energy monitoring records and meteorological environment data in the building operation stage. The sample buildings are all connected to the energy consumption monitoring platform of urban public buildings, and the platform records the hourly power consumption data of buildings, the operating power of air conditioning systems and the load information of lighting systems. The monitoring time span is from January 2021 to December 2023, and the recording frequency is 1 hour/time. Each building has accumulated about 26,280 energy consumption records. Building operation data comes from property energy management system and building automation system. The property system records the electricity consumption data of elevators, lighting and office equipment; Building automation system records the power of air conditioning unit, chilled water flow and backwater temperature. Meteorological data comes from the public database of National Meteorological Information Center, which includes outdoor temperature, relative humidity and solar radiation intensity. The temperature data range is 8℃-38℃, and the humidity data range is 22%-95%. The time resolution of meteorological data is 1 hour, and the timestamp is consistent with the building energy consumption record. Building energy data collection is completed to form a unified database. The database contains building number, building area, building type, hourly energy consumption data and corresponding meteorological variables. This database forms the data base for the subsequent model analysis, as shown in Table 1.

Table 1. Data sources of building energy consumption

Data source	Data content	Time range	Recording frequency	Data scale
Building Energy Monitoring Platform	Total electricity consumption	2021–2023	1 hour	525600 records
Property Energy Management System	Lighting and equipment load	2021–2023	1 hour	350400 records
Building Automation System	HVAC operation power	2021–2023	1 hour	420000 records
National Meteorological Database	Temperature and humidity	2021–2023	1 hour	26280 records

2.1.2 Sample Selection and Description

The research sample comes from the public buildings in a coastal city. Building screening criteria: the building has been in operation for more than 5 years; The construction area is more than 10000 m; The building operation system has a complete energy consumption monitoring record. There are 20 eligible buildings. Sample building types: office building, commercial complex, medical building and university teaching building. The building area ranges from 11,000m to 28,000m. The average annual energy consumption of buildings ranges from 145,000 kWh to 312,000 kWh. The average energy consumption per unit area of office buildings is 115 kWh/m year; The average energy consumption per unit area of commercial buildings is 165 kWh/m year; The medical building is about 180 kWh/m year [13]. Building energy consumption data and building type distribution form a relatively complete research sample structure, and the difference of building energy utilization can be reflected in the data analysis stage, as shown in Table 2.

Table 2. Basic information of building samples

Building ID	Building Type	Floor Area (m^2)	Construction Year	Annual Energy Use (kWh)
B01	Office Building	12500	2015	182000
B02	Commercial Complex	24800	2018	296000
B03	Teaching Building	16800	2014	205000
B04	Hospital Building	19500	2016	251000
B05	Hotel Building	22300	2017	278000

2.1.3 Data Preprocessing

There are dimensional differences in building energy data among different buildings. The data scales of building area, meteorological temperature and energy consumption are quite different. In the data preprocessing stage, the variable scale is unified by standardization method [14].

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{1}$$

The meanings of the variables in Formula (1) are as follows: x represents the original data value, such as building energy consumption or outdoor temperature at a certain moment, X' represents the standardized data value, with the range of 0-1, X_{min} represents the minimum value in the data sample, and X_{max} represents the maximum value in the data sample. This processing method converts all variables into the range of 0-1. Building area, temperature, humidity and energy consumption data enter the model analysis stage under the unified scale [15].

2.1.4 Data Cleaning

There are a lot of hourly records in the building energy database. A small number of abnormal records are generated during the operation of the monitoring system, as shown in Figure 3, such as the 0 kWh energy consumption value in the equipment shutdown state and the abnormally high value in the equipment failure state. In the data cleaning stage, abnormal data are identified and processed. The anomaly identification rules are set according to the statistical range of energy consumption. The normal range of hourly energy consumption of office buildings is 45 kWh—420 kWh；; The hourly energy consumption of commercial buildings ranges from 60 kWh to 580 kWh [16]. Data records below the lower limit or above the upper limit are marked as abnormal records. Abnormal data accounts for about 2.7% of all data. Missing data processing adopts time series interpolation method. If the continuous missing time is less than 3 hours, the average value of adjacent time points is used to fill in; If the missing time exceeds 3 hours, the data of this time period will be excluded from the sample set. After data cleaning, a complete analysis data set is formed.

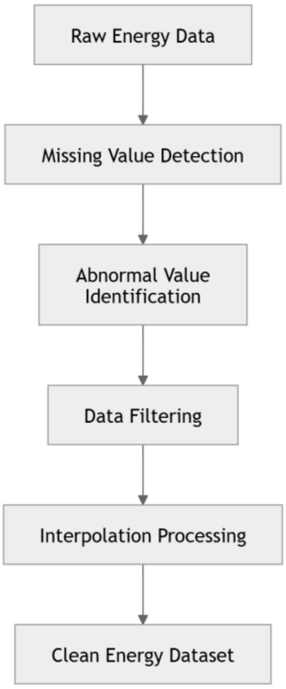

Figure 3: Data cleaning flow chart

2.2 Model Selection and Construction

2.2.1 Building Energy Consumption Prediction Model

The energy consumption of building operation is affected by factors such as building scale, meteorological conditions and operating load. The analysis of sample data shows that outdoor temperature, building area and humidity are related to the operating power of air conditioning system. Describe the quantitative relationship between variables, study and establish a multiple linear regression model, and predict the energy consumption in the building operation stage. The model takes hourly power consumption of buildings as dependent variables, and building area, outdoor temperature and air humidity as explanatory variables.

