Assel Abdildayeva

DEVELOPMENT OF AN INTELLIGENT INFORMATION COMPLEX AND MATHEMATICAL MODELS FOR MODERN ELECTRIC POWER SYSTEMS

MINISTRY OF EDUCATION AND SCIENCE OF THE REPUBLIC OF KAZAKHSTAN

Assel Abdildayeva

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The monograph is devoted to the creation of a universal mathematical model and the development of an intelligent information system for quick response to emergencies, short-term forecasting and long-term planning of electricity consumption based on retrospective data of the corresponding consumption in the past and taking into account changes in other influential factors in real time.

Designed for students, undergraduates, doctoral students and specialists in this industry.

Reviewed and approved by the Academic Council of the IICT (Minutes No. 4 dated April 13, 2020)

Монография посвящена созданию универсальной математической модели и разработке интеллектуальной информационной системы для быстрого реагирования на аварийные ситуации, краткосрочного прогнозирования и долгосрочного планирования объемов потребления электроэнергии на основе ретроспективных данных соответствующего потребления в прошлом и с учетом изменения других влиятельных факторов в режиме реального времени

Предназначена для студентов, магистрантов, докторантов и специалистов в данной отрасли.

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TERMS AND DEFINITIONS

Electric power system — the electrical part of the power system and the electric energy receivers fed from it, united by the common process of production, transmission, distribution and consumption of electric energy.

Power System — a technical object as a set of power plants, electric energy receivers and electric networks connected to each other and connected by a common mode.

Information Systems – a system designed for storing, searching and processing information, and the corresponding organizational resources (human, technical, financial, etc.) that provide and distribute information.

Time series analysis is a regression-based method of data analysis that aims to establish causal relationships through data ordering.

Forecasting-determining trends and prospects for the development of certain processes based on the analysis of data on their past and current state.

Time Series Forecasting involves building a model for predicting future events based on known past events, predicting future data before it is measured.

The Processor of a Multi-agent Management system is a server for collecting, processing and storing information, from which a specific agent can get the necessary data in the event of a failure.

A Software Interface is a system of unified communications designed to exchange information between components of a computer system and an operator.

LIST OF ABBREVIATIONS

ARIMA-autoregressive integrated moving average model
SARIMA-seasonal model of autoregressive integrated moving average
RMSE - root mean square error
MAE - average absolute error
MAPE is the average relative error
ARCH-autoregressive models of conditional heteroskedasticity
TBATS-seasonal exponential smoothing model
ANN-artificial neural networks
SVM support vector machines
GDP – Gross domestic product
UML-unified graphical modeling language
ARV-automatic excitation regulator
ARCV – automatic regulator of frequency of rotation
EES – electric power systems Is-information system
AWP — automated working place

INTRODUCTION

The relevance of this project is due to objective changes in macroeconomic trends that lead to an increase in the cost of energy resources, the cost of generated electricity and foreign policy circumstances that dictate the need to reduce the state's energy dependence on other countries, to reduce the energy consumption of the economy as a whole. The scientific novelty of the work is due to the fact that an intelligent information control system will be developed and new algorithms for assessing the state will be proposed, which will be used in conditions of partial and incomplete observability and will provide effective assessments of the state of the system in real time.

Currently, in the world, as well as in Kazakhstan, new concepts for the development of the electric power system on a global and national scale are being studied and formed, which correspond to new goals and trends in the development of the world and national economies of countries and the new nature of threats of an economic, environmental and social nature. The technological infrastructure of modern electric power systems is complex and includes many different spatially distributed but interconnected technical elements that carry out the processes of production, transmission and distribution of electrical energy in real time and implement the common strategic goal - to ensure reliable power supply to energy consumers. For this, there are a number of methods for predicting electricity consumption. But they are all based on information that comes from each point of consumption with the help of meters, which have the ability to transmit information about the instantaneous values of consumed power to data centers. Kazakhstan does not have such a developed infrastructure, which makes it impossible to use foreign methods. The creation of such an extensive system of sensors and meters on a national scale requires a rather long time and investment of large funds, which will make the payback period of this system very significant, which neutralizes the economic effect of the introduction of foreign systems. The approach proposed does not require the introduction of a large-scale technical infrastructure, is not costly from the financial side and can be quickly adapted to changes in the infrastructure of the consumer-producer system.

Modern methods of forecasting time series are based mainly on the principle of historical reservations of the future. At the same time, both methods of interpreting information representing past events and methods of their extrapolation to the future acquire constant improvement. Parametric modeling has become widespread, a classic example of which is regression analysis. The most common methods for estimating model parameters are the Gaussian least squares method and the maximum likelihood method. Approaches to the specification of parametric models can be conditionally divided into structural models based on a system of equations and constraints on parameters, and special ad hoc models that do not have a theoretical basis [1].

So, after the massive use of the structural approach in macroeconomic modeling in the 1950s, in the 1960s. Scientists began to actively explore the seasonal and cyclical characteristics of time series. In 1970 Box and Jenkins systematized the results of these works and proposed an integrated approach to modeling and forecasting time series based on autoregressive and moving average models (ARMA / ARIMA). This technique gained popularity because it was easier for complex structural models and made it possible to obtain equally high-quality forecasts. Its software implementation is presented in such software econometric packages as EViews, Stata, Statistica, SPSS.

Within the framework of the structural approach, since the 1980s, dynamic linear and nonlinear Bayesian models with the use of the Kalman filter have successfully proven themselves [1]. The Kalman filter is also used in ARIMA models to eliminate the problem of unreliable parameter estimation by the maximum likelihood method and to determine the unobservable components of the series [2].

Reliable and effective control of the power supply mode at all levels of dispatch control in new, more complex economic and technical conditions of power systems operation requires the creation of a fundamentally new system for collecting and processing a huge amount of information, the development of automated modules for solving specific problems of the complex process of operational dispatch control of heat and electric power industry of Kazakhstan. It is possible to solve this problem based on the use of the concept of intelligent control systems, developed in recent years and used in foreign energy companies.

Simultaneously with the autoregressive approach, it models the dynamics of a series based on its own previous values, vector autoregressive models that study multidimensional time series have been actively developed. The VAR (Vector Autoregression) technique proposed by Sims [3] in 1980 was improved by Angle and Granger (1987) [4] and Johansen and Uselius (1990, 2000) [5] to analyze long-term equilibrium relationships between non-stationary variables based on vector error correction models forecast (CVAR / VECM). Derivative dynamic models of general stochastic equilibrium (DSGE) [1] are widely used.

In Kazakhstan, most of these functions are performed in a “manual” mode, which is associated with the presence of many errors due to insufficient qualifications of service personnel, which result in high economic and social losses. The main conceptual idea of smart energy systems is to create a system-integrated and self-managed in real time energy system with a single network infrastructure, technologically and informationally connecting all generating energy sources and all many consumers within the entire country or a separate region. The economic strategic goal of creating intelligent energy systems is the ability to provide the most reliable, safe and energy-efficient operating mode of the system at any real time under any changing conditions of their external and internal environment.

Another technique for modeling complex weakly formalized systems of a nonlinear nature in conditions of uncertainty, which has been dynamically developing in recent years, is neural network forecasting [6]. An example of the application of this approach in the modeling of energy systems is the work of the scientist S. Kalogirou [7]. Domestic scientists actively use fuzzy models and neural networks in forecasting financial, economic, technological and other processes [8].

In works [7; 9] deals with the management of the power grid according to the principles of fuzzy logic. It is proposed to consider three parameters - the power required by the consumer, the price of energy and the distance from the energy source. Fuzzy criteria are introduced by parameters - low, medium and high, and a clear framework is set for the criteria.

To solve the problem of managing the power grid, a rule base is introduced that regulates the operation of the system, for example, if the power is low, the number of consumers is high, then the level is low. The level is calculated from the membership function and one of the solutions is applied based on the rule base.

In works [1; 7; 11] the control system of the basic control element for which is the microgrid is considered. In general, a microgrid can combine small local electrical, heat, gas, and other networks that share common control. In a purely electrical microgrid, under common control, a number of low-power and micro-sources of electricity, various types of energy storage devices, as well as all energy consumers connected to this microgrid are combined. In such a microgrid, different types of sources can be used: power plants based only on renewable energy sources, fuel cells, traditional power plants, or their various combinations. The ratio of the capacities of all types of power plants is optimized in order to obtain the highest possible economic and technical efficiency - maximum use of local renewable energy sources and alternative energy resources, minimize the price of electricity and maximize the reliability of its supply to the consumer.

There are many microgrid options. They can work autonomously or be connected to the power grid of the power system (ES). Innovations in energy, electronics, control technologies, informatics and communications create favorable conditions for the development and improvement of microgrids, their optimal management while maintaining standard and stable electricity parameters, despite the integration of sources of unstable power, such as wind (WP) and solar power plants (SE). The microgrid control system basically has a target function that reflects the economic effect [12].

In a number of works by foreign authors [6; ten; 13] deals with the issue of demand management on the consumer side. The works propose methods for calculating the required power for the consumer in terms of economic benefits. Techniques are being developed to reduce the cost of consumed energy, depending on the floating tariffication of the cost of electricity. It is assumed that during peak hours, the cost of electricity should be increased to avoid overloading existing energy sources, which is intended to allow the existing energy capacity to be bypassed without the need to introduce new energy sources. The load can be reduced in several ways: a preliminary hourly tariff can be calculated for the day ahead, on the basis of which the consumer solves the problem of minimizing financial costs on his own, such as using his own generating sources or energy storage systems, charging during hours with the lowest tariffs. A consumer notification system can be used to recalculate tariffs for the upcoming period of time, on the basis of which the consumer can decide to reduce energy consumption in a way available to him. It should be noted that such systems are not a completely separate class of control systems, but rather are used to form target functions in other control methods.

All the considered control concepts are insufficiently formed, which does not allow to say with accuracy about the effectiveness of the proposed methods and algorithms. Also, the tasks of the basic law of management and target functions are aimed at ensuring the economic benefits of the manufacturer, consumer, or the ability to get by with the existing energy capacities. Providing economic benefits in this case should be a sufficient criterion for ensuring the energy efficiency of the network, which is not always true. Also, as a basic rule, the judgment is taken that the power grid is self-sufficient and the energy capacity is always sufficient to provide consumers, which is also not always the case. In this regard, the task of developing a control system aimed at autonomous and automatic distribution of energy capacities is urgent. Such a system should have a target function aimed at sufficient and uninterrupted power supply to electricity consumers. For the system to work, it must solve the problem of producing electricity of proper quality, reducing energy losses, ensuring the reliability of the operation of all local elements of the power grid, which will increase the quality of work, energy efficiency and safety of the smart grid.

The main goals of this complex are: availability - providing consumers with energy in accordance with the parameters of time, place and quality they need; reliability - the ability to resist the power system to physical and informational negative impacts without total outages or high costs of restoration work, as well as its fastest possible recovery (self-recovery); profitability - optimization of tariffs for the supply and reduction of system-wide costs for the production and distribution of electrical energy; efficiency - maximizing the efficiency of using all types of resources and technologies in the production, transmission, distribution and consumption of electricity; being organic with the environment - reducing the negative impact on the environment; safety - avoiding situations in the power industry that are potentially dangerous to people and the environment.

The creation of innovative intelligent systems for managing energy consumption processes is a vital task both for individual objects (institutions), countries, and for the global economy as a whole. Solving such urgent problems as reducing energy consumption, ensuring energy independence, and reducing greenhouse gas emissions requires the identification of adequate methods of analysis, modeling and forecasting of time series of consumption and production of various types of energy, their integration with existing information systems for making management decisions on the scale of individual enterprises, cities, industries and states. The insufficient degree of development of theoretical and methodological approaches and practical aspects of the application of forecasting and assessment systems for the efficiency of electricity use in Kazakhstan and Ukraine actualizes the need to create integrated automated energy management systems using modern machine learning methods.

The purpose of this work is to compare modern methods of analysis, modeling and forecasting of electricity consumption at the national, sectoral and individual (by facility) levels, as well as to study the experience of their application in various countries and industries.

1 ANALYTICAL REVIEW OF MODERN DOMESTIC AND FOREIGN METHODS FOR FORMING A MATHEMATICAL MODEL OF ELECTRIC POWER SYSTEM AND DEVELOPMENT OF INTELLECTUAL INFORMATION SYSTEM

1.1 Review of modern scientific and technical literature

Currently, the improvement of the management system for the processes of consumption and saving of electricity by individual objects (institutions) and sectors of the economy as a whole, provides for the creation of a regional-sectoral organizational and economic model. The developed approach to the development of the energy saving management system on the example of educational institutions creates a methodological basis and an algorithmic basis for collecting, processing, analyzing information on the use of electricity, making managerial decisions and conducting an electrical energy audit, and also provides functions for controlling electricity consumption, improving the electricity limiting system; automated creation of electric power passports of objects [14]. The urgent need to create an effective energy saving management system on the example of educational institutions and the insufficient degree of development of theoretical and methodological approaches to assessing the level of efficiency of electricity use, indicate the objective need for further deepening of this scientific research. Currently, in Kazakhstan and Ukraine, there are no such complex industry-level management systems.

In the course of the analytical review, the main provisions of the theory of modeling efficiency management systems and predicting the use of electric energy by consumers were formed, which are based on the regularities of the dynamics of time series of internal (technical and economic, structural, regime) and external (meteorological, environmental, energy, macroeconomic) factors, characterizing the "generation - climatic conditions - energy consumption" system. It has been established that the dynamics of the time series of these factors is characterized by poor predictability. At the same time, despite this negative factor, there is a relationship between them (cointegration), which leads to some general, interrelated changes. It is this feature of the dynamics of time series of internal and external factors that makes it possible to apply the theory of R. Engle and K. Granger in their study.

A characteristic feature of the system "object - energy consumption" is the stationary nature of the time series of factors of its functioning. In other words, the distribution functions of stationary time series do not change with the time shift. This feature of the dynamics of time series of the system "object - energy consumption" allows applying the theory of autoregressive modeling in their study.

Within the framework of the structural study, the collection and preparation of statistical data necessary for further testing of various modeling techniques, checking models for adequacy and assessing the quality of the obtained forecasts were carried out.

It has been established that an important stage is the combination of various autoregressive approaches, structural modeling and neural network forecasting [15] for further mathematical and computer implementation of an adaptive model of energy consumption with elements of artificial intelligence.

The analysis shows that in order to support the management system and decision-making on the use and saving of electricity, it is necessary to detail interdisciplinary, systemic approaches, which, in turn, will ensure the functioning of the energy saving system at all levels, including issues: analysis and comparison of objects with others, optimization expenditures of budgetary and own funds of educational institutions for electricity payments, development of reporting forms and methodological and accompanying documents, creation of an automated software complex for the implementation of a system for collecting and analyzing information on the use of electricity by facilities, and the introduction of pilot systems for managing the efficiency of electricity use for individual system consumers.

As a result of the analytical review, the theoretical foundations of modeling efficiency management systems and predicting the use of electrical energy by consumers were selected, based on a combination of elements, generalized autoregressive moving average models (ARIMA), structural and cointegration models (the theory of R. Englu and K. Granger). On the basis of the selected theoretical models, it is proposed to develop scientific and methodological support (tools) to create a multi-level (in the pilot case, a two-level) system for managing the processes of efficient electricity consumption: universal economic and mathematical models of energy consumption processes.

Today, new concepts for the development of electric power systems are being studied and formed. The technological infrastructure of modern electric power systems is complex and includes many different spatially distributed, but interconnected technical elements that carry out the processes of production, transmission and distribution of electrical energy in real time and implement a common strategic goal - to provide reliable power supply to energy consumers. For this, there are a number of methods for predicting electricity consumption. However, all of these methods can process the information that comes from each point of consumption using counters. In turn, meters have the ability to transmit information about the instantaneous values of consumed power to data centers. Kazakhstan does not have such a developed infrastructure, which makes it impossible to use foreign methods, therefore, it becomes necessary to create an intelligent system for EPS based on mathematical models. The existing methods of the world scale have an extensive system of sensors and counters.