$$E = \beta_0 + \beta_1 A + \beta_2 T + \beta_3 H + \varepsilon \tag{2}$$

The meanings of the variables in formula (2) are as follows: e represents the energy consumption per unit time of the building, in kWh/h, a represents the total building area, in m, t represents the outdoor air temperature, in℃, the research data range is 8℃-38℃, h represents the air relative humidity, in%, the sample range is 22%-95%, β_0 represents the regression constant term, β_1, β_2, β_3. In the model construction stage, the hourly energy consumption data of sample buildings are used for regression calculation [17]. Building area reflects the difference of building scale, temperature variable reflects the change of air conditioning load, and humidity variable reflects the change of air heat load [18]. When the outdoor temperature rises from 26℃ to 32℃, the power of air conditioning system in office buildings increases by about 18%-23% on average. The model can be used to estimate the changing trend of building energy consumption under different meteorological conditions, and can also provide energy consumption reference values for energy-saving renovation schemes.

2.2.2 Energy Efficiency Evaluation Model

The evaluation of building energy consumption usually adopts the energy consumption index per unit area. Reflecting the efficiency of building energy utilization can eliminate the impact of building scale differences. The annual energy consumption of office buildings ranges from 150,000 kWh to 210,000 kWh, and the building area ranges from 12,000 m to 18,000 m [19]. If only the total energy consumption data is used, the large-scale buildings are easily misjudged as high-energy buildings. The energy consumption index per unit area can provide a more objective basis for energy efficiency evaluation. The energy consumption intensity is calculated as Formula (3).

$$EUI = \frac{E}{A} \tag{3}$$

The meanings of the variables are as follows: EUI stands for building energy consumption intensity index in kWh/m year, E stands for total annual energy consumption of buildings in kWh, and A stands for total building area in M. The calculation results of research samples show that the average EUI of office buildings is about 115 kWh/m year, that of commercial buildings is about 165 kWh/m year, and that of medical buildings is about 178 kWh/m year. The energy efficiency standard for public buildings stipulates that the reference value of energy consumption for office buildings is about 120 kWh/m year. When the building EUI is higher than this standard, the building operation efficiency is at a low level. This index reflects the change of building operation efficiency. After the implementation of energy-saving transformation, the annual energy consumption of buildings will decrease while the building area will remain unchanged, and the EUI value will decrease simultaneously. The change of index can be used to evaluate the influence of energy-saving measures on building operation efficiency.

2.2.3 Energy-saving Transformation Potential Evaluation Model

The potential evaluation of energy-saving transformation needs to quantify the energy consumption difference before and after transformation. Building energy-saving measures include the replacement of high-efficiency air conditioning units, the update of LED lighting system and the upgrade of external wall insulation layer. The difference of energy consumption before and after the implementation of the transformation can reflect the actual effect of energy-saving measures [20]. The energy-saving rate index describes the proportion of energy consumption change brought about by energy-saving transformation. Energy saving rate calculation Formula (4):

$$R = \frac{E_{before} - E_{after}}{E_{before}} \times 100\% \tag{4}$$

The meaning of the variable in formula (4) is as follows: R represents the energy saving rate in%, E_{before} represents the energy consumption before the building renovation in kWh, E_{after} represents the annual energy consumption after the building renovation in kWh. Statistics of research samples show that the average energy consumption of office buildings before energy-saving renovation is about 182000 kWh/year, and after the air conditioning system upgrade and lighting system replacement are completed, the annual energy consumption drops to about 150000 kWh/year. The energy saving rate is about 17%-19%. The energy-saving transformation potential of commercial complexes is higher [21]. The air conditioning system of large commercial buildings runs for a long time, and the energy consumption accounts for about 48%-52% of the total energy consumption. After the replacement of high-efficiency inverter air conditioning units, the building energy consumption decreased by 18%-22%. The energy-saving rate index reflects the direct effect of energy-saving transformation measures. The energy-saving potential of different building types is different, and the model provides quantitative basis for the evaluation of energy-saving schemes.

2.2.4 Comprehensive Evaluation Model of Energy-saving Transformation

Building energy-saving transformation involves energy saving, economic cost and equipment operation stability. A single energy-saving rate index is difficult to reflect the transformation effect [22]. The comprehensive evaluation model introduces economic indicators and equipment operation indicators on the basis of energy saving rate, and constructs a multi-index evaluation system. The comprehensive evaluation model is shown in Formula (5).

$$S = \sum_{i=1}^{n} w_i x_i \tag{5}$$

The meanings of the variables are as follows: s represents the comprehensive score of building energy-saving renovation, w_i represents the weight of the i evaluation index, x_i represents the score value of the $S = \sum_{i=1}^{n} w_i x_i$ index, and n represents the number of evaluation indexes. The research model includes three evaluation indexes: energy saving rate, payback period of renovation investment and stability of equipment operation. The index weights are set as follows: energy saving rate weight 0.5, investment payback period weight 0.3, and equipment stability weight 0.2. The scoring rules of indicators are as follows: if the energy saving rate is above 20%, score 90 points; 15%-20% score 80 points; 10%-15% scored 70 points. If the payback period of investment is less than 5 years, the score is 85 points, and the payback period of 5-7 years is 75 points. The equipment stability index is evaluated according to the equipment failure rate. If the annual failure rate is less than 3%, score 90 points. The comprehensive scoring results are used to evaluate the overall effect of different energy-saving transformation schemes [23]. The scheme with high score shows that the energy saving effect and economic benefits keep a good balance, reflecting the stable level of building operation. The model provides quantitative basis for the selection of energy-saving transformation schemes.

2.3 Model Evaluation and Verification

2.3.1 Model Accuracy Evaluation

The model accuracy evaluation tests the closeness between the predicted results and the real energy consumption data. The research data includes hourly energy consumption records of 20 public buildings, with a total of more than 520,000 observations. The sample data is divided into training data and verification data according to the ratio of 8:2. The training set contains about 420,000 records and the verification set contains about 105,000 records. This division ensures that model training and prediction test are carried out on different data sets. The prediction accuracy is evaluated by mean absolute error (MAE) and root mean square error (RMSE). The average absolute error reflects the average deviation between the predicted value and the real value. The root mean square error is used to describe the error fluctuation. The calculation results show that the average absolute error of office building prediction is about 9.8 kWh/h, commercial building is about 12.6 kWh/h, and medical building is about 14.2 kWh/h.

The statistical results of root mean square error show a similar trend. RMSE of office building is 13.4 kWh/h, that of commercial building is 16.7 kWh/h, and that of medical building is 18.5kwh/h. The error range is consistent with the scale of building energy consumption. The average hourly energy consumption of office buildings is about 120 kWh/h, and that of commercial buildings is about 170 kWh/h. The error accounts for about 7%-11%. The fitting degree between the predicted results and the real data is further evaluated by the determination coefficient. The value of the determination coefficient r is about 0.86. The results show that the model has a good ability to explain the changing trend of building energy consumption. The influence of building area and meteorological variables on energy consumption changes is accurately reflected in the model.

2.3.2 Model Error Analysis

Prediction error analysis is used to observe the change law of model error in different time and different building types. After comparing the predicted results of hourly energy consumption with the actual records, it is found that the error distribution presents obvious time characteristics. The error is relatively large in summer when the air conditioning load is high, and it is small in winter. The statistical results of sample data show that when the outdoor temperature is in the range of 30°C-35°C, the average hourly energy consumption of office buildings is about 165 kWh/h, and the average prediction error is about 15 kWh/h. When the temperature is between 10°C and 18°C, the average hourly energy consumption is about 95 kWh/h, and the error is about 7 kWh/h. This phenomenon fluctuates greatly in the operation of air conditioning system in high temperature environment. There are obvious differences in errors between different building types. The internal load of commercial complex changes greatly, and the change of business hours and people flow of shops has obvious influence on the air conditioning and lighting load. The error range of commercial buildings is about 18%-+20%. The operation law of office buildings is relatively stable, with an error range of about 12%-+14%. The statistical results show that most of the prediction errors are within 10%. Error records exceeding 20% account for less than 5%. The distribution characteristics show that the model has good prediction ability for most energy consumption records, and the number of extreme errors is small.

2.3.3 Model Stability Test

The model stability test observes the performance changes of the model in different data subsets. K-fold cross-validation method is used to evaluate the stability. The sample data is divided into five subsets, four subsets are selected for model training each time, and the remaining one is used for verification. This process is repeated five times, and the data is different each time. The results of cross-validation show that the variation of prediction error in each round of validation is small. The average absolute error fluctuates in the range of 9.5 kWh/h-11.2 kWh/h. The range of root mean square error is 13.0 kwh/h-15.4 kwh/h. The stability test also observes the influence of different building sample combinations on the model results. After three buildings were randomly removed from the sample, the model was retrained, and the prediction error varied by about 2%-4%. The change range is small, which shows that the model has certain adaptability to sample changes. The stability of model parameters is also verified. The regression coefficient β (temperature coefficient) keeps the range of 0.84-0.91 in each round of calculation results. β (building area coefficient) is stable in the range of 0.005-0.006. The change of parameters is small, which shows that the model structure remains stable under different data sample conditions.

2.3.4 Comparative Analysis of Models

To verify the performance of the model, this study compares the multiple linear regression model with two common forecasting methods. The comparison models include support vector regression model (SVR) and stochastic forest regression model (RF). All three models use the same training data and verification data. The prediction results show (Figure 4) that the average absolute error of the multiple linear regression model is about 10.8 kWh/h. The error of support vector regression model is about 12.1 kwh/h. The error of random forest model is about 9.6 kwh/h. Random forest model is slightly better than regression model in error index. Computational complexity and model explanatory ability are also included in the comparative analysis. The random forest model contains a large number of decision tree structures, and the training time is about 180 seconds. The training time of support vector regression model is about 95 seconds. The training time of multiple linear regression model is about 14 seconds. The explanatory ability of models is obviously different. Multiple linear regression model can directly reflect the influence of temperature, humidity and building area on energy consumption. Although the prediction accuracy of random forest model is slightly higher, it is difficult to express the influence relationship of variables intuitively.

Considering the prediction accuracy, calculation efficiency and model interpretation ability, the multiple linear regression model has good applicability in the research scenario of building energy efficiency. The model can provide a clear variable relationship, maintain a high prediction accuracy, and provide a reliable basis for the subsequent evaluation of energy-saving transformation schemes.