The creation of innovative intelligent systems for managing energy consumption processes is a vital task both for individual objects (institutions), countries, and for the global economy as a whole. Solving such urgent problems as reducing energy consumption, ensuring energy independence, and reducing greenhouse gas emissions requires the identification of adequate methods of analysis, modeling and forecasting of time series of consumption and production of various types of energy, their integration with existing information systems for making management decisions on the scale of individual enterprises, cities, industries and states. The insufficient degree of development of theoretical and methodological approaches and practical aspects of the application of forecasting and assessment systems for the efficiency of electricity use in Kazakhstan and Ukraine actualizes the need to create integrated automated energy management systems using modern machine learning methods.

In the last decade, scientific research has intensified both in the field of forecasting electricity consumption for industrial, utility and energy distribution enterprises, housing complexes, business structures, and individual houses [16-20]. This is due to the need to ensure energy efficiency in buildings, recognized by the International Energy Agency as one of five conditions for reducing final energy consumption and associated CO2 emissions [21]. Environmental prerequisites and economic feasibility have contributed to the development of national rules for energy efficient design for various types of buildings, which gave impetus to the development of computer software for energy efficient design of new homes, such as EnergyPlus, DOE-2, eQUEST, IES, ECOTECT, etc. [22] ...

Maintaining energy efficiency in buildings requires constant monitoring of energy consumption and identifying factors that affect them in real time. Most researchers identify weather conditions as the main factors that determine the dynamics of electricity demand. These include: temperature indicators (air, environment, dry lamps, dew point, wet point, room temperature); indicators of humidity, pressure, wind speed and direction, cloudiness and sun brightness; atmospheric precipitation [23]. Among the additional independent factors, the authors use in the models the variables of electrical load, heat transfer, or heat index; calendar variables; indicators of the size and operational characteristics of buildings, urban infrastructure development; indicators of living standards and socio-economic development [23].

For example, to predict the demand for electricity in the residential sector in Chile [19], the authors use data on average daily energy consumption in kW as the dependent variable, and the variables of the average daily temperature in Celsius and the daily value of the Chilean account unit as explanatory variables. To display calendar effects, researchers include dummies, namely a variable for all Saturdays, a variable for all Sundays, and a variable for holidays in the study interval [19]. It should be noted that the frequency of the time series used in the models is determined by the source and availability of the data.

So, in [20] hourly series of electricity consumption are presented, in the study [18] - half-hour data with an annual time interval. Accordingly, forecasts obtained on such a sample can only be short-term, for example, for a week. To obtain medium-term and long-term forecasts, models are used that are estimated on data of a higher frequency (for example, monthly data [24]) and a longer time interval (several decades). Real-time forecasting requires data acquisition from measuring instruments per minute or per second.

Analysis of open statistical information on electricity consumption in Ukraine and Kazakhstan [25], [26] shows that statistical data on gross electricity consumption by all sectors of the economy are available only by year; final consumption indicators, taking into account renewable energy sources by households, industry, transport, services, agriculture, forestry and fisheries sectors, as well as non-energy energy consumption, are available only since 2007. At the same time, from the reports of the relevant ministries [27], it is possible to obtain monthly indicators on the gross energy consumption in the country, and only within the last decade.

A comparative analysis of methodological approaches to calculating the energy security indicator revealed a number of weaknesses in national systems for assessing energy security as a component of the country's national security. In particular, the disadvantages of the approach to calculating the level of energy security of Ukraine are identified [28]. These include: the limited range of aspects of energy security for which the assessment is carried out, the lack of a basis for comparison and a long series of statistical data on energy security indicators, a slow update of the threshold values of indicators embedded in the rationing algorithm. In addition to the domestic approach, the analysis of methods for assessing the energy security risk indicator developed by the United States Institute of Energy and the International Energy Agency was carried out [29]; carried out a comparative analysis of these techniques with the domestic approach. Based on the results of the analysis, differences were revealed in the normalization of individual indicators, the qualitative characteristics of individual indicators and the methodology for determining the appropriate weighting factors for each indicator. It is proposed to include in the list of indicators of the country's energy security such indicators as market volatility, indicators of the intensity of energy use, the state of world and regional fuel reserves, etc. To solve the problem of modeling real statistical data represented by different frequencies, it is proposed to use mixed-frequency models, Mixed-Data Sampling Models (MIDAS) [30], to determine the relationship between possible factors of energy security and energy efficiency of the national economy.

One of the options for solving the problem of a small sample of data to obtain adequate statistically significant results and high-quality forecasts can be the use of panel models that assess similar indicators for a group of objects, for example, simultaneously for all educational institutions of the region, regions of the country or for countries with similar development parameters.

Thus, in article [31], a panel sample of annual data on electricity consumption by residential buildings in the context of cities in China was used to identify the most significant factors in the construction of "green houses". The authors of [32] investigate the demand for electricity in industry and services in Taiwan, analyzing panel data for 23 industrial sectors and 9 service sectors for 1998-2015.

The article [33] assesses the efficiency of electricity consumption for an unbalanced group of 27 transition economies and 6 OECD countries in Europe in the period from 1994 to 2007. Thus, we can conclude that for countries such as Kazakhstan and Ukraine, the most acceptable models are based on panel data.

At the same time, the focus of scientific research in these countries should be shifted towards modeling the demand for electricity by individual objects that have the appropriate equipment for measuring the consumption of high-frequency fixing electricity, with the subsequent extrapolation of the results obtained to higher levels (industry, regional).

The above approach is presented in detail in the work of Canadian scientists [31], who identified two methods for modeling the demand for electricity in the residential sector: “top down” and “bottom up”.

The first approach focuses on identifying key factors and forecasting electricity consumption for residential buildings of different levels, depending on historical data on residential buildings and top-level variables, which include macroeconomic indicators (gross domestic product, unemployment and inflation rates), prices for various types of energy, climatic factors.

The second approach is based on the use of statistical and engineering methodologies to predict electricity consumption at regional and national levels by extrapolating indicators from a representative set of individual houses [34].

It should be noted that engineering models that describe final energy consumption as a natural phenomenon based on physical laws and do not require historical energy consumption data are now practically not used. The rapid increase in the sources and volumes of data, technologies for their processing and the capacity of processing systems, contributed to the shift of scientific interests towards statistical methods.

The variety of statistical models is due to both differences in data structure (linear and nonlinear; discrete and continuous models), and the development of machine learning methods and software that implement them. Parametric and nonparametric methods are widely used, which can be classified into regression, autoregressive methods, Fourier models, neural networks, fuzzy logic models, Wavelet analysis, Bayesian methods.

The use of parametric methods presupposes the availability of information about the nature of the data distribution, which is fraught with obtaining biased estimates of parameters and false conclusions in the case of an incorrectly selected model. For cases where the true distribution of the data is unknown, the use of nonparametric methods is preferred. A significant drawback and limitation of nonparametric models focused more on testing hypotheses than on estimating parameters is the complexity of their calculations and high requirements for software and hardware [19].

1.2 Principles of EES control in real time

The domestic information and intellectual system is, first of all, knowledge of technology and local conditions, including knowledge of domestic regulatory and technical documentation. The concept of the intelligence of the system consists in programmed algorithms that allow automatic control of the system, depending on the emerging situation.

Today's IES is a very complex entity that interacts with various factors and feedback. Therefore, to solve any problems associated with the design, management and operation of electric power facilities, it is necessary to use powerful computers, computers, communication and telecommunication systems.

Also used are tools for calculating energy parameters and computer-aided design of various electrical installations and substations. To ensure reliable and high-quality operation of the power system, operational dispatch control of electricity is carried out in a stationary mode. Nowadays, this type of management requires the use of an accumulative system and an information processing complex. There are many software packages that provide data collection and processing. At first they were only about data collection and demonstration. Currently, they are equipped with additional modules for calculating and analyzing information.

In modern automated substation control systems (ACS), a so-called three-level system is used. The upper level is a part of the ACS PS complex, usually installed at the control room. The middle level is a part of the complex, installed in the control center and controlled points, which connects the upper level in the hierarchy of the complex with the lower one. The middle level acts as a coordinator or router of signals and commands of the automated control system. The lower level is a part of the complex, usually installed in a controlled point. At the lower level, as a rule, there are microprocessor-based relay protection and automation devices and various measuring converters and sensors, the purpose of which is to control and directly read data from the substation's primary equipment. All levels of the automated control system were examined.

The main types of information systems and automatic control systems used in the electric power industry of Kazakhstan [35]:

- telemechanics, information collection and transport system;
- operational information complexes (UAC, SCADA-systems);
- tracking transition modes (SMRP, WAMS-systems);
- Software systems for model evaluation, analysis and EPS mode model;
- SCADA / EMS systems for measurement functions, condition assessment, optimization and forecasting.

When developing an intelligent information system, the SCADA software package is used. The developed system will ensure the stability and efficiency of the power system using the following functions:

- receiving information from the data collection device;
- restoration of the power system (emergency) using mathematical models;
- applying a mechanism to represent the situation;
- archiving information (archive of daily, weekly user actions);

- use of a system for displaying text information;
- automatic control of electrical and energy systems.

The system will autonomously take actions to prevent the occurrence or development of an emergency when certain parameters go beyond the set limits, or optimize the operation to achieve the greatest savings, etc. It will allow you to fully monitor the operation of the system and record it in the event log.

The embedded system consists of a three-tier architecture:

1) hardware level - a software technical device that provides data collection;

2) information level - providing access to any system parameters;

3) application level - the presentation and processing of data to solve specific issues.

The system and functional addition of the information system is intended for numerical modeling and analysis of electromechanical transient electromagnetic processes. Numerical modeling of electromechanical transformations - creation of computational models, data preparation, discretization of model equations, solution of a system of equations and processing of the results obtained [36].

To create an intelligent information system, a set of measures was used, which includes the following stages [35]:

- a comprehensive analysis of the structure, characteristics and problems of the energy system;
- analysis and assessment of the scope of work;
- determination of the principles of decomposition of the information system into subsystems;
- choice of design methodology;
- determination of means of implementation of the selected methods;
- implementation of the information system.

The system will be able to provide control of remote control and monitoring of protection signals, manage communication channels with the dispatch center, measure power quality indicators, control time stamps, conduct constant exchange with the commercial electricity metering system, block equipment in case of personnel incorrect actions, as well as monitor parameters main and auxiliary equipment operating for a long time in the mode of constant readiness for the localization of the accident. The developed model of the intelligent information system is shown in Figure 1.

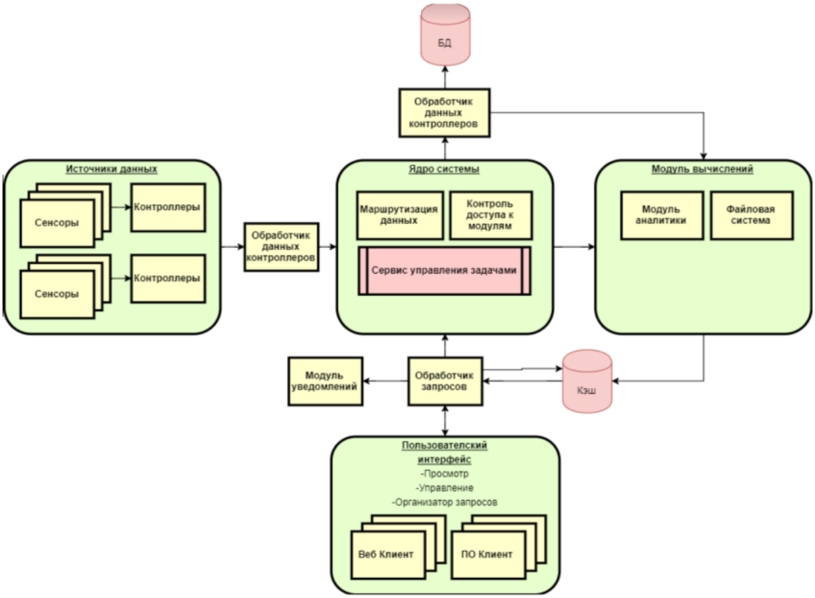


Figure 1 - System model

1.3 Comparative analysis of modern software and computing systems in electric power systems

At present, modern electric power systems are so complex objects with various feedbacks and factors of mutual influence that the solution of any issues related to the design, management and operation of electric power facilities is unthinkable without the use of a powerful apparatus of computational mathematics and all types of computer technology, communication systems and telecommunications. ...

The software used in the electric power industry is designed to solve one of two types of tasks - design and operational.

The solution of design problems is aimed at choosing the parameters of the projected network and the corresponding equipment. To solve these problems, the means of calculating electric power parameters, computer-aided design systems for various electrical installations and substations are used.

During the operation of electric power systems, to maintain a reliable and high-quality power supply in a constant mode, operational dispatch control is carried out. Such control in modern conditions requires the use of a large complex of systems for collecting and processing information. There are a lot of such systems on the market. They were originally used only for collecting and displaying data. At the moment, they can be equipped with additional modules for calculating and analyzing information and presenting recommendations to the dispatcher.

Taking into account the analyzed material on industrial applications, they can be classified into the following:

- software for collecting and storing telemetric information;
- software for software for electrical calculations;
- computer-aided design systems;
- software for personnel training;
- software for solving other production tasks.

This division is very arbitrary, since software developers are constantly improving and expanding the capabilities of their own products.

This paper describes the most common programs used for electrical calculations and for automated design of power facilities.

The software was considered, the developers of which are Russian (and in some cases Soviet) specialists, such as: SDO-6, Dakar, RastrWin, ANARES-2000, KASKAD-RETREN, KOSMOS, RTP 3, Energy CS, TKZ-3000, ARM SRZA. The functions of the most famous programs of foreign firms used in Kazakhstan for solving similar problems are described: EUROSTAG, PSS / E, DigSILENT PowerFactory.

To assess the functionality, the user documentation of the above software systems (PC) was studied for calculating the modes [37], on the basis of this, a comparative characteristic of the functionality was formed (Table 1). The table shows that the most functional PCs are Digisilent, PSS / E, ANARES-2000 and DAKAR - they allow you to solve almost all types of power grid problems. Such software systems as RastrWin and Cosmos are designed mainly for calculating steady-state modes and analyzing damage. Mustang and Eurostag software packages are aimed at analyzing the static and dynamic stability of the electric power system. It should be noted that the PSS / E and Digisilent software packages do not have a Russian-language interface, which significantly complicates their use in Kazakhstan. Since the analysis of functionality is not enough for a complete assessment of the PC, an assessment of the advantages and disadvantages of the PC was also made, which is presented in Table 1.2.

Table 1.1 - Comparative characteristics of the functional capabilities of software systems

Function	RastrWin	Mustang	DAKAR	ANARES-2000	PSS/E	DigSilent	Космос	EUROSTAG
Electrical Mode Calculation Function	+	+	+	+	+	+	+	+
The presence of restrictions on the dimension of the mathematical models.	-	-	-	-	+	-	-	+

Function	RastrWin	Mustang	DAKAR	ANARES-2000	PSS/E	DigSilent	Космос	EUROSTAG
Electromechanical transient calculation function processes.	-	+	+	+	+	+	-	+
Variable integration step.	-	-	-	-	-	-	-	+
Function for calculating electromagnetic transients.	-	-	-	-	-	-	-	-
Possibility of taking into account asymmetries in ES elements.	+	-	+	+	+	+	-	-
The presence of a base of elements of the electrical network.	-	-	+	-	+	+	-	+
Frequency analysis function. Mode optimization functions.	-	-	+	+	-	-	-	-
Equivalent functions of the power system diagram.	+	-	-	-	-	+	-	+
Availability of PPT and FACTS models for calculation electric mode of the dynamics.	+	-	-	+	+	+	+	-
Availability of standard RZ and PA models.	+	-	-	-	+	-	-	-
Possibility of weighting the mode along a given trajectory.	-	-	+	-	+	+	-	+
The ability to create custom models.	-	-	+	+	+	+	-	+
Russian language interface.	+	+	+	+	-	+	-	-
Licensing.	+	-	+	-	+	+	+	+

Table 1.2 - Assessment of the advantages and disadvantages of software systems

PC	Advantages	Disadvantages
RastrWin	Convenient and intuitive interface. Ability to calculate modes using various algorithms. The ability to use macros to create formulas. The ability to import and export information to Excel file.	Lack of library of power grid elements.
Mustang	Easy to use. Free distribution. The ability to set the characteristics of any automation.	Inconvenient graphical display of data. There are no ready-made sets of automatics.
DAKAR	The presence of a base of network elements (transformers, overhead lines, UKRM, etc.). Multifunctionality.	Inconvenient interface. Inability to keep a history of changes in the calculation model.
АНАРЭС-2000	The presence of a base of network elements (transformers, overhead lines, UKRM, etc.). Multifunctionality.	Inconvenient interface. The inability to keep a history of changes in the equivalent circuit.
PSS/E	Can combine raw data with Google Earth ™ and map electrical networks geographically. You can solve any power grid problems	There is no Russian version. Not adapted for use in Russian сетях.
DigSilent	The vertically integrated software allows the use of a single software "engine" and Power Factory interface for various applications and market segments - generation, transmission, distribution of electricity, power supply systems.	There is no Russian version. Lack of library of power grid elements. Not adapted for use in Russian networks.