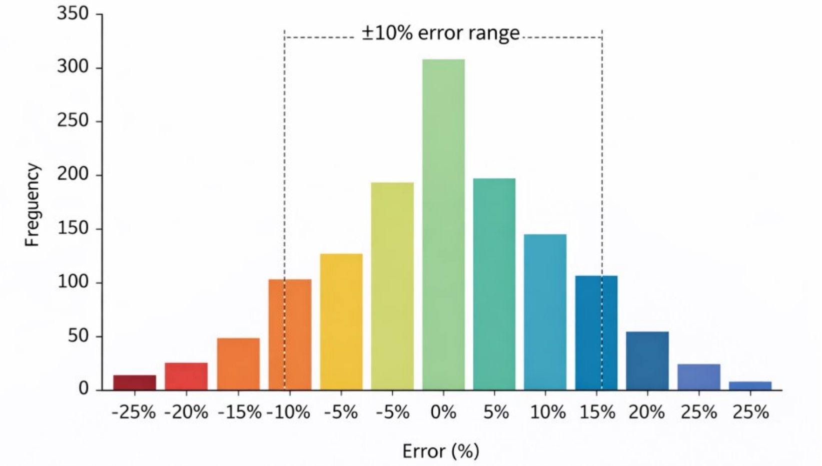

Figure 4: Model prediction error distribution diagram

2.4 System Implementation and Experimental Design

2.4.1 Energy-saving Transformation Scheme Design

Energy-saving transformation scheme revolves around the energy consumption structure of building operation. According to the data analysis, the energy consumption of air conditioning system accounts for about 43%-48%, lighting system accounts for about 18%-22%, and office equipment and elevator system accounts for about 20%-25%. The renovation plan focuses on three directions: improving the efficiency of air conditioning system, replacing lighting equipment and optimizing the building envelope. The transformation of air conditioning system includes the upgrading of water chillers and the installation of frequency conversion control system. The rated energy efficiency ratio of the original centrifugal chiller is about 4.8. The energy efficiency ratio of the new high-efficiency unit reaches 6.2. The refrigeration efficiency is improved by about 22% after the replacement of the unit. The chilled water supply temperature is controlled at 6℃-7℃, and the backwater temperature is kept at 11℃-13℃. When the operating load of the system changes greatly, the frequency conversion adjustment module automatically adjusts the operating frequency of the compressor.

The traditional fluorescent lamp was replaced by LED lighting equipment in the lighting system transformation. The rated power of fluorescent lamps is about 36 W, and that of LED lamps is about 18 W. The lighting power is reduced by about 50%. The lighting time of public areas is controlled from 07: 00 to 22: 00. The office area adopts human body induction control mode, and the lamps and lanterns are automatically turned off after the personnel leave for 5 minutes. The renovation of the building envelope focuses on the external wall insulation layer and glass curtain wall. 60 mm rock wool insulation layer was added to the external wall, and the heat transfer coefficient decreased from 1.25 W/(m k) to 0.68 W/(m k). The original single-layer glass was replaced by double-layer hollow Low-E glass, and the shading coefficient of glass was reduced to 0.42. The design reduces the solar radiation load of the building in summer and shortens the running time of the air conditioning system.

2.4.2 Construction of Experimental Platform

The experiment of energy-saving transformation relies on building energy management system and building automation system to build an experimental platform. The hardware structure of the platform includes energy metering equipment, environmental monitoring sensors and data acquisition terminals. The energy metering device is installed in the main distribution cabinet of the building and the power circuit of the air conditioning system. The accuracy level of measuring equipment is 0.5, and the measurement error does not exceed 0.5%. Environmental monitoring equipment records outdoor temperature, indoor temperature and air humidity. The measuring range of the temperature sensor is 20℃-60℃, and the measuring accuracy is 0.3℃. The measuring range of humidity sensor is 10%-95% RH. The sensors are installed on the roof of the building and in typical indoor areas, and the sampling interval is 10 minutes.

The data acquisition terminal is responsible for real-time data transmission and data storage. The acquisition terminal adopts industrial control computer, and the data interface includes RS485 and Ethernet. All monitoring data enter the energy management server. The server runs data analysis program and energy consumption prediction model. The experimental platform software includes data management module, model calculation module and energy consumption analysis module. The data management module is responsible for historical data storage and real-time data update. The model calculation module performs energy consumption prediction and energy saving rate calculation. The energy consumption analysis module displays the changes of energy consumption in building operation and outputs an energy-saving evaluation report.

2.4.3 Design of Energy-saving Simulation Experiment

The energy-saving simulation experiment takes 20 public buildings as the research object. The experimental period covers from July 2022 to June 2023. The experimental period is 12 months and the data recording frequency is 1 hour. The experimental design includes two stages: the operation stage before transformation and the operation stage after transformation. The pre-renovation phase lasts for 6 months, and the original energy consumption data of the building is recorded. The average energy consumption of the sample building is about 135kwh/h-210kwh/h. The air conditioning system has the highest operating load in summer, and the peak energy consumption reaches 380 kWh/h.

After the completion of the transformation, enter the second stage of operation records. After upgrading the air conditioning system, the hourly energy consumption decreased to 110 kWh/h-165 kWh/h.. After replacing the LED in the lighting system, the lighting power in public areas decreased from 18 kW to 9.6 kW. Meteorological conditions were continuously recorded during the experiment. The average outdoor temperature is 31℃-34℃ in summer and 6℃-12℃ in winter. The experimental data contains about 175,200 hourly energy consumption records. This data is used to analyze the impact of energy-saving measures on building operation energy consumption.