PC	Advantages	Disadvantages
EUROSTAG	The presence of a set of automatics. The ability to create models of system automation. In the program, you can set the transient characteristics of non-traditional sources of electricity (WPP, SES, etc.).	Inconvenient interface. To model transient processes, a detailed specification of the characteristics of each network element is required.
Space	A powerful component of condition assessment. Sufficiently broad possibilities for linking calculation programs to OIC and other complexes through the mechanism of CDU formats.	An outdated interface technology that, although implemented graphically under Windows, actually imitates the Windows interface, having many limitations. Orientation to textual storage of data and results, graphical schematic editor with limited capabilities.

After analyzing the above presented PCs, the following conclusions can be drawn.

1) Software systems for the analysis of electrical modes have minor differences associated with the presentation of the initial data, the parameters for outputting information and the export / import capabilities.

2) Software systems produced by the CIS, as a rule, have a narrow focus on specific technological tasks.

3) Foreign-made products are positioned as complex tools capable of solving all operational tasks, as well as tasks of economic optimization or selection of the optimal strategy in the conditions of the electricity market.

4) Software systems produced by the CIS can work with the format of the dispatch control center, which allows the import and

export of data from one software and computer complex to another for solving various problems.

2 STUDIES OF DETERMINED AND STOCHASTIC COMPONENTS OF TIME SERIES

2.1 Power Simulation

Modeling technical, biological, economic and other processes requires a preliminary study of the data structure, the nature of stationarity, and the presence of anomalous observations. A feature of energy consumption indicators is the presence of multidirectional trends, seasonal and cyclical fluctuations, structural breaks, which causes their nonstationarity and causes autocorrelation, heteroscedasticity, and the absence of a normal distribution law for the residuals of the models constructed from these data. This makes it impossible to use the classical statistical apparatus and actualizes the search for methods and models that can reduce the negative impact of these problems to obtain better mathematical models and reliable forecasts.

Modern methods of forecasting time series are based mainly on the principle of historical prediction of the future. At the same time, both methods of interpreting information representing past events and methods of their extrapolation to the future are constantly being improved. Parametric modeling has become widespread, a classic example of which is regression analysis. The most common methods for estimating model parameters are the Gaussian least squares method and the maximum likelihood method. Approaches to the specification of parametric models can be conditionally divided into structural models based on a system of equations and constraints on parameters, and special "ad hoc" models that do not have a theoretical basis.

So, after the massive use of the structural approach in macroeconomic modeling in the 1950s, in the 1960s. scientists began to actively explore the seasonal and cyclical characteristics of time series. In 1970, Box and Jenkins systematized the results of this work and proposed an integrated approach to modeling and forecasting time series based on autoregressive and moving average models (ARMA / ARIMA). This technique gained popularity because it was simpler than complex structural models and made it possible to obtain equally high-quality forecasts. Its software implementation is presented in such econometric software packages as EViews, Stata, Statistica, SPSS, R, Python.

Within the framework of the structural approach, since the 1980s, dynamic linear and nonlinear Bayess models using the Kalman filter have successfully proven themselves. The Kalman filter is also used in ARIMA models to eliminate the problem of unreliable parameter estimation by the maximum likelihood method and to determine the unobservable components of the series [38]. Justification of a model that is optimal in terms of statistical characteristics and predictive qualities requires the determination of the main components of the series, the nature of its stationarity, specification, parameterization, and verification and testing of models; testing dummy variables in order to improve their qualities.

Stationary time series are characterized by the equilibrium of values (constant variance) around the mean value, which is constant. In practice, this means the absence of a trend, seasonal fluctuations and systematic variance changes [37].

To identify the stationarity of the data, you can use the approach of constructing an autocorrelogram of a series, that is, a graphical representation of the autocorrelation function (ACF). In the case of a stationary series, the value of the ACF will tend to zero with increasing lag. In addition, the form of the correlogram characterizes the process as follows: a gradual approach of the ACF to zero is characteristic of autoregression processes, and a sharp transition to zero indicates a moving average process.

Also, when studying the autocorrelation of a series, an approach is used to test the hypothesis of the absence of autocorrelation up to lag k using the Ljung-Box Q-test [38]. For this, a statistical value is calculated:

$$Q = T(T+2)\sum_{j=1}^{k} \frac{\rho^2}{T-j}, \qquad (2.1)$$

where T is the number of observations; ρ2 - autocorrelation of the j-th order; k is the number of lags. The resulting statistic is compared with the theoretical distribution

$$\chi 2(1-\alpha, m)$$

Another widely used method for checking the stationarity of data is using the criteria proposed in 1979. W. Fuller and D. Dickey and its improved form of the extended Dickey-Fuller test (ADF) [37]. This technique consists in testing the statistical hypothesis of the presence of a unit root (with the alternative hypothesis of the presence of a root, less than one). If the t-statistic is less than the critical values of the ADF statistic, then the null hypothesis is rejected, which indicates that the series is stationary. In the case of the presence of unit roots, the series is considered to be integrated of the kth order I (k) and requires differentiation to bring it to stationarity. The condition for applying this test is the homoscedasticity of perturbations, that is, the constant variance of random perturbations ε [39].

The Dickey-Fuller test is used to determine whether a series belongs to DS or TS classes [38]. The TS class is characterized by the fact that such a series is stationary relative to some deterministic trend, and for these series it is necessary to identify the trend component. Series of the DS class have a stochastic trend, that is, unlike TS series, each deviation equally affects all subsequent values of the series. The null hypothesis of the Dickey-Fuller test corresponds to the hypothesis that the series belongs to the DS-type; accordingly, the alternative hypothesis says that the series under study is of the TS type, but at the same time the series can be non-stationary (characterized by a deterministic trend) or stationary (characterized by the absence of a trend). The reliability of the test results in this case is affected by the specification of the model (inclusion of a constant and (or) a deterministic trend in the model).

If seasonality is revealed, to assess the stationarity of the data and further correct construction of the model, it is necessary to eliminate it or to include dummy variables of seasonality. Common methods of smoothing are: methods of exponential and adaptive smoothing, additive and multiplicative Holt-Winters models [38].

When using the exponential smoothing method, a new representation of a data series is carried out according to the rule:

$$S_1 = y_1,\ S_t = \alpha y_t + (1-\alpha)S_{t-1},\ t = \overline{2, T}\ , \quad (2.2)$$

where St is the new value of the row level; yt - initial value of the row level; α is the smoothing constant. This method is advisable to apply when the data has a slowly growing or horizontal trend.

The adaptive smoothing method allows you to change the smoothing constant during the calculation, for which the following scheme is used:

$$S_{t+1} = \alpha y_t + (1-\alpha_t)S_t\ . \quad (2.3)$$

Here α changes in time according to the rule:

$$\alpha_t = \left|\frac{E_t}{M_t}\right|,\ E_t = \beta(y_t - \hat{y}_t) + (1-\beta)E_{t-1},$$
$$M_t = \beta\left|y_t - \hat{y}_t\right| + (1-\beta)M_{t-1}\ ,\ \beta \in (0;1). \quad (2.4)$$

A more advanced modification of exponential smoothing is the additive Holt-Winters model, based on the use of smoothed data, a trend component, and a seasonality index. Smoothing in this case occurs according to the scheme:

$$S_{t+p} = \alpha_t + b_t p + c_{t+p}\ , \quad (2.5)$$

where bt is the trend parameter; p = 1, 2 ... is the number of forecast periods, ct is the seasonality parameter. Components α, b, c are calculated by the formulas:

$$\begin{aligned} \alpha_t &= \alpha(y_t - c_{t-s}) + (1-\alpha)(\alpha_{t-1} + b_{t-1}), \\ b_t &= \beta(\alpha_t - \alpha_{t-1}) + (1-\beta)b_{t-1}, \\ c_t &= \gamma(\gamma_t - \alpha_t) + (1-\gamma)c_{t-s}, \; 0 \le \alpha, \beta, \gamma \le 1. \end{aligned} \tag{2.6}$$

Here s is the number of seasonality cycles; α, β, γ - smoothing parameters for the series level, trend and seasonality, respectively.

If there are two full seasonality cycles in the observations, smoothing is possible by constructing the Holt-Winters multiplicative model. In this case, the following rule applies:

$$S_{t+p} = (\alpha_t + b_t p)c_{t+p} \tag{2.7}$$

Further modeling based on non-stationary data requires their reduction to a stationary form. If a series is identified as belonging to the TS class, it is sufficient to select the trend from the database. If, when checking the data using the ADF test, it was determined that the series belonged to the DS type, then the problem of nonstationarity can be solved by using a series of i-order differences instead of levels. In this case, an autoregressive integrated moving average model ARIMA (AutoRegressive Integrated Moving Average) [38] is used for modeling, which predicts future values of the time series based on a linear combination of its previous values and disturbances (also known as random shocks or innovations).

In this case, an autoregressive process (AR) of order p is described by an equation of the form:

$$Y_t = \varphi_0 + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} + \ldots + \varphi_p Y_{t-p} + \varepsilon_t \,, \tag{2.8}$$

where Yt is the dependent variable at time t; φ, p - autoregression coefficients; εt is the error at time t (“white noise”) [17].

The moving average (MA) equation of order q is:

$$Y_t = \mu + \varepsilon_t - \omega_1 \varepsilon_{t-1} - \omega_2 \varepsilon_{t-2} - \ldots - \omega_q \varepsilon_{t-q}\,, \qquad (2.9)$$

where ωq are MA coefficients; μ is the constant average of the process.

Any stationary model AR (p) can be written as MA (∞). For example, performing the corresponding substitutions for AR (1), we obtain the MA (∞) model:

$$\begin{aligned} Y_t &= \phi_1 y_{t-1} + \varepsilon_t = \phi_1(\phi_1 y_{t-2} + \varepsilon_{t-1}) + \varepsilon_t = \\ &= \phi_1^2 (y_{t-2} + \phi_1 \varepsilon_{t-1} + \varepsilon_t) \ = \ \ldots \\ Y_t &= \varepsilon_t + \phi_1 \varepsilon_{t-1} + \phi_1^2 \varepsilon_{t-2} + \phi_1^3 \varepsilon_{t-3} + \ldots \end{aligned} \qquad (2.10)$$

As noted above, a non-stationary process of the DS class can be reduced to a stationary one using the operator of successive differences -. In this case, the integrated autoregressive moving average model ARIMA (p, d, q) is used, where p is the model lag, d is the integration order, and q is the moving average order:

The ARIMA model uses the well-known Box-Jenkins methodology, which assumes that the future values of a time series are a linear function of its previous values and random errors [38]:

$$y'_t = c + \varphi_1 y'_{t-1} + \ldots + \varphi_p y'_{t-p} + \theta_1 \varepsilon_{t-1} + \ldots + \theta_q \varepsilon_{t-q} + \varepsilon_t \qquad (2.11)$$

where and represent the actual values and random error in the time period t; Are the parameters of the model, p is the lag of the model, d is the order of integration (the order of differentiation of the series to reduce to stationarity) and q is the order of the moving

average.
The seasonal SARIMA model additionally includes, in addition to the parameters (p, d, q), the seasonal parameters (P, D, Q) m, where m is the number of periods in a season.
In the presence of heteroskedasticity in the data, it becomes expedient to use ARCH (Autoregressive Conditional Heteroskedasticity) models of conditional heteroskedasticity [38]. When building such a model for a certain time series, which can be represented as yt = ut, the conditional variance property is used:

$$\sigma_t^2 = \gamma + \delta \cdot u_{t-1}^2 \tag{2.12}$$

where ut is a sequence of independent identically distributed random variables with zero mean; γ, δ satisfy the condition> 0 for all t.

A prerequisite for a reliable forecast is the quality and adequacy of the resulting model. When diagnosing a model, in particular, the residuals of the model are checked for autocorrelation, normal distribution and heteroscedasticity.

To check the normal distribution law of the residuals of the model, in particular, the Jacques-Berre test is used, which consists in testing the statistical hypothesis of the normal distribution law.

Based on the coefficients of skewness and kurtosis, the statistical value of the Jacques-Berre test is calculated [39]:

$$JB = \frac{T-k}{6}(S^2 + \frac{(K-3)^2}{4}) \tag{2.13}$$

Here S is the value of the asymmetry coefficient; K is the value of the kurtosis coefficient; k is the number of model parameters that are estimated. Jacques-Bera statistics are distributed according to the χ2 distribution.

One of the methods for testing the residuals of a model for heteroscedasticity is the test proposed in 1980 by G. White [39] to test the statistical hypothesis of the absence of heteroscedasticity using LM statistics:

$$LM = nR^2, \tag{2.14}$$

where n is the number of observations; R2 is the coefficient of determination of auxiliary regression. In the case of homoscedasticity of the residuals of the model, the LM-statistic has an asymptotic distribution $\chi 2$ (N-1), where N is the number of auxiliary regression parameters.

An integral part of determining the quality of the model is also the calculation of the coefficient of determination R2, the standard error of regression, the information criteria of Akaike and Schwarz, and the Durbin-Watson statistics.

The information criterion presented in 1971 by H. Akaike [19] is used to select a model among several alternative ones:

$$AIC = \ln\left(\frac{\varepsilon'\varepsilon}{T}\right) + \frac{2(p+q)}{T}. \tag{2.15}$$

However, the Akaike criterion is characterized by the choice in favor of the overparametrized model. This problem is partially eliminated by the Schwarz information criterion [38]:

$$BIC = \ln\left(\frac{\varepsilon'\varepsilon}{T}\right) + \frac{(p+q)}{T}\ln T. \tag{2.16}$$

To check the model residuals for autocorrelation, a residual correlogram is constructed, the interpretation of which is similar to the corresponding test for the time series. Another criterion for checking the presence of autocorrelation in the deviations of ε of the constructed model is the value of DW-statistics of J. Durbin and J. Watts, which is calculated by formula (17) and is compared with the upper and lower critical values d1 and d2.

$$d = \sum_{t=1}^{n} (\varepsilon_t - \varepsilon_{t-1})^2 / \sum_{t=1}^{n} \varepsilon_t^2 \ . \qquad (2.17)$$

Analysis of publications in the field of forecasting electricity consumption shows that traditional parametric methods such as regression models (linear regression and multiple regression) and autoregressive methods (autoregressive and moving average models, ARMA, integrated models, ARIMA, vector autoregression, VAR, and cointegration models, VEC) have recently been used less frequently. Nevertheless, some authors still note the high efficiency and accuracy of both univariate seasonal integrated autoregressive moving average models, SARIMA [16, 37], and SARIMAX models [19, 37], which include, in addition to the data on electricity consumption itself, additional exogenous variables.

An analysis of the empirical data on the hourly electricity consumption of the Estonian municipal utilities [40] shows the seasonal nature of the data and the presence of some anomalous observations in a biennial sample of 17,544 data points. The graph of the dynamics of hourly electricity consumption is shown in Figure 2.

To identify the most significant factors affecting the volume of hourly consumption, we examined the following exogenous variables:

– average temperature for the observation period in degrees Celsius at a height of 2 meters above the ground;

– atmospheric pressure (mmHg);

– relative humidity (%) at a height of 2 m above the ground;

– wind direction and speed (angular degrees) at a height of 1-12 m above the ground;

– amount of precipitation (mm) for the period;

– cloudy (sunny / cloudy);

– night / dusk / day;

– weekends and holidays (separate dummies for Saturday (1/0); Sunday (1/0) and holidays (1/0)).

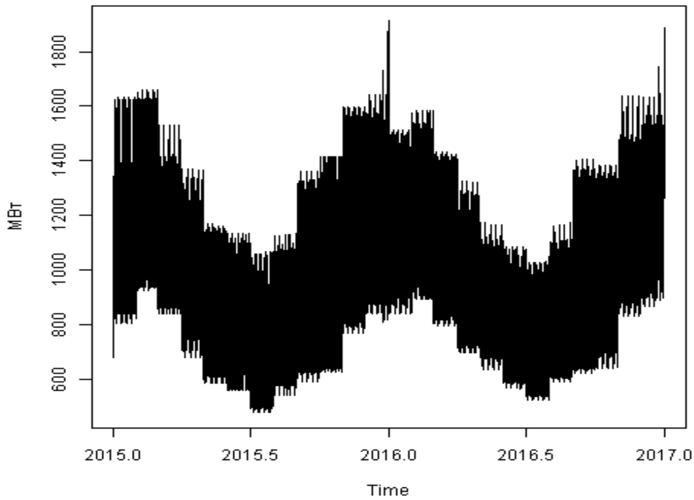


Figure 2 - Dynamics of electricity consumption in 2015-2017

Figure 3 and Figure 4 show the results of forecasting electricity consumption based on the seasonal autoregressive moving average model ARIMA and the seasonal exponential smoothing model TBATS.

The parameters of the SARIMA seasonal model include the autoregressive order parameters (model lag) p = 3, the integration order (the order of differentiation of the series to bring to stationarity) d = 1, and the moving average order q = 5. The model also includes seasonal parameters Qm = 1.

To justify the choice of the model, we use the smallest values of information criteria and quality indicators of the obtained short-term forecasts - the root mean square error (RMSE), the average absolute error (MAE) and the average relative error (MAPE). To improve the quality of models and forecasts, it is necessary to include additional explanatory variables, choosing the most significant indicators, and explaining the anomalous values by including dummy variables. Further research should be continued in the search for other types of models.

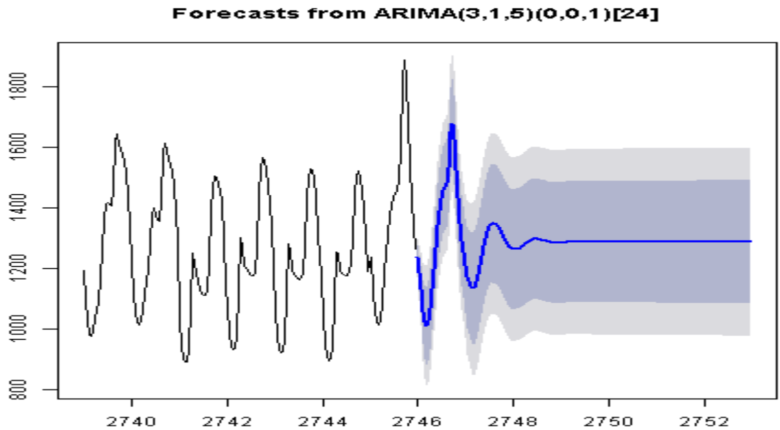


Figure 3 - Forecasting electricity consumption based on the ARIMA model

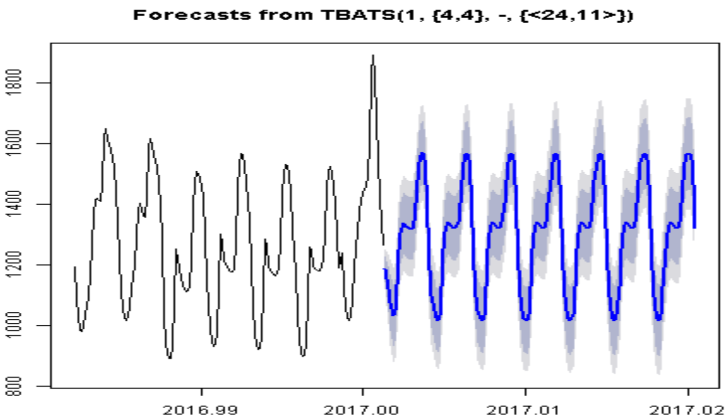


Figure 4 - Forecasting electricity consumption based on the seasonal exponential smoothing model TBATS

Deep theoretical and practical development, as well as relative ease of use, allows them to remain relevant and in demand. Artificial intelligence methods (artificial neural networks, ANN, and support vector machine, SVM) are gaining more and more popularity in the scientific and business environment [34]. A significant advantage of

ANN models is their ability to model nonlinear relationships. The predicted values of the time series in the time period t, obtained using a nonlinear autoregressive model of neural networks, are described by the following equation [38]:

$$y_t' = f\,(y(t-1), y(t-2), \ldots , y(t-p), + \varepsilon_t \qquad (2.18)$$

Neural network models often give an ideal approximation of the actual and model data within the training sample, but in the case of insufficient data for training, large forecast errors. To improve the predictive qualities of ANN, a number of methods are used, including: various options for cross-validation, noise reduction, error regularization, error backpropagation [38], an optimized approximation algorithm, and SVM models. The latter are based on minimizing the structural risk of data, while neural networks are based on minimizing empirical risk [23]. Scientists are currently proposing a range of hybrid models that are based on two or more traditional machine learning or artificial intelligence methods. Traditionally, time series forecasting methods such as ANN, ARIMA are supplemented with optimization methods, which include the particle swarm method, PSO, genetic algorithm, GA, ant algorithm, ASO. Examples include the hybrid model presented by Malaysian students [23], which combines the ARIMA model to identify periodicity, seasonality, and linearity with an evolutionary algorithm (EA) to efficiently determine and optimize residuals, or a hybrid harmonic regression model that uses a stochastic differential approach. equations (SDE) for simulating residuals [19].

3 MATHEMATICAL MODELS OF ELECTRIC POWER SYSTEMS

3.1 Mathematical model of a multi-machine power system Statistics of the power system of Kazakhstan

Electricity throughout the world is divided into several types such as: thermal, nuclear, hydropower and the last time is actively developing renewable energy sources, wind power and solar power. According to the rating agency ARFC (Almaty Regional Financial Centre), the share of energy consumption for the period 2005–2015 was: oil — 32.9, natural gas — 23.8, coal — 29.2, nuclear energy — 4.4, hydropower — 6.8, renewable sources — 2.8. (figure 5) [3].

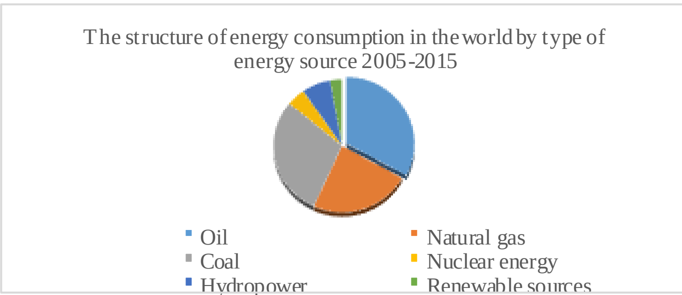


Figure 5. The structure of energy consumption in the world by type of energy source 2005-2019

Electric power generation in Kazakhstan is carried out by 138 power plants of various forms of ownership. As of 01.01.2009, the total installed capacity of power plants in Kazakhstan is 21 901.9 MW, the available capacity is 18 894.9 MW.

Transmission lines and distribution networks of Kazakhstan are divided into 3 parts: two in the North and one in the South, each of which is connected to an external energy system (the Russian energy system in the North and the Unified energy system of Central Asia in the South).

However, these systems are connected by only one line. The Northern networks, which serve coal-fired power plants and make up most of the installed capacity, have started to export electricity to Russia.

The initial stage of research in the field of power system management is associated with the definition of new principles of their construction and the beginning of the creation of system automation.

At this stage, a computational experiment and full-scale tests were carried out, which showed that the method of coarse synchronization leads to unacceptable voltage fluctuations in the electric power system and imposes excessively stringent requirements for the accuracy and speed of the generator speed control systems. Existing regulators during synchronization through the reactor led to the rotation of the synchronous generator rotors. As a result, the first automatic synchronizer for the electric power system with a frequency of 400 Hz – E1 – 16 – 1 was created.

With the development of computer technology, research on the behavior of the electric power system in the management process continued. In particular, a study was conducted of power fluctuations in parallel operation of generating units with failures of speed and voltage regulators. Several generations of functional automation devices of the electric power system are created for frequency and voltage regulation, distribution of active and reactive loads, switching on generators for parallel operation, power plant load programming, protection, control and signaling.

The Unified Electric Power System of the Republic of Kazakhstan includes:

• The national power transmission system, consisting of overhead lines with voltage 110-220- 500-1150 kV serviced by the Kazakhstan Electricity Grid Operating Company (JSC KEGOC);

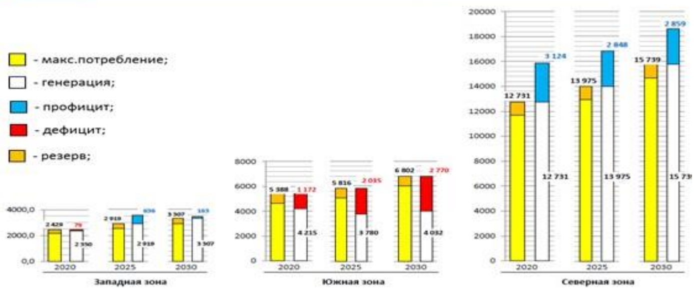
• 8 power plants of national importance, ensuring the production of significant amounts of electricity and connected directly to the National Transmission Network;

• 49 power plants integrated with territories connected to the National network directly or through networks of distribution companies and networks of other legal entities;

• 21 Electric Distribution Company (JSC EDC), software containing distribution networks kV distribution networks and below and connected directly to the National network;

• large consumers whose substations are directly connected to the National network.

The united electric power system of Kazakhstan can be divided into four main zones: Northern, Southern, Eastern and Western.



The Northern zone, which includes the East Kazakhstan, Pavlodar, Akmola, Karaganda, North Kazakhstan, Kustanai regions and the capital of the Republic - Nur-Sultan, is the center of formation of the Unified energy system of Kazakhstan, where most of the electricity sources are concentrated and there are developed electrical networks 220-500- 1150 kV, linking the Unified Electric Power System of Kazakhstan with the Unified Electric Power System of Russia. This zone is energy abundant, part of it is transferred to the Southern region of Kazakhstan and part of it is exported to Russia.

The southern zone, which includes Almaty, Zhambyl, Kyzylorda, South Kazakhstan regions, the country's largest metropolis is Almaty, is united by a common network and has a developed electrical connection with Kyrgyzstan and Uzbekistan.

The Western zone, which includes Atyrau, West Kazakhstan, Mangystau regions, due to its geographical distance and lack of electrical connections, operates in isolation from the rest of the Unified Energy System of Kazakhstan and is not connected with it by a single technological process.

Kazakhstan has large reserves of energy resources (oil, gas, coal, uranium) and is a commodity country, living through the sale of natural energy reserves (80% of exports are raw materials, and the share of industrial exports is reduced annually).

The total installed capacity of all power plants in Kazakhstan is 20 thousand MW, and the actual capacity is 15 thousand MW. Generation by type of power plant is distributed as follows [4]:

TPP (thermal power plants) — 87.7 %, including:

- condensing power plants— 48,9 %;
- combined heat power plants— 36,6 %;
- gas turbine electric power plants— 2,3 %;

hydro power plants — 12,3 %.

About 72% of electricity in Kazakhstan is produced from coal, 12.3% -from hydro resources, 10.6 % — from gas and 4.9 % — from oil. Thus, the four main types of power plants generate 99.8% of electricity, while alternative sources account for less than 0.2%. In the capacity structure, 88% is accounted for by thermal power plants, 12% by hydro power plants and less than 1% by other types of generation [19].

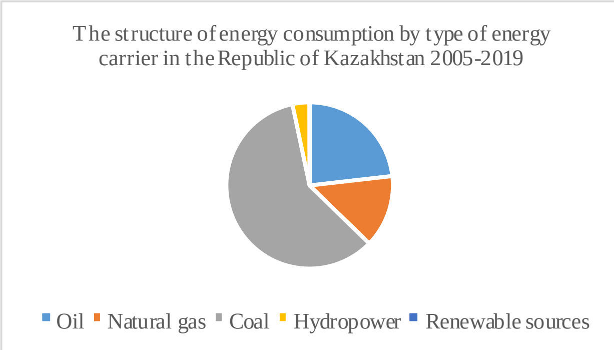


Figure 6. The structure of energy consumption by type of energy carrier in the Republic of Kazakhstan 2005-2015

According to the rating agency ARFC (Almaty Regional Financial Centre), the share of energy consumption for the period 2005-2019 in Kazakhstan was: oil - 23.2, natural gas - 14.1, coal - 59.4, hydropower - 3.3, renewable sources - 0.02 [20].

The following table shows the consumption and production of electricity and the share of renewable energy in production in recent years in Kazakhstan.

Table 3. The consumption and production of electricity and the share of renewable energy in production in recent years in Kazakhstan.

Year	**Production**	**Consumption**	**Renewable energy**
2019	106,797billion kWh	103,228 billion kWh	1,352 billion kWh
2018	102,384 billion	97,857 billion.	1,100 billion kWh
2017	93,9 billion kWh	92,1 billion kWh	0,928 billion kWh
2016	90.8 billion kWh	90,9 billion kWh	0,704 billion kWh
2015	93.9 billion kWh	90,4 billion kWh	0,580 billion kWh

According to the data, it can be seen that the share of use of renewable energy sources in the production of electricity in

Kazakhstan is insignificant, since this industry has been developing recently.

The electric power system of the Republic of Kazakhstan was inherited from the former USSR, and now there is a need to upgrade equipment and build new transmission and distribution facilities. In the modern conditions of development of the power industry of Kazakhstan with a high level of wear and insufficiently high rates of equipment modernization, this issue is even more acute. In addition to the need for modernization in the power industry of Kazakhstan, it is required to evaluate the effectiveness of the use of modern equipment and the conditions of its normal operation.

3.2 Mathematical model of unsteady processes in the electrical system

The importance of the problem of stability of equilibrium states, or in general, the stability of motion, in various fields of science and technology is well known. It is also of great importance for electric power systems. Without a reliable solution to this problem, it is impossible to provide reliable and high-quality electricity to consumers in almost all industries.

The mathematical model of a modern electric power complex consisting of turbine generators and complex multiply connected energy blocks is a system of nonlinear ordinary differential equations. It is known that this model serves as the basis for a wide and relevant class of control tasks.

It should be noted that mathematical modeling of various processes and systems, including electric power, is closely interrelated with the problems of making the best decisions. Problems of optimality, stability, as well as the creation of algorithms for building controls on the feedback principle for such systems still attract the attention of many researchers and are relevant

Mathematical models of problems of stability, optimal control and stabilization of electric power systems have been developed to describe the operation of electric power systems.

The general mathematical model of multidimensional complex electric power systems, which is described by a system of nonlinear differential equations is shown below:

$$\begin{aligned}
&\frac{d\delta_i}{dt} = S_i, \\
&\frac{dS_i}{dt} = w_i - D_i S_i - f_i(\delta_i) - \psi_i(\delta_{i^*}), \quad w_i = C_i^* x_i, \\
&\frac{dx_i}{dt} = A_i x_i + q_i S_i + b_i u_i, \quad i = \overline{1,l},
\end{aligned} \tag{3.1}$$

where the function

$$\psi_i(\delta_{i^*}) = \sum_{\substack{k=1, \\ k \neq i}}^{l} P_{ik}(\delta_{ik}), \qquad \delta_{ik} = \delta_i - \delta_k \tag{3.2}$$

The function $\psi_i(\delta_{i^*})$ describes the interactions of the generators and will be expanded as follows:

$$\psi_i(\delta_{i^*}) = \sum_{\substack{j=1, \\ j \neq i}}^{l} \frac{1}{T_i}\left[P_{ij}\sin(\delta_{ji0} + \delta_{ji} - P_{ij}\sin\delta_{ij0})\right] \tag{3.3}$$

Periodic continuously differentiable function $f_i(\delta_i)$ is determined by the following formula:

$$f_i(\delta_i) = \frac{1}{T_i}[P_i \sin(\delta_{i0} + \delta_i) - P_i \sin\delta_i], \quad i = \overline{1,l}, \tag{3.4}$$

In system (1) δ_i is rotor angle of the i -th generator respect to a synchronous rotational axis; S_i - sliding the i -th generator; $D_i > 0$ - damping coefficient.