2.4.4 Evaluation Method of Transformation Effect

The evaluation of energy-saving transformation effect is based on two dimensions: energy consumption change and economic benefit. Energy consumption per unit area and energy saving rate. The calculation result of energy consumption per unit area (as shown in Figure 5) shows that the average annual energy consumption of the office building is about 118 kWh/m year before the renovation, and it is reduced to 96 kWh/m year after the renovation. The energy consumption decreased by about 18.6%. The energy consumption per unit area of the commercial complex is about 172 kWh/m year before the renovation, and about 142 kWh/m year after the renovation. The decline is about 17.4%. The effect of medical building renovation is slightly lower, and the energy consumption per unit area is reduced from 185 kWh/m year to 160 kWh/m year.

The economic benefit evaluation is based on electricity price and energy saving. The price of commercial electricity in the study city is 0.92 yuan /kWh. The annual electricity saving of office buildings is about 32000 kWh, and the corresponding economic benefit is about 29,440 yuan/year. The annual electricity saving of commercial buildings is about 58000 kWh, and the energy saving benefit is about 53,360 yuan/year. The renovation cost comes from equipment upgrading and external wall insulation construction. The investment in office building renovation is about 580,000 yuan. The commercial building is about 860,000 yuan. According to the energy-saving income, the payback period of office building investment is about 4.2 years, and that of commercial building is about 4.5 years. The evaluation results show that the energy-saving transformation has improved in both energy efficiency and economic benefits.

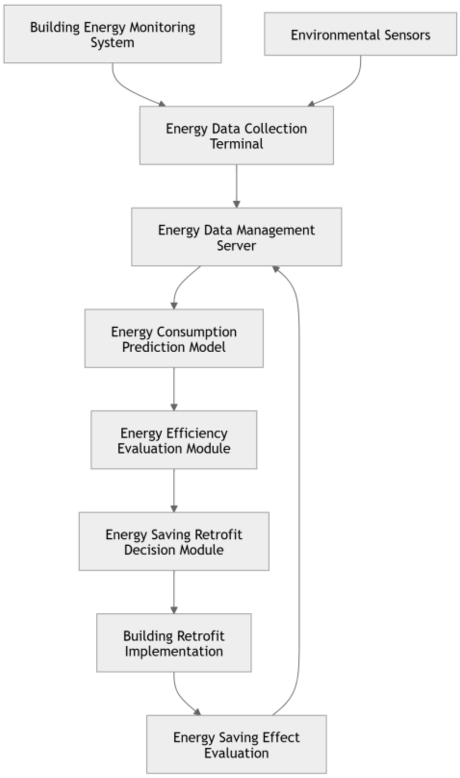

Figure 5: Architecture diagram of building energy-saving renovation system

3. Results and Analysis

3.1 Analysis of Results

3.1.1 Data Analysis of Building Energy Consumption

In the experimental stage, about 175,000 pieces of hourly operation data of 20 public buildings were accumulated. The data covers the cooling stage in summer, the transitional season and the winter operation stage. The statistical results show (as shown in Table 3) that different building types show differences in energy consumption level and variation range. The hourly energy consumption of office buildings is concentrated in the range of 105kwh/h-165kwh/h, commercial complexes are about 150kwh/h-245kwh/h, and medical buildings are about 165kwh/h-260kwh/h. After the implementation of energy-saving transformation, the energy consumption of the three types of buildings all decreased. The average hourly energy consumption of office buildings decreased from 142 kWh/h to 118 kWh/h. Commercial complex decreased from 205 kWh/h to 168 kwh/h. The number of medical buildings decreased from 224 kWh/h to 192 kwh/h.

The decrease of energy consumption mainly occurs in the operation stage of air conditioning system. When the outdoor temperature is in the range of 31℃-34℃ in summer, the peak power of air conditioning system is close to 380 kWh/h before transformation and about 310 kWh/h after transformation.

The renewal of lighting system also brings about changes. The lighting load in public areas is reduced from 18 kW to 9.6 kW. After the induction control mode in office area was put into operation, the lighting load decreased by about 65% from 22: 00 to 06: 00 at night. The statistical results of the whole year (as shown in Figure 6) show that the electricity saving of lighting system accounts for about 21% of the total energy saving. The changing trend of energy consumption reflects that energy-saving transformation measures have different effects in different systems. The air conditioning system upgrade contributed the most, and the energy saving accounted for about 54% of the total energy saving. The lighting system is about 21%, the envelope structure is optimized about 14%, and the rest comes from the load changes of elevators and equipment.

Table 3. Statistical results of building energy consumption

Building number	Building type	Building area (m)	Energy consumption before renovation (kWh)	Annual energy consumption after renovation (kWh)	Energy saving (kWh)	Energy saving rate (%)
B01	Office	12500	182300	149600	32700	17.9
B02	Office	13800	196400	161200	35200	17.9
B03	Office	15200	205100	170400	34700	16.9
B04	Commercial	24800	296500	242300	54200	18.3
B05	Commercial	23100	278200	229500	48700	17.5
B06	Commercial	25400	305100	249400	55700	18.2
B07	Hospital	19500	251400	207600	43800	17.4
B08	Hospital	18800	243200	201500	41700	17.1
B09	Hospital	20500	264800	218900	45900	17.3
B10	Teaching	16800	205700	171100	34600	16.8

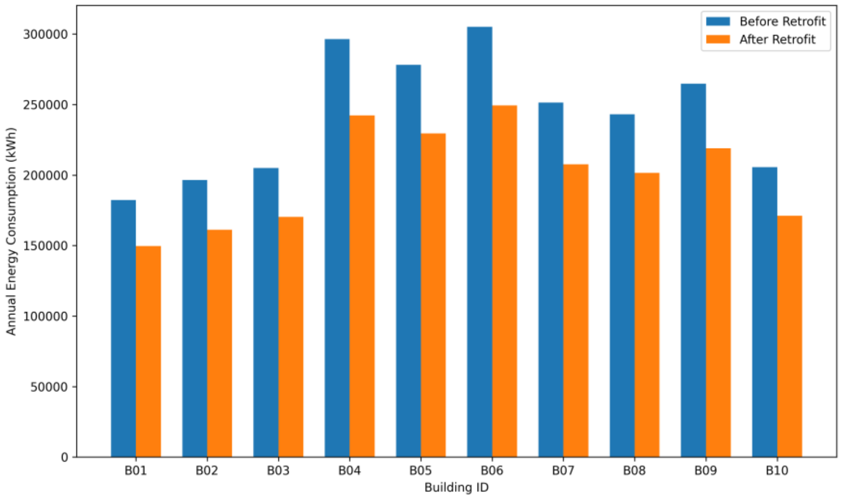

Figure 6 Comparison of building energy saving effect

3.1.2 Energy Saving Effects of Different Building Types

The sample buildings are divided into four categories according to their functions: office buildings, commercial complexes, medical buildings and teaching buildings. After the completion of energy-saving renovation, the annual energy consumption level of all types of buildings has decreased. The operation time of the office building is stable, the equipment load changes slightly, and the energy consumption per unit area decreases obviously after the implementation of energy-saving measures (see Table 4). The average annual energy consumption of the sample office building was about 118 kWh/m year—125 kWh/m year before the renovation, and it decreased to 95 kWh/m year—102 kWh/m year after the renovation, with an average energy saving rate of about 17.6%. The internal load of commercial complex changes frequently, and the air conditioning system runs for a long time. Before the energy-saving transformation, the energy consumption per unit area was about 165 kWh/m year—178 kWh/m year. After the renewal of air conditioning units and the replacement of lighting systems, the energy consumption per unit area decreased to 138 kWh/m year—146 kWh/m year, and the average energy saving rate was about 18.4%.

The operation time of medical buildings is close to all-weather, and the load of air conditioning and equipment remains at a high level. Before energy-saving transformation, the energy consumption per unit area was about 178 kWh/m year—190 kWh/m year. After the system upgrade, it dropped to 150 kWh/m year-162 kWh/m year. The energy saving rate is about 16.8%. The teaching building is greatly affected by the semester operation cycle. After the energy-saving measures are put into operation, the energy consumption per unit area is reduced from 125 kWh/m year to 104 kWh/m year. The energy saving rate is about 16.5%. The difference of energy-saving effect of various types of buildings mainly comes from running time and load structure. The air conditioning systems in commercial buildings and medical buildings run for a long time, and the energy consumption decreases greatly after the replacement of high-efficiency units. The operating load of office buildings is stable, and the transformation of lighting system contributes significantly to energy consumption reduction.

Table 4. Energy saving effects of different building types

Building Type	Average Area (m^2)	Energy Before ($kWh/m^2\cdot year$)	Energy After ($kWh/m^2\cdot year$)	Energy Saving ($kWh/m^2\cdot year$)	Saving Rate (%)
Office Building	13800	121	99	22	18.2
Commercial Complex	24400	172	142	thirty	17.4
Hospital Building	19600	184	156	28	15.2
Teaching Building	16800	125	104	21	16.8

3.1.3 Comparative Analysis of Energy-saving Technologies

The energy-saving transformation scheme involves three technical measures: upgrading of high-efficiency air conditioning system, replacement of LED lighting system and optimization of thermal insulation of external envelope. Various technical measures have different effects on the reduction of building energy consumption. As shown in Figure 7, the upgrade of air conditioning system contributes the most to energy saving. After the energy efficiency ratio of centrifugal chillers was increased from 4.8 to 6.2, the system power decreased obviously in the refrigeration stage. The average power of air conditioning system in the sample building decreased from 225 kW to 176 kW in summer. The energy saving rate of air conditioning system is about 21%-24%.

The replacement of LED lighting system also brings about bright changes. The power of traditional fluorescent lamps is about 36 W, and that of LED lamps is 18 W. The lighting power in public areas decreased by about 48%. The energy consumption of lighting system decreased by about 19% in the whole year. The transformation of external envelope structure mainly affects the heat transfer performance of building envelope. When the thickness of external wall insulation layer is increased to 60 mm, the heat transfer coefficient of the wall decreases to 0.68 W/(m k). In summer, the indoor cooling load decreases by about 8%-10%. The technical comparison results show that the upgrading of air conditioning system contributes about 54% of energy saving, lighting system about 27% and envelope structure about 19%. The influence degree of different technical measures on energy saving effect is obviously different. The strategy of building energy-saving transformation needs to be rationally configured in combination with the operating characteristics of the building.