To ensure reliable operation of electric power systems for the system (3.1), it is necessary to determine the area where the phase trajectories tend to a specific stable equilibrium position. The stability study “in a large” system (3.1) will be carried out in a band $G_{0i} = \{(\delta_i, S_i, x_i) | \delta_{-1i} < \delta_i < \delta_{0i},\ S_i \in R_i^1,\ \ x_i \in R_i^{n_i}\}$ using the second Lyapunov method.

The article also considered a mathematical model of motion stabilization of the electric power system for n synchronous generators, which is described by the following system of differential equations:

$$\frac{d\delta_i}{dt} = S_i,$$
$$\frac{dS_i}{dt} = c_i x_i - K_i S_i - f_i(\delta_i) - P,$$
$$\frac{dx_i}{dt} = A_i x_i + u_i$$

where the first 2 equations describe the operation of the system, and the last equation describes the state of the regulator. As well as x_i –phase variables; c_i – scalars; u_i – control; δ – angle of rotation of the rotor; S — sliding the generator;

$$f_i(\delta_i) = \frac{1}{T}[P_i \sin(\delta_{i0} + \delta_i) - P_i \sin \delta_{i0}]$$
$$P_{ij} = \sum_{i \neq j, j=1, i=1}^{n} \frac{1}{T_i}(P_{oj}(\sin(\delta_{ji} - \delta_{ii}) + \delta F_{ji} - \sin(\delta F_{ij}))$$

Numerical solution

For the numerical implementation of the problem of stabilization of electric power systems, the following algorithms will be used, which will give a more accurate solution of these problems.

Table 4. Coefficients and error constants for the Adams–Bashforth method[21]

k	β1	β2	β3	β4	β5	β6	β7	β8	C
1	1								$-\frac{1}{2}$
2	$\frac{3}{2}$	$-\frac{1}{2}$							$\frac{5}{12}$
3	$\frac{23}{12}$	$-\frac{4}{3}$	$\frac{5}{12}$						$-\frac{3}{8}$
4	$\frac{55}{24}$	$-\frac{59}{24}$	$\frac{37}{24}$	$-\frac{3}{8}$					$\frac{251}{720}$
5	$\frac{1901}{720}$	$-\frac{1387}{360}$	$\frac{109}{30}$	$-\frac{637}{360}$	$\frac{251}{720}$				$-\frac{95}{288}$
6	$\frac{4277}{1440}$	$-\frac{2641}{480}$	$\frac{4991}{720}$	$-\frac{3649}{720}$	$\frac{959}{480}$	$-\frac{95}{288}$			$\frac{19087}{60480}$
7	$\frac{198721}{60480}$	$-\frac{18637}{2520}$	$\frac{235183}{20160}$	$-\frac{10754}{945}$	$\frac{135713}{20160}$	$-\frac{5603}{2520}$	$\frac{19087}{60480}$		$-\frac{5257}{17280}$
8	$\frac{16083}{4480}$	$-\frac{1152169}{120960}$	$\frac{242653}{13440}$	$-\frac{296053}{13440}$	$\frac{2102243}{120960}$	$-\frac{115747}{13440}$	$\frac{32863}{13440}$	$-\frac{5257}{17280}$	$\frac{1070017}{3628800}$

Table 5. Coefficients and error constants for the Adams-Moulton method [21]

k	β0	β1	β2	β3	β4	β5	β6	β7	C
0	1								$\frac{1}{2}$
1	$\frac{1}{2}$	$\frac{1}{2}$							$-\frac{1}{12}$

2	$\frac{5}{12}$	$\frac{2}{3}$	$-\frac{1}{12}$						$\frac{1}{24}$
3	$\frac{3}{8}$	$\frac{19}{24}$	$-\frac{5}{24}$	$\frac{1}{24}$					$-\frac{19}{720}$
4	$\frac{251}{720}$	$\frac{323}{360}$	$-\frac{11}{30}$	$\frac{53}{360}$	$-\frac{19}{720}$				$\frac{3}{160}$
5	$\frac{95}{288}$	$\frac{1427}{1440}$	$-\frac{133}{240}$	$\frac{241}{720}$	$-\frac{173}{1440}$	$\frac{3}{160}$			$-\frac{863}{60480}$
6	$\frac{19087}{60480}$	$\frac{2713}{2520}$	$\frac{235183}{20160}$	$-\frac{10754}{945}$	$\frac{135713}{20160}$	$-\frac{5603}{2520}$	$-\frac{863}{60480}$		$\frac{275}{24192}$
7	$\frac{5257}{17280}$	$\frac{139849}{120960}$	$-\frac{4511}{4480}$	$\frac{123133}{120960}$	$-\frac{88547}{120960}$	$\frac{1537}{4480}$	$-\frac{11351}{120960}$	$\frac{275}{24192}$	$-\frac{33953}{362880}$

1 algorithm. Multistep method of Adams–Bashforth.

1-step. The initial values δ, S, x for $t=0$ and c, K, P, A are known.

2-step. For finding δ, S, x at points 1,2,3,4, we use the 4th order Runge-Kutta method.

$$\delta_{i+1} = \delta_i + \frac{1}{6}(m_1 + 2m_2 + 2m_3 + m_4)$$

$$m_1 = \Delta t(S_i)$$

$$m_2 = \Delta t\left(S_i + \frac{1}{2}m_1\right)$$

$$m_3 = \Delta t\left(S_i + \frac{1}{2}m_2\right)$$

$$m_4 = \Delta t\left(S_i + \frac{1}{2}m_3\right)$$

$$S_{i+1} = S_i + \frac{1}{6}(m_1 + 2m_2 + 2m_3 + m_4)$$

$$m_1 = \Delta t((cx_i - KS_i - f_i(\delta_i) - P_{12}))$$

$$m_2 = \Delta t\left((c(x_i + \frac{1}{2}m_1) - K(S_i + \frac{1}{2}m_1) - f_i(\delta_i + \frac{1}{2}m_1) - P_{12})\right)$$

$$m_3 = \Delta t\left((c(x_i + \frac{1}{2}m_2) - K(S_i + \frac{1}{2}m_2) - f_i(\delta_i + \frac{1}{2}m_2) - P_{12})\right)$$

$$m_4 = \Delta t\left((c(x_i + \frac{1}{2}m_3) - K(S_i + \frac{1}{2}m_3) - f_i(\delta_i + \frac{1}{2}m_3) - P_{12})\right)$$

$$x_{i+1} = x_i + \frac{1}{6}\left(m_1 + 2m_2 + 2m_3 + m_4\right)$$

$$m_1 = \Delta t((Ax_i + u)$$

$$m_2 = \Delta t\left(A(x_i + \frac{1}{2}m_1) + u\right)$$

$$m_3 = \Delta t\left(A(x_i + \frac{1}{2}m_2) + u\right)$$

$$m_4 = \Delta t\left(A(x_i + \frac{1}{2}m_3) + u\right)$$

3-step. Starting i=4 to i=n, we find δ, S, x by the multistep Adams–Bashforth method. The coefficients of the Adams–Bashforth method are shown in Table 4.

$$\delta_{i+1} = \delta_i + \Delta t\left(\frac{1901}{720}S_i - \frac{1387}{360}S_{i-1} + \frac{109}{30}S_{i-2} - \frac{637}{360}S_{i-3} + \frac{251}{720}S_{i-4}\right)$$

$$S_{i+1} = S_i + \Delta t\left(\begin{array}{l} \frac{1901}{720}(cx_i - KS_i - f_i(\delta_i) - P_{12}) - \\ -\frac{1387}{360}(cx_{i-1} - KS_{i-1} - f_{i-1}(\delta_{i-1}) - P_{12}) + \\ +\frac{109}{30}(cx_{i-2} - KS_{i-2} - f_{i-2}(\delta_{i-2}) - P_{12}) - \\ -\frac{637}{360}(cx_{i-3} - KS_{i-3} - f_{i-3}(\delta_{i-3}) - P_{12}) + \\ +\frac{251}{720}(cx_{i-4} - KS_{i-4} - f_{i-4}(\delta_{i-4}) - P_{12}); \end{array}\right)$$

$$x_{i+1} = x_i + \Delta t \begin{pmatrix} \frac{1901}{720}(Ax_i + u) - \frac{1387}{360}(Ax_{i-1} + u) + \\ + \frac{109}{30}(Ax_{i-2} + u) - \frac{637}{360}(Ax_{i-3} + u) + \frac{251}{720}(Ax_{i-4} + u); \end{pmatrix}$$

2 algorithm. Multistep method of Adams-Moulton.

1-step. The initial values δ, S, x for $t = 0$ and coefficients c, K, P, A are known.

2-step For finding δ, S, x at points 1,2,3,4, we use the Euler's method.

$$\begin{aligned} \delta_{i+1} &= \delta_i + \Delta t(S_i) \\ S_{i+1} &= S_i + \Delta t(cx_i - KS_i - f_i(\delta_i) - P_{12}) \\ x_{i+1} &= x_i + \Delta t(Ax_i + u) \end{aligned}$$

3-step. Starting i=4 to i=n we find i=n δ, S, x by the multistep Adams–Bashforth method. The coefficients of the Adams–Bashforth method are shown in Table 5.

$$\delta_{i+1} = \delta_i + \Delta t\left(\frac{251}{720}S_i + \frac{323}{360}S_{i-1} - \frac{11}{30}S_{i-2} + \frac{53}{360}S_{i-3} - \frac{19}{720}S_{i-4}\right)$$

$$S_{i+1} = S_i + \Delta t \begin{pmatrix} \frac{251}{720}(cx_i - KS_i - f_i(\delta_i) - P_{12}) + \\ + \frac{323}{360}(cx_{i-1} - KS_{i-1} - f_{i-1}(\delta_{i-1}) - P_{12}) + \\ - \frac{11}{30}(cx_{i-2} - KS_{i-2} - f_{i-2}(\delta_{i-2}) - P_{12}) + \\ + \frac{53}{360}(cx_{i-3} - KS_{i-3} - f_{i-3}(\delta_{i-3}) - P_{12}) + \\ - \frac{19}{720}(cx_{i-4} - KS_{i-4} - f_{i-4}(\delta_{i-4}) - P_{12}); \end{pmatrix}$$

$$x_{i+1} = x_i + \Delta t \begin{pmatrix} \frac{251}{720}(Ax_i + u) + \frac{323}{360}(Ax_{i-1} + u) - \\ -\frac{11}{30}(Ax_{i-2} + u) + \frac{53}{360}(Ax_{i-3} + u) - \frac{19}{720}(Ax_{i-4} + u); \end{pmatrix}$$

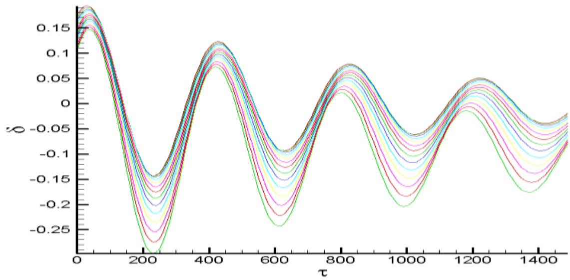


Figure 7. Angle of rotor rotation at l = 15

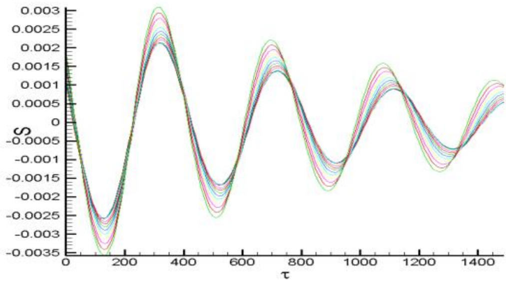


Figure 8. Generator slide at l=15

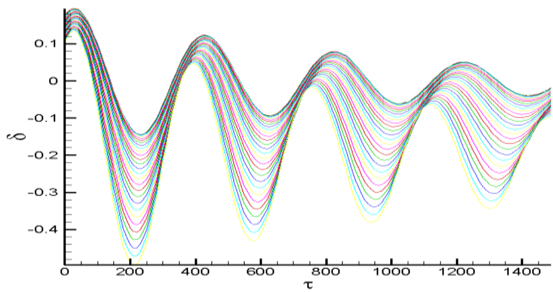


Figure 9. Angle of rotor rotation at l=30

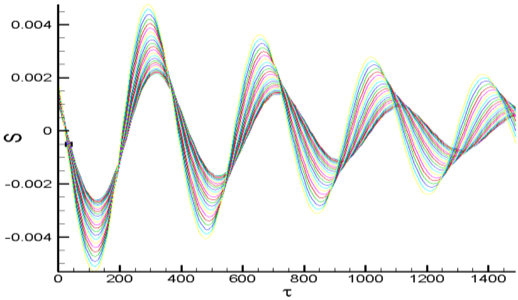


Figure 10. Generator slide at l=30

4 DEVELOPMENT OF AN INTELLIGENT INFORMATION COMPLEX FOR ELECTRIC POWER SYSTEMS

4.1 Creation of information models and definition of IMS concepts based on mathematical models

4.1.1 Requirements for the information system of the electric power system

The information system is designed to generate automatic control commands and issue them to the remote control subsystem and other subsystems. The information system includes means of logical transformation and formation of control commands. The system should be built according to a hierarchical principle and provide: reception and processing of information and commands; formation of group control teams according to specified programs; issuance of information about the progress of programs and the reasons for its delay or non-execution.

The control hierarchy should be determined by the conditions for ensuring the reliability and quality of control, taking into account the possibility of failure of control devices of various levels (rank). Moreover, each level of control must have a specific functional purpose.

With automatic control, it must be possible to execute both the entire program and a part of it specified by the operator. In case of failure of higher-level devices, the corresponding commands must be executed by devices of a lower rank.

The automatic control system receives the following information: the position of the controlled object; values of technological parameters; teams of operating personnel.

Control commands are issued to the remote control, alarm and automatic regulation system.

The system must allow multiple changes to the control program at each control level.

In the event of a loss of power and its subsequent restoration, no false control commands should be issued.

At the top level of management, the organization of the corresponding lower levels should take place. When developing a control system, it is necessary to decide for which lower levels the upper control level should be provided.

Based on the requirements for an intelligent information system, information models were created using the unified graphical modeling language (UML) to describe, visualize, design and document the system.

Figure 11 shows a diagram of the distribution of activity States between roles.

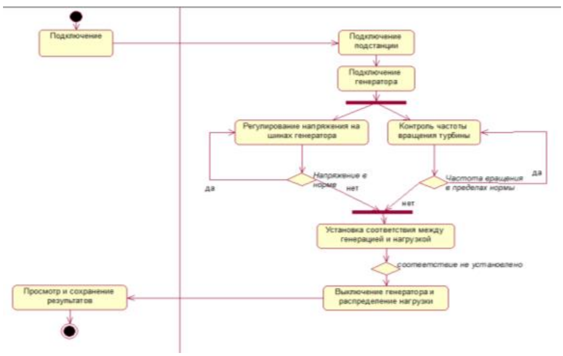


Figure 11-Diagram of activity state distribution between roles

The next step in developing a software product is to build a case diagram. Figures 12-13 show diagrams: sequences of use cases and classes.

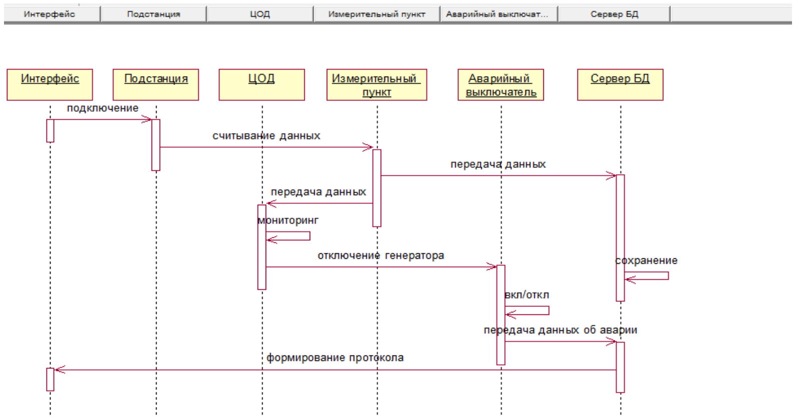


Figure 12- Diagram of case sequence

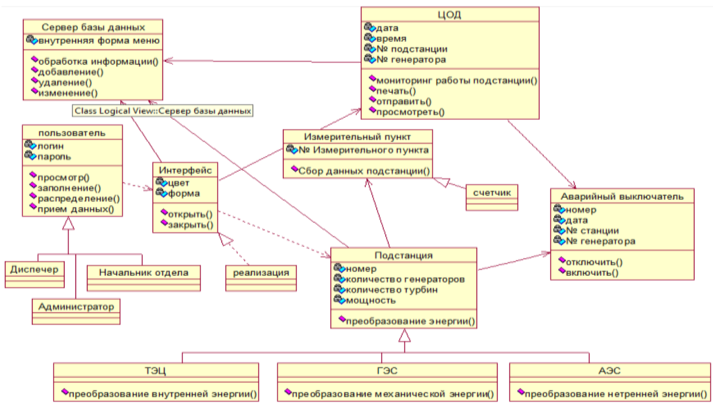


Figure 13- Diagram of classes

In figures 14-18 present the interface of the information system

Figure 14-Logging in

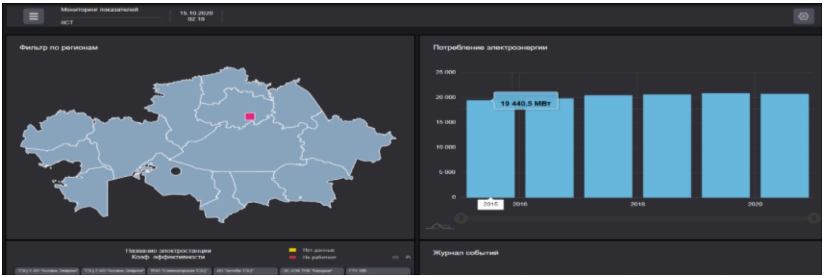


Figure 15-General characteristics of electric power systems in the information system

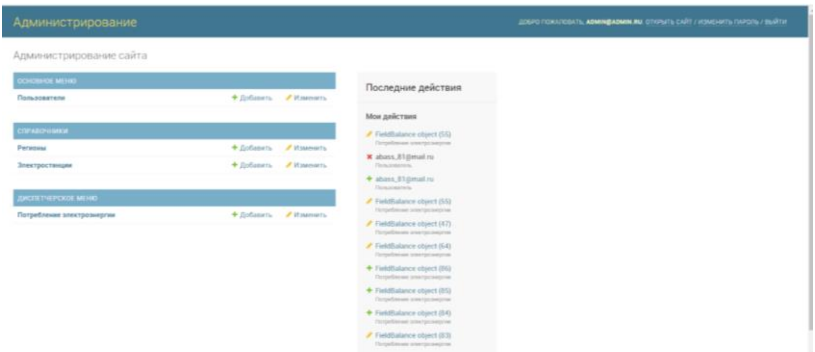


Figure 16 - Administrator interface for the system

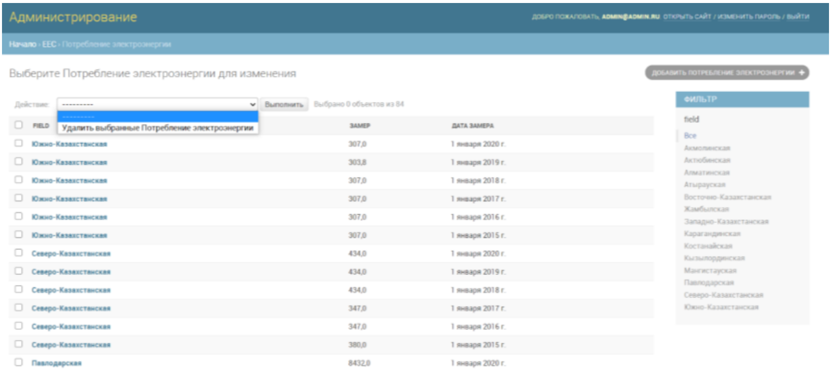


Figure 17-MS SQL DBMS

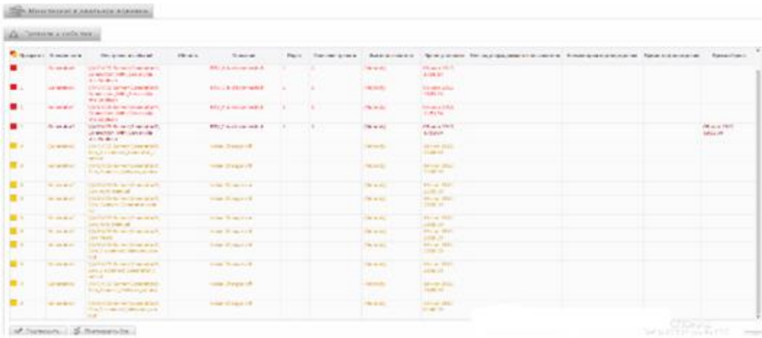


Figure 18-Operator screen. Threats and events

The concept of intelligent power systems has the following characteristics [1]:

- Smart electricity systems facilitate consumer participation in the grid. Consumers can produce energy from various distributed energy resources, see in real time how much electricity they are using, and thus they can decide to participate in a demand / response plan.

- Smart power systems support all generation types and plug-and-play storage options. Generation can either be centralized, such as nuclear, which we usually have in a plant, or distributed using different natural resources.

- Intelligent power systems enable new products to be introduced to the market. New real-time markets are possible for buying and selling electricity and services.
- Intelligent power systems optimize the operation of electricity in the grid system.
- Intelligent power systems are self-healing and resistant to attacks such as cyber and physical attacks. They are expected to recover quickly from natural disasters such as tornadoes and hurricanes.

4.2 Modeling and implementation of multi-agent systems

The proposed multi-agent system includes various intelligent agents representing various components. Each agent has a localized knowledge base containing rules and behaviors that governs the decision-making process. The use of a multi-agent control system in the electric power industry will make it possible to form a distributed real-time control system that implements the interaction of the personnel of an intelligent electric power system with automated and automatic complexes based on software and hardware intelligent agents. Figure 19 shows the relationship of agents in electric power systems.

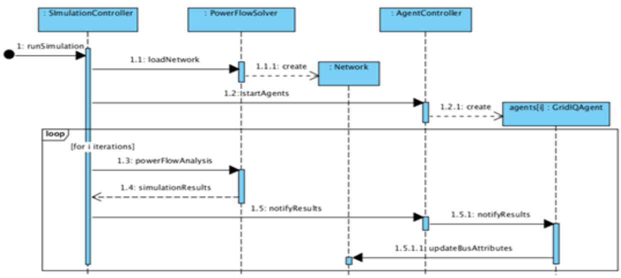


Figure 19-Relationships of agents in electric power systems

When using a multi-agent control system in the electric power industry, it is necessary to take into account the specifics of the operation of electrical equipment and individually approach the development of a multi-agent control system for individual objects.

In the proposed system, as receptors, sensors are used, as well as counters and analyzers of electric power quality indices. Effectors are programmable controllers that implement automatic regulators of excitation (ARV) and rotation frequency (ARV) of generators. The main functions of the agents of the proposed multi-agent control system and their communication (Figure 20) can be shown as follows:

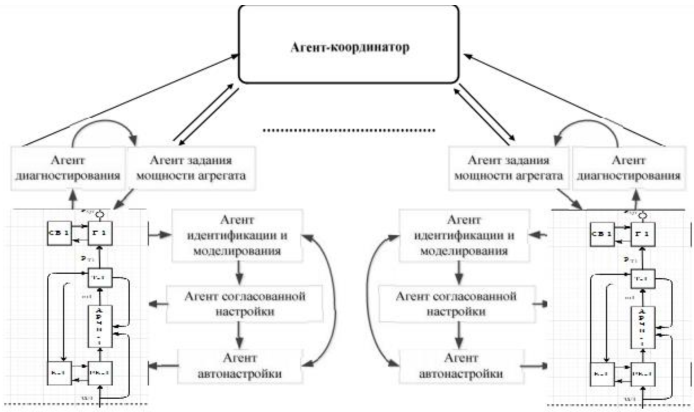


Figure 20-Structure of a multi-agent control system

The proposed multi-agent control system is positioned as a self-organizing system with the ability of agents to initiate a dialogue based on the analysis of a situation that is not prescribed in advance and operates under conditions of uncertainty.

The model structure developed using the AnyLogic platform system dynamics library is shown in figure 21. Circles represent dynamic variables that can change during the simulation. Squares indicate the storage devices that allow the differentiation process to be implemented.

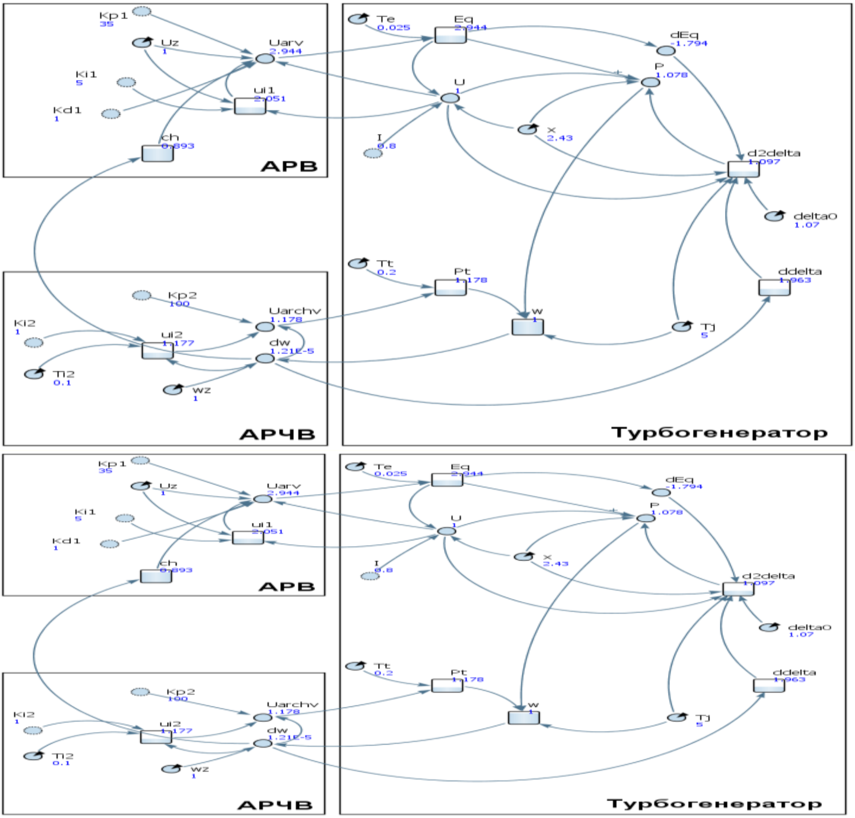


Figure 21-Structure of the distributed generator installation model with ARV and ARV in AnyLogic [24]

The model is based on the following system of equations:

$$\frac{d\delta_i}{dt} = S_i, \qquad i = \overline{1,l}$$

$$\frac{dS_i}{dt} = w_i - K_i S_i - f_i(\delta_i) - \psi_i(\delta_{i^*}), \qquad w_i = C_i^* x_i, \qquad i = \overline{1,l}$$

$$\frac{dx_i}{dt} = A_i x_i + q_i S_i + b_i u_i + R_i(S_i, x_i), \qquad i = \overline{1,l}$$

where δ_i-angular coordinates; S_i- angular velocities; $x_i - n_i$-state vector of the controller; w_i- managing the impact on facilities management; $K_i > 0$–the damping coefficients of the control object; C_i, q_i, b_i - constant-dimensional vectors for each; n_i - constant matrix of order i; A_i - the control effect of the regulator $n_i \times n_i$, A_i - formed on the principle of feedback; functions

$$\psi_i(\delta_{i^*}) = \sum_{\substack{k=1 \\ k \neq i}}^{l} p_{ik}(\delta_{ik}), \qquad \delta_{ik} = \delta_i - \delta_k, \qquad i = \overline{1,l}$$

characterize the effects on the subsystem and other subsystems; $f_i(\delta_i)$ - continuously differentiable periodic functions satisfying the conditions

$$f_i(\delta_i) = f_i(\delta_i + 2\pi), \qquad \forall \delta_i \in E^1, \qquad \gamma_{0i} = \frac{1}{2\pi}\int_0^{2\pi} f_i(\delta_i)d\delta_i \leq 0,$$

$$f_i(0) = 0, \qquad \frac{df_i(\delta_i)}{d\delta_i}\Big|_{\delta_i=0} > 0, \qquad f_i(\delta_{0i}) = 0, \qquad \frac{df_i(\delta_i)}{d\delta_i}\Big|_{\delta_i=\delta_{0i}} < 0,$$

$$0 < \delta_{0i} < 2\pi, \qquad i = \overline{1,l}$$

For each fixed, i second-order differential equations (3.1) describe the processes in i the control object (total control objects l), and the vector differential equation (3.2) defines the equation of motion of the control i object controller.

In particular, for electric power control systems, equations (3.1) describe the rotational motion of the rotor of i synchronous generator, the δ_i value is the difference in the rotation angles of the rotor at the nominal frequency and the electromotive force generated by the generator in relative units, i the function determines the power of the generator in relative units $f_i(\delta_i)$, and Express the mutual effects of the generators i on each other through a common electric line $\psi_i(\delta_{i^*})$.

Equations (3.2) describe the dynamics of the steam boiler, i the steam turbine automatic speed controller and the excitation system on generator, w_i exposure, develop a controller to stabilize the rotational motion of the rotor i - generator, u_i - control generated by the computer to ensure synchronous operation of all generators running the electricity network.

The equations of perturbed motion i - generator in the classical model of the power system [25] have the form:

$$\frac{d\delta_i}{dt} = w_{ном} s_i,$$
$$H_i \frac{dS_i}{dt} = -D_i S_i - f_i(\delta_i) - \sum_{\substack{j=1 \\ j \neq i}}^{l} f_{i,j}(\delta_i - \delta_j) + P_{T_i}, \quad i = \overline{1,l},$$

Where $f_i(\delta_i) = P_i \sin(\delta_i^0 + \delta_i) - P_i \sin\delta_i^0$, P_i, δ_i^0 - constant,
$f_{ij}(\delta_i - \delta_j) = P_{ij} \sin(\delta_{ij}^0 + \delta_i - \delta_j) - P_{ij} \sin\delta_{ij}^0$, $\delta_{ij}^0 = \delta_i^0 - \delta_j^0$, P_{ij}, δ_i^0 - constant.

Here δ_i is the deviation of the angle between the EMF of the generator and the voltage at the bus i -th generator from its value in steady δ_i^0 -state disaster mode, $s_i = (w_i - w_{ном}) / w_{ном}$ a deviation of angular velocity (sliding) i -th generator, D_i is the damping factor on the generator, the deviation of the power turbine from their values in steady i -state post P_{T_i} -fault mode, $P_{T_{i0}}$ - moment of inertia of the rotor on the generator, H_i – electrical power of the i - th generator and external mutual P_i, P_{ij} power flow between i – th and j –th generator.

The relationship between the control effect $w = w_i(t)$ and the i power deviation of the turbine P_{T_i} in the simplest case [26,27] is determined by the differential equation

$$T_{ni}\frac{dP_{Ti}}{dt} = \mu_i - P_{Ti}, \qquad T_{S_i}\frac{d\mu_i}{dt} = -\mu_i - \frac{1}{\sigma_i}S_i + K_i w_i,$$

where the $\mu_i = \mu_i(t)$ relative movement of the flap closing the access to couple T_{n_i} – time constant representing the inertia of the steam in the reheater tubes, the σ_i ratio of droop on the speed controller (ARCU), K_i – the gain channel to the central control system, the i control action depends on phases the status of all generators.

The structure of relations of agents in the model shown in figure 22. The diagnostic agent has the receptors, allowing to measure parameters of the turbine, and the agent job power osnan an effector which changes the output active power of the turbine.

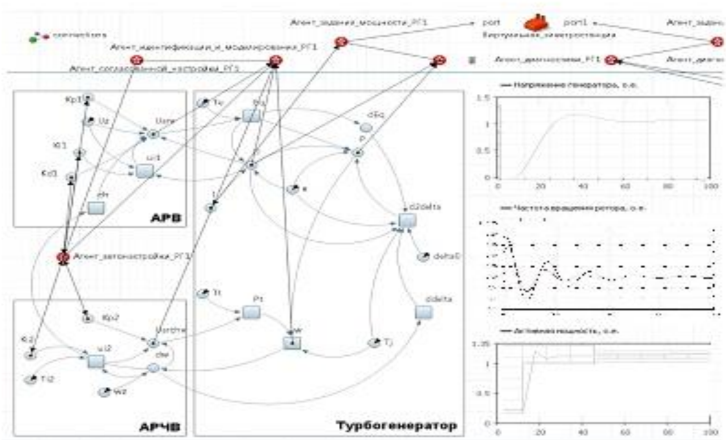


Figure 22-Model of a multi-agent control system with agent connections Shown

4.3 Application of IT technologies in electric power systems based on a mathematical model for an intelligent information system

IT technologies make it possible to build multi-agent control and optimize the shutdown time of generating equipment, as well as minimize the risk of accidents in power systems.