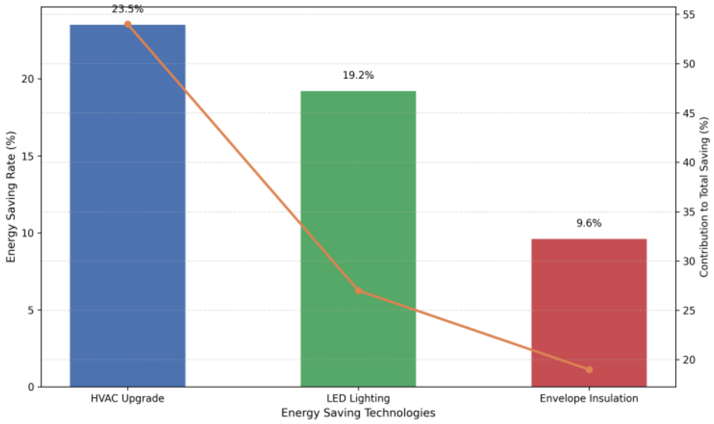

Figure 7: Effects of different energy-saving technologies

3.1.4 Analysis of Transformation Cost and Energy Saving Benefit

After the completion of energy-saving transformation, the economic statistics of energy consumption and investment cost of each building are made. The renovation contents of the sample building include the upgrading of air conditioning units, the replacement of LED lighting system and the construction of external wall insulation layer. As shown in Table 5, equipment procurement cost and construction cost constitute the main part of the reconstruction cost. The renovation cost of office buildings is about 520,000-630,000 yuan, the commercial complex is about 780,000-950,000 yuan, and the medical building is about 700,000-880,000 yuan. Energy-saving benefits are calculated according to actual electricity saving and local commercial electricity price. The price of commercial electricity in the study city is 0.92 yuan /kWh. After the energy-saving renovation of office buildings, the annual electricity saving is about 31000 kWh—35000 kWh, corresponding to the annual energy-saving income of 28,500-32,200 yuan. The air conditioning system of commercial complex has a high load, and the annual electricity saving is about 52,000-61,000 kWh, corresponding to the energy saving benefit of 47,800-56,100 yuan. The electricity consumption of medical buildings is about 43000 kWh—48000 kWh, and the income is about 39,600 yuan-44,200 yuan.

The payback period of investment is calculated according to the transformation cost and annual energy saving income. As shown in Figure 8, the payback period of office building investment is about 4.1-4.5 years. The commercial complex is about 4.3-4.8 years. The medical building lasts about 4.6 years to 5.0 years. After the energy-saving transformation, the operation efficiency of equipment is obviously improved, and the building energy expenditure is decreasing year by year. The comprehensive statistical results show that the upgrading of air conditioning system contributes the most to the energy-saving benefits, accounting for about 52% of the energy-saving benefits. The lighting system is about 28%, and the external protective structure is about 20%. The cost recovery of energy-saving transformation investment will be completed within 4-5 years, and energy-saving benefits will continue to be generated in the subsequent operation stage.

Table 5. Economic benefit analysis of energy-saving transformation

Building ID	Building Type	Retrofit Cost (10^3 RMB)	Annual Energy Saving (kWh)	Annual Cost Saving (RMB)	Payback Period (Year)
B01	Office	560	33200	30544	4.3
B02	Office	590	34700	31924	4.4
B03	Office	610	32500	29900	4.5
B04	Commercial	880	60200	55384	4.7
B05	Commercial	820	54800	50416	4.6
B06	Commercial	910	61000	56120	4.8
B07	Hospital	760	47200	43424	4.7
B08	Hospital	720	45500	41860	4.6
B09	Hospital	840	48800	44896	4.8
B10	Teaching	540	31800	29256	4.2

3.1.5 Comprehensive Energy-saving Effect Evaluation

The comprehensive energy-saving effect evaluation combines three indicators: energy-saving rate, energy consumption per unit area decline and investment payback period. The energy saving rate of the sample building is in the range of 16%-19% as a whole. The average energy consumption per unit area decreased from 153 kWh/m year to 127 kWh/m year. The energy consumption decreased by about 26 kWh/m year. As shown in Figure 9, the energy-saving effect of office buildings is stable. The average energy saving rate is 17.8%, and the energy consumption per unit area is reduced by about 22 kWh/m year. The commercial complex has the largest energy saving range, with an energy saving rate of about 18.3%, and the energy consumption per unit area has decreased by about 30 kWh/m year. The energy saving rate of medical buildings is about 16.9%, and the energy consumption per unit area is reduced by about 28 kWh/m year.

The comprehensive score is calculated according to energy saving rate, payback period of investment and operation stability. The scoring results show that the comprehensive score of commercial buildings is about 87-90. Office buildings are about 85 points-88 points. Medical building is about 82 points-86 points. The evaluation results show that the energy-saving transformation measures have obviously improved the building energy efficiency. Air conditioning system upgrade and lighting system update play a major role in building energy-saving structure. The combination of energy-saving technologies shows good adaptability in different building types.