IT technologies consist of intelligent sensor devices, such as smart sensors, intelligent systems, actuators, and an intelligent processor, to create a relationship between each other [28]. To develop an automated information management system, we use the following mathematical model:

$$x_{k+1} = A_d x_k + B_d u_k + n_k \tag{4.1}$$

where A_d is the system state matrix, x_k is the system state at time k , B_d is the input matrix, u_k is the control value, and n_k is the process noise.

To identify and control sensors and actuators, system operators place IoT elements. Basically, the system measurements are obtained using the IOT element, in the form of the following system:

$$z_k = Cx_k + w_k \tag{4.2}$$

where z_k is the observation information at time k, C is the observation matrix, and a w_k is the measurement noise. Monitoring information is sent to the merge center over the IoT network, which leads to a delay or loss of measurements due to packet drop [28]. Taking into account the loss of observation information, the measurement model (4.1) can be reformulated as follows:

$$y_k = a_k C x_k + a_k w_k$$

where λ_k is the obtained measurements under the condition of observation information loss, and $a_k \in \{0,1\}$ is an IoT-based information loss parameter that follows the Bernoulli distribution modeled as follows [28]:

$$a_k = \begin{cases} 1, & \text{with probability of } \lambda_k \\ 0, & \text{with probability of } 1-\lambda_k \end{cases}$$

where λ_k is the rate at which information is received from each observation in the merge center. As a rule, the estimation of the dynamic state taking into account information loss in the IoT network is written as follows:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(y_k - a_k C\hat{x}_{k|k-1})$$

where $\hat{x}_{k|k}$ is the updated state estimate, $\hat{x}_{k|k-1}$ is the predicted state estimate, and K_k is the gain.

Usually the predicted state and error covariance are calculated as follows:

$$\hat{x}_{k|k-1} = A_d\hat{x}_{k-1|k-1} + B_d u_{k-1}$$
$$P_{k|k-1} = A_d P_{k-1|k-1} + A_d' + +Q_{k-1}$$

where $\hat{x}_{k-1|k-1}$ is the estimated state of the previous step, and $P_{k-1|k-1}$ is the covariance matrix of errors of the previous phrase. Based on the above-mentioned filtering process, the optimal gain is designed so that the assumed state converges with the actual state K_k. The IOT communication infrastructure with the evaluator and controller is illustrated in figure 22.

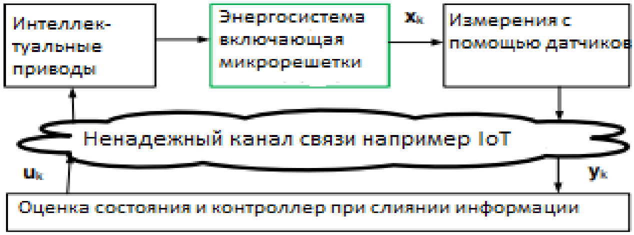


Figure 22-IOT Application for monitoring and stabilizing the microplastics

Life cycle management of power equipment status

Smart enterprises use Internet of things technology through RFID, GPS and other sensors to monitor and collect all aspects of power equipment information (including environment, conditions, accounting, testing, defects, reasonable choice of statistical methods), analyze the current state of equipment, future development law and major influencing factors to form a method of equipment risk assessment based on Internet of things technology, this system can dynamically update added, distributed, maintenance, inactive, unnecessary and other historical data. In this system, equipment status information and asset management information are effectively integrated, and supervision management is unified. The IOT-based power equipment lifecycle management system is shown in figure 23.

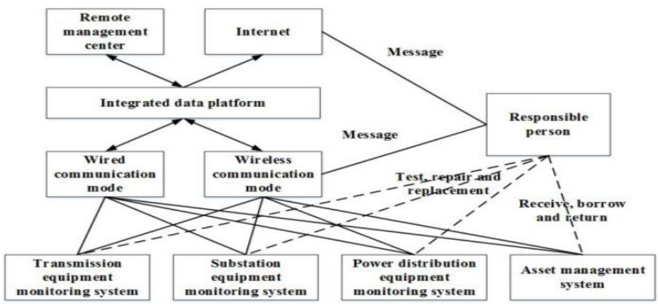


Figure-23 Life cycle management System for power equipment based on the Internet of things

To check the effectiveness of the system, a simulation test will be conducted for the performance of power equipment. The system can detect the operating state of power equipment in real time to improve management efficiency and realize intelligent and digital management of the power industry.

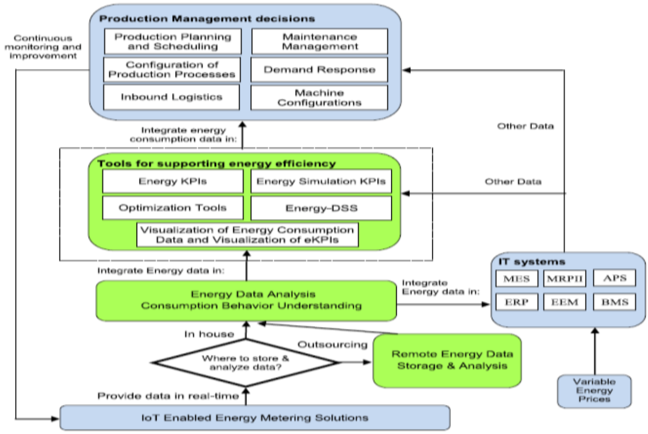


Figure 24-IOT-based energy data integration Framework in production management solutions

Internet of things has been an integral part of the transformation towards smart power grids. Examples of IoT technologies currently used in smart electrical systems include advanced measurement infrastructure (AMI) and dispatch control and data acquisition (SCADA) [12, 13]. There are several advantages to deploying IoT in smart electrical systems:

- Increased reliability, fault tolerance, adaptability, and energy efficiency
- Reduced the number of communication protocols
- Networking and advanced information management features
- Improved control over household appliances
- Enable on-demand and end-to-end access to information provision of services

- Improved touch capabilities
- Improved scalability and compatibility
- Mitigating damage from natural disasters
- Reduced physical attacks (for example, substation break-ins)

5 IMPLEMENTATION OF SHORT-TERM FORECASTING AND LONG-TERM PLANNING OF ELECTRICITY CONSUMPTION VOLUMES

Forecasting electricity consumption is critical in the operation and management of power systems and thus is a major research area in energy markets. There are many statistical methods that are used to predict the behavior of electrical loads, varying in different market conditions [17]. In this approach, the load circuit is treated as a time series signal, where various time series techniques are applied. The most common approach is the Box-Jenkins ARIMA model and SARIMAX [18,19]. SARIMA uses forecasting with dual seasonality (intraday and intraweekly cycles) inherent in load data. Neural networks (NN) and artificial neural networks (ANN) [20, 21] have been used to calculate long-term simulations.

The seasonal (or multiplicative) SARIMA model is an extension of the (ARIMA) model [22,23], when the series contains both seasonal and non-seasonal behavior, like the proposed time series loading model. Let and be non-negative integers, the series is a seasonal process ARIMA S with seasonality or period s, if the difference series is:

$$y_t = (1 - B)^d (1 - B^s)^D x_t$$

a random process ARMA (Brockwell and Davis, [20]), defined as:

$$\varphi_p(B)\Phi_p(B^s)y_t = \theta_q(B)\Theta_Q(B^s)\varepsilon_t$$

where B is the difference or delay operator, and the polynomials, θ (x) and are defined as follows:

In the ARIMA S form, the member is the non-seasonal part and the S is the seasonal part. Note here that the process yt is random if and only if = 0 and Φ (x) = 0 for | x | ≤ 1, while in applications d rarely exceeds 1, D = 1, and P and Q are usually less than 3 [20]. In addition, if the fitted model is appropriate, the recalculated residuals should have properties similar to those of the noise driving the ARIMA process. All subsequent diagnostic tests for residuals after model fitting are based on the expected properties of the residues, provided that the fitted model is correct and $\{\varepsilon_t\} \sim WN(O, \sigma^2)$

To include seasonal variables in the SARIMA model to obtain the SARIMAX model, the previous model is modified as follows:

$$\varphi_p(B)\Phi_p(B^s)y_t = c + \beta X_t + \theta_q(B)\Theta_Q(B^s)\varepsilon_t$$

where, as before, is a one-dimensional series of answers, in our case load is a row t from X, which is a matrix of predictors or explanatory variables, is a vector with regression coefficients corresponding to the predictors, c is the interception of the regression model, and εt is noise. Φp, ΦP, θq and ΘQ are as defined earlier, that is, the polynomials of the delay operator, seasonal and non-seasonal:

$$\underbrace{\Phi_p(B)}_{\textit{off-season AR}} \quad \underbrace{\Phi_p(B^s)}_{\textit{Season AR (SAR)}} \quad \underbrace{(1-B)^d}_{\textit{off-season integration}} \quad \underbrace{(1-B^s)^D}_{\textit{season integration}}$$

$$x_t = \underbrace{c}_{\textit{interception}} + \underbrace{\beta X_t}_{\textit{seasonal variables}} + \underbrace{\theta_q(B)}_{\textit{off-season MA}} \quad \underbrace{\Theta_Q(B^s) \quad \varepsilon_t,}_{\textit{season MA (SMA)}} \quad \varepsilon_t \sim WN(0,\upsilon^2)$$

5.1 Using machine learning to predict electricity consumption

Forecasting the generation, consumption, and balance of fuel and energy resources is an urgent global problem. According to the BP Statistical Review of World Energy [22], the consumption of primary energy resources in the world has grown 1.5 times over the past 20 years: from 9 billion metric tons of oil equivalent in 1998 to 13,5 billion tons in 2017. According to forecasts of the International Energy Agency (EIA), [23] energy consumption will increase by another 40% by 2050, primarily in Asian countries that are not members of the Organization for Economic Cooperation and Development (non-OECD Asia). In terms of energy sources, the largest growth in consumption of natural gas, hydropower, and renewable sources is expected [24].

According to experts, meeting the growing demand for energy, with a significant depletion of traditional sources, should be ensured by increasing the generation of electricity from renewable sources – solar radiation, biomass, wind energy, geothermal energy, hydropower, wind energy, tidal energy, dissipated thermal energy. Their rational use, as well as improving the energy efficiency of the economy, should contribute to sustainable economic development, to reduce damage to future generations, to decrease greenhouse gas emissions, to increase energy security and independence.

As the successful experience of developed European countries shows, the main factors for ensuring energy efficiency and uninterrupted safe supply of electricity are a competitive model of the energy market, which helps to attract investment and to predict the demand for electricity in the context of the main sectors of the economy and business entities.

Advances in information technology, computing power, and data analytics have fueled the rapid development of research in forecasting electricity demand at the macro- and microlevels. Since the main approaches are based on models that investigate historical data on energy consumption, much attention has been paid to studying the factors that explain its dynamics. In particular, the subject of research by many scientists in recent years has been the modeling of causal relationships between the factors of economic growth and energy consumption. It should be noted that the conclusions regarding what is the cause and what is the consequence the growth of the economy stimulates the increase in energy consumption, or vice versa, differ [25].

That is why the issues of studying the factors affecting the final energy consumption and the selection of optimal models for predicting electricity consumption at the level of States and regions are relevant.

Forecasting electricity consumption is critical in the operation and management of power systems and thus it is a major area of research in energy markets. There are many statistical methods used to predict the behavior of electrical loads, with variables depending on the sales market [26]. In this approach, the load circuit is treated as a time series signal, where various time series techniques are applied. The most common approach is the Box-Jenkins ARIMA model and SARIMAX [27], [28]. SARIMA uses forecasting with dual seasonality (intraday and intraweek cycles) inherent in load data. Neural networks (NN) and artificial neural networks (ANN) [46], [47] are useful for multivariate modeling, but they are not as efficient for one-way short-term forecasting.

The seasonal (or multiplicative) SARIMA model is an extension of the (ARIMA) model [27], [28] when the series contains both seasonal and non-seasonal behavior. This load behavior makes the typical ARIMA model inefficient to use. This is due to the fact that it may not be able to «capture» the behavior during the seasonal part of the series of loads and therefore, it cannot provide an acceptable forecast result if the non-seasonal component is selected incorrectly.

When applying the computer-aided learning to predict electricity consumption, we used two of the most common approaches: artificial neural networks (ANNs) and support vector machines (SVMs).

The computer-aided learning methods are the basis of modern developments in the field of short-term load forecasting. These methods provide reliable results in a very short forecasting period.

The number of neurons in each layer can vary and it is usually chosen by optimization. Each neuron has one input, and its output is connected to all neurons of the next layer, creating a network connection. A neural network model with 28-day forecasting of power systems is shown in Fig. 25.

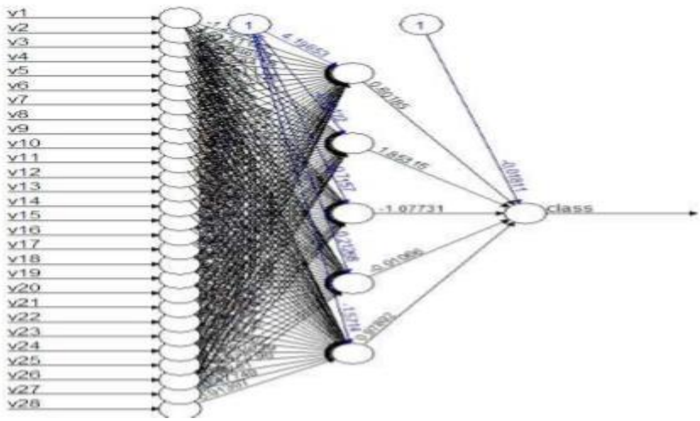


Figure 25 – A neural network model with 28-day forecasting of power systems

For the analysis, panel series of the 31 factors have been used (Table 1.1) for 46 countries of Europe and Central Asia for 2000-2019. The total number of observations is 920. The data sources were statistical samples of the World Bank [31] and estimates of the index of economic freedom of the US Heritage Foundation [26].

Analysis of electricity consumption per capita in the context of individual countries of Europe and Central Asia (Fig. 1.2) shows an increase in the indicator for most countries (except Azerbaijan) until 2014. At the same time, the study of GDP per capita statistics for the selected countries (Fig. 26) indicates a possible relationship between economic growth indicators and energy consumption.

In particular, ATF Bank experts estimate that a 1% growth in the country's GDP provokes an increase in electricity consumption by 0,5% [24]. This is primarily due to the low added value and high consumption of electricity in the extractive and agricultural industries, which form a large part of the GDP of countries such as Kazakhstan, Ukraine, Russia, and Azerbaijan. In such countries, energy resources form a significant part of consumer spending. The gap in energy efficiency indicators, defined in the volume of electricity consumption per unit of output, between the post-Soviet countries and developed countries is on average 200-300% (Fig. 27) [28].