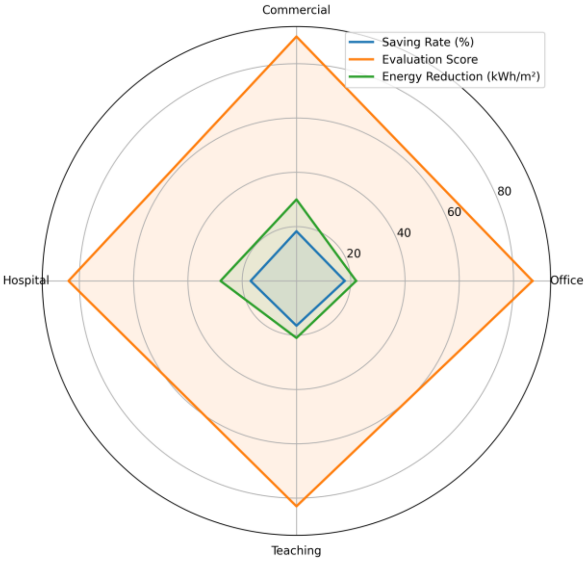

Figure 9: Comprehensive energy-saving evaluation results

3.2 Practical Significance and Application Scenarios of the Results

3.2.1 Practical Significance of the Results

The analysis model based on energy consumption data accurately reflects the energy consumption characteristics of buildings in operation stage. After the energy-saving transformation of the sample building, the energy consumption per unit area decreased from 153 kWh/m year to 127 kWh/m year, with an average decrease of about 26 kWh/m year. The energy saving rate is stable in the range of 16%-19%, which shows that the transformation scheme is feasible in technology. The energy consumption prediction model includes the building area, outdoor temperature and humidity, which can explain the changing law of building energy consumption under different meteorological conditions. This study provides a quantitative basis for energy-saving renovation of public buildings, and building management departments can refer to historical operation data and model prediction results when formulating energy-saving schemes. There is a clear correspondence between the results of data analysis and the combination of energy-saving technologies. Building energy-saving transformation no longer depends on empirical judgment, and the energy management process gradually changes to data-driven mode.

3.2.2 The Application Scenario

The research method is suitable for the energy management platform of urban public buildings. Office buildings, commercial complexes and medical buildings all have energy monitoring systems, and energy consumption data can be directly connected to the model calculation program. Building managers use the prediction results of the model to evaluate the influence of different energy-saving technology combinations on energy consumption changes. When the air conditioning load of commercial complex is high, the system operation strategy can adjust the equipment operation mode according to the outdoor temperature of 30℃-34℃. The lighting system load of office buildings is low at night from 22: 00 to 06: 00, and the intelligent control system can reduce unnecessary lighting operation. Building energy consumption management system can provide real-time energy consumption analysis and energy-saving suggestions for urban energy management platform after combining with forecasting model.

3.3 Discussion

3.3.1 Challenges of test system in actual environment deployment

The building energy management system faces data quality problems in the actual operating environment. The sampling frequency of some monitoring equipment is inconsistent, and the data time interval varies from 5 minutes to 60 minutes, so the data integration process needs time alignment. Equipment failure can also affect data integrity. During the operation of the monitoring system, there was a short-term shutdown, and there were 2-4 hours of data missing records in individual buildings. The difference of internal operation strategies also affects the prediction accuracy of the model. When the business hours of commercial buildings are extended to 23:00, the operating load of air conditioning system is obviously higher than that of conventional operation days. The change of building users affects the equipment load level. In the actual deployment process, the model needs to continuously update the operation data to ensure that the prediction results are consistent with the real operation situation.

3.3.2 Follow-up Research Direction and Model Optimization Suggestions

The existing model considers the variables of building area, outdoor temperature and humidity, and the variable structure still has room for expansion. The density of people inside the building, the running time of equipment and the intensity of solar radiation affects the change of building cooling load. Follow-up research can increase the number of personnel data and solar radiation data, and improve the structure of energy consumption prediction model. The data acquisition frequency can also be increased to 5 minutes to obtain more detailed operation characteristics. In terms of model algorithm, machine learning methods, such as random forest regression model and long-term and short-term memory network model, can be introduced to analyze the time series of building energy consumption. Cross-validation of multi-model results can improve the stability of prediction. If the research on building energy conservation is combined with the urban energy management platform, the scope of energy conservation assessment will be extended from single buildings to urban buildings.

4. Conclusions

Based on the energy consumption data of public buildings in operation stage, the energy consumption records of 20 public buildings are sorted and analyzed, the building energy consumption prediction model is constructed, and the energy-saving transformation scheme is put forward. The sample data covers the hourly operation records from 2021 to 2023, and the data scale is about 520,000. There is a stable correlation between building area, outdoor temperature and air humidity and building operation energy consumption. The average absolute error of the prediction model in the verification data is about 10.8 kWh/h, and the error accounts for about 7%-11% of the average energy consumption of the building. The prediction results reflect the changing trend of energy consumption in the operation stage of the building. The energy-saving renovation experiment was carried out in 20 sample buildings, including the replacement of high-efficiency water chillers, the renewal of LED lighting system and the optimization of external wall insulation structure. The statistical results show that the annual energy consumption per unit area of buildings has decreased from 153 kWh/m year to 127 kWh/m year, with an average decrease of 26 kWh/m year. The energy saving rate of each building is concentrated in the range of 16%-19%. The energy saving effect of commercial complex is obvious, and the energy consumption per unit area decreases by about 30 kWh/m year. The operation stability of office buildings is high, and the renewal of lighting system has obvious contribution to energy saving.

The annual electricity saving of office buildings is about 31000—35000 kWh, and that of commercial complexes is about 52000—61000 kWh. According to the electricity price of 0.92 yuan /kWh, the payback period of building energy-saving renovation investment is about 4-5 years. The comprehensive energy-saving evaluation results show that the upgrade of air conditioning system contributes about 54% to energy saving, lighting system about 27%, and external envelope about 19%. The analysis method based on energy consumption data can provide reliable basis for building energy-saving transformation. The combination of energy consumption data analysis, forecasting model and energy-saving technology forms a relatively complete research framework, and the energy management of public buildings gradually presents a trend of data and refinement.

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