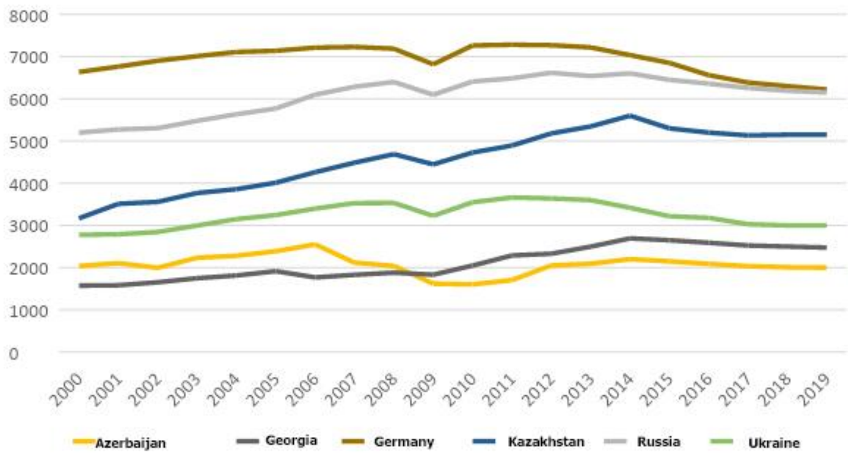


Figure 26 – Electricity consumption kW per capita, [28]

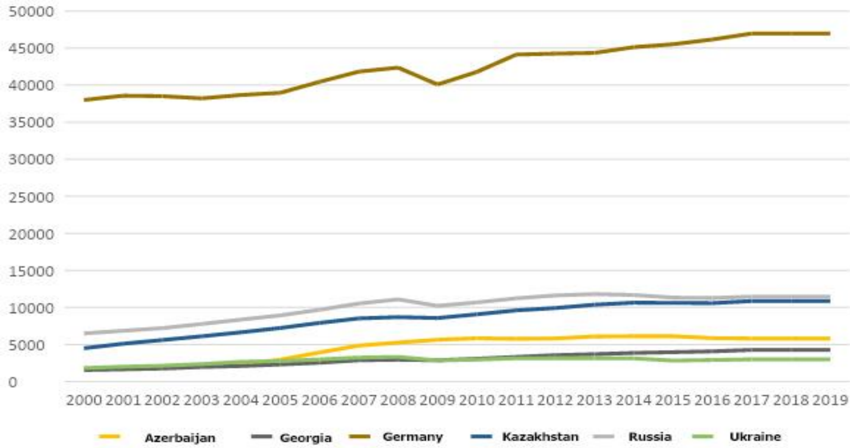


Figure 27 – GDP per capita at constant 2010 prices, USD , [28]

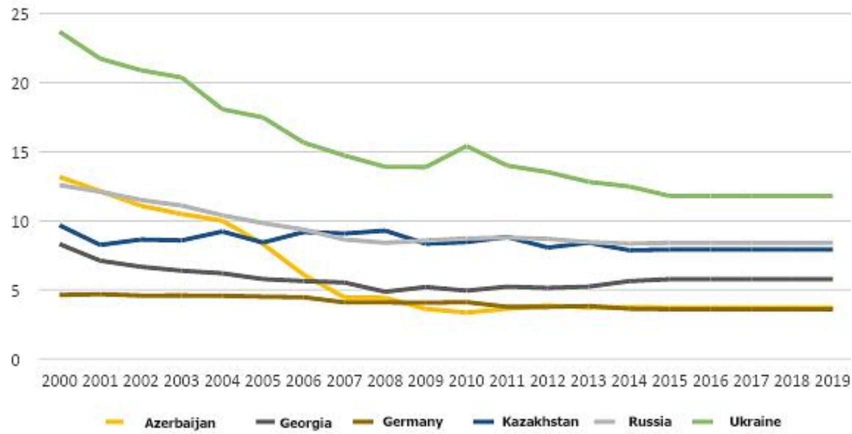


Figure 28 – Energy consumption per unit of GDP (MJ / 2011 $ PPP) [28]

The study of the electricity consumption distribution depends on the parameters of price and geographic location. The grouping, according to the criterion of price above average, reflects the differences between European countries with market competitive pricing and post-Soviet countries, where, in most cases, a centralized market with state regulation of prices still operates. Abnormally high values of electricity consumption are typical for northern countries with the least number of sunny days per year and, at the same time, with a relatively low price of electricity (Norway, Iceland, partly Finland)

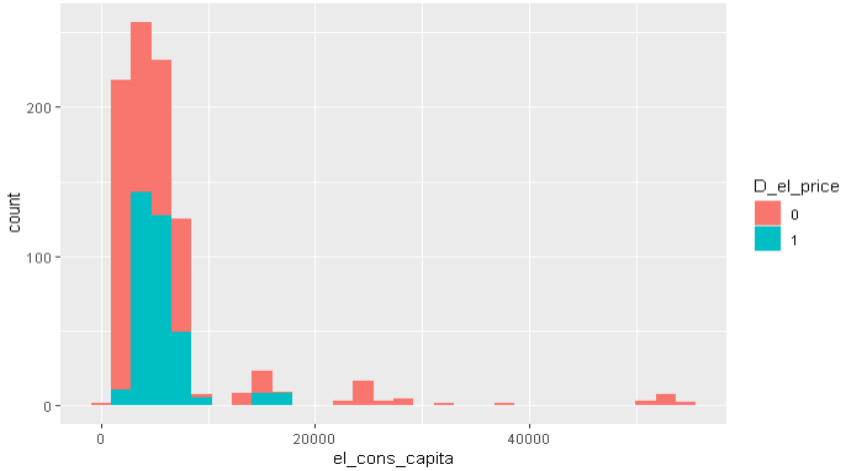


Figure 29 – Distribution of electricity consumption depending on the price of electricity [28]

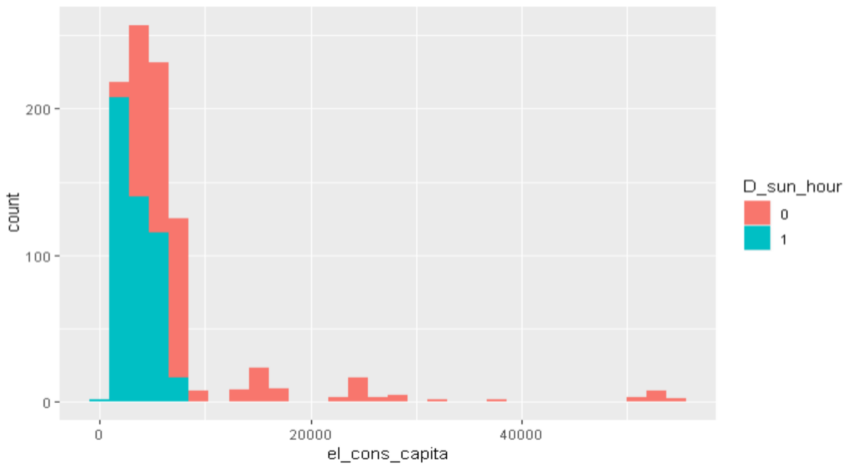


Figure 30 – Distribution of electricity consumption depending on the number of sunny days per year [28].

Comparative analysis of the average values of electricity consumption by countries, presented in Fig. 1.7, makes it possible to cluster States into groups with consumption above 7 000kW; in the range of 4 000-7 000kW; not less than 4 000kW per capita.

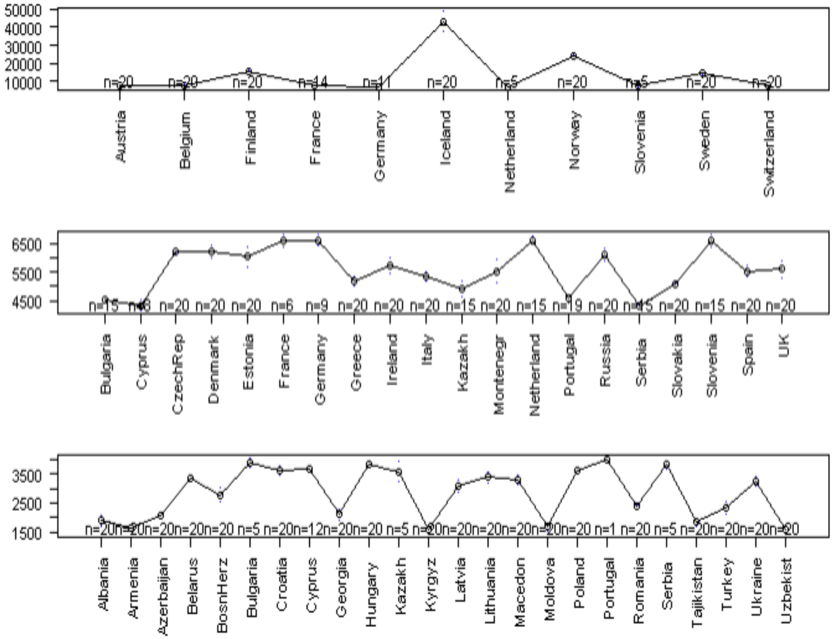


Figure 31 – Comparative analysis of average values of electricity consumption per capita by countries [48]

Comparative analysis over the years provided in Fig. 32 shows an upward shift of the central trend in energy consumption in Europe and Central Asia with slight decreases in the crisis year of 2009 and starting from 2014, as well as an increase in the confidence intervals of the average values for the period under study.

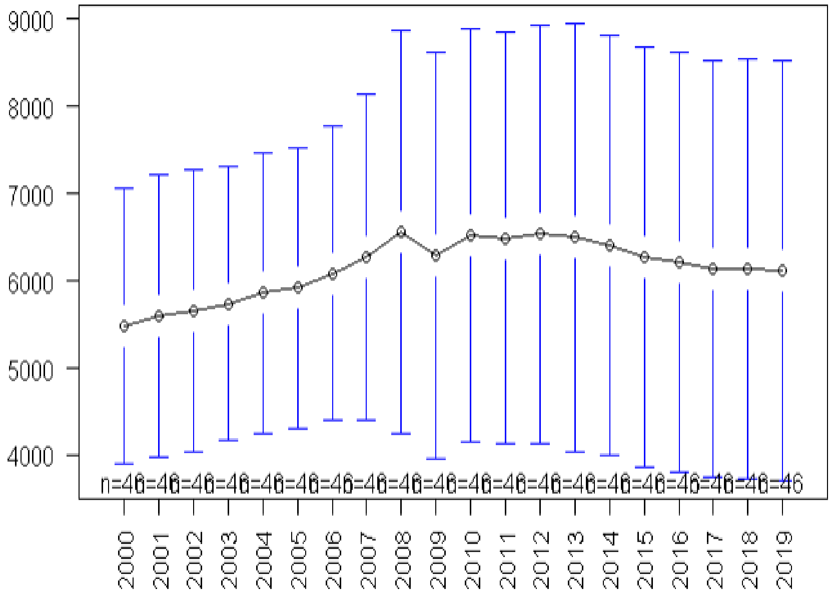


Figure 32 – Comparative analysis of average values of electricity consumption per capita by years [48]

In order to build adequate models, statistical tests for correlation and causality have been carried out. The analysis of scatter diagrams (Fig. 33-34) shows the directly proportional linear stochastic relationships between electricity consumption and GDP per capita, population growth and aging. A complete list of significant linear stochastic dependences is provided in the correlation matrix in Fig. 32. It is noteworthy that such indicators, as the price of electricity, the share of industry in GDP, have little effect on electricity consumption. Significant directly proportional relationships have been also found with indicators of the share of renewable energy sources, the availability of electricity, the degree of government intervention in the economy, and freedom of doing business

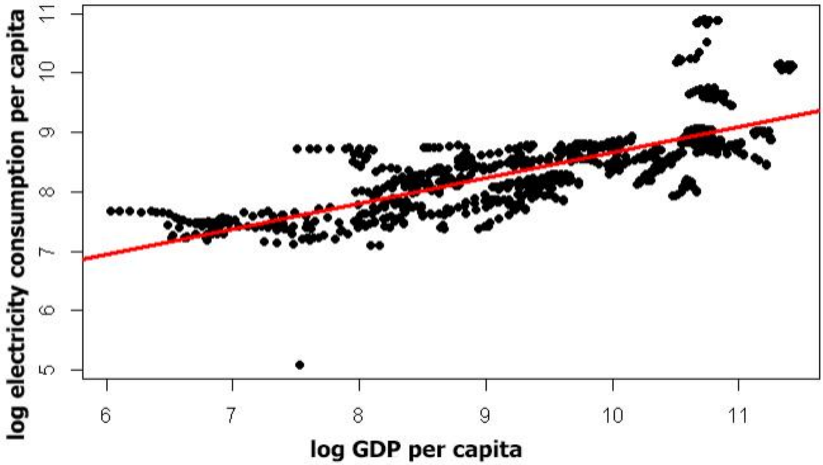


Figure 33 – Electricity consumption GDP per capita [28]

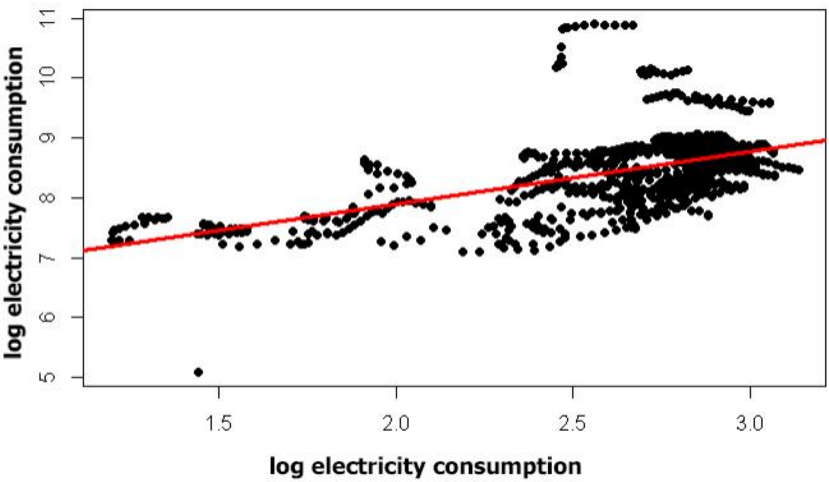


Figure 34 – Dependence of electricity consumption on population aging [28]

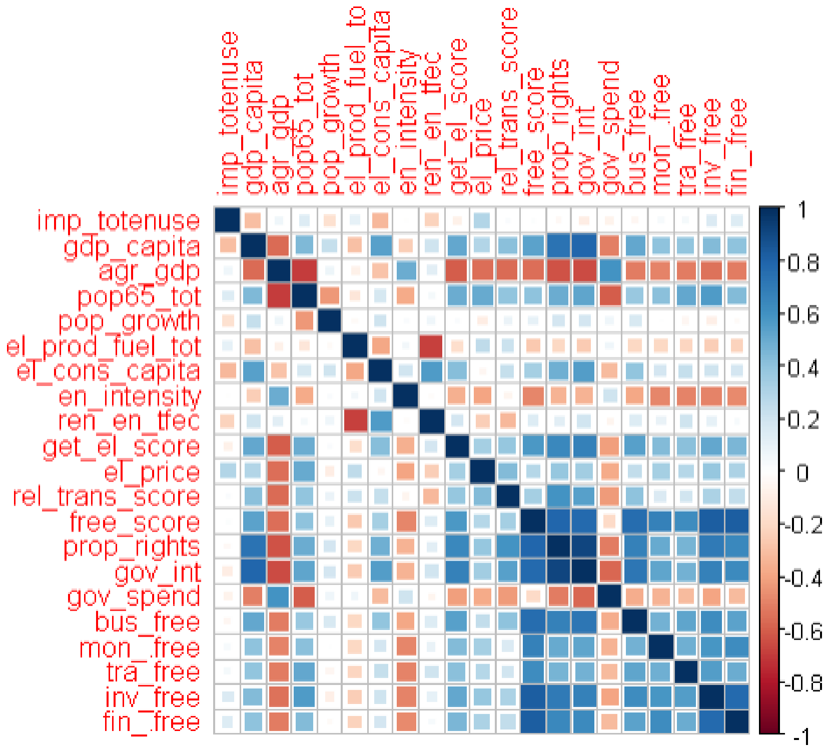


Figure 35 – Correlation matrix [31]

In the correlation matrix and during modeling, the following designations of variable factors have been used (Table 5.1).

Table 5.1 – Designation of modeling variables

	Indicator label	The essence of the indicator
Macroeconomic relative indicators		
	gdp_growth	annual GDP growth,%;
	gdp_capita	GDP per capita at constant 2010 US dollar prices;
	ind_gdp	the share of industry in the country's GDP, %;
	agr_gdp	the share of agriculture in the country's GDP, %.
Demographics		
	pop_growth	annual population growth, %;
	pop65_tot	the proportion of the population over 65 years.

Indicators of energy balance, efficiency and consumption		
	el_cons_capita	electricity consumption kW per capita, calculated as the sum of production of power plants and heating plants, net imports (import-export) less losses during transportation and maintenance, kW;
	en_intensity	energy intensity of the market - a measure of energy inefficiency, which determines the number of units of energy in MJ per unit of GDP in US dollars at purchasing power parity, MJ / 2011 $;
	totel	gross electricity production, GW;
0	imp_totenuse	share of energy imports in gross energy use, %;
1	el_prod_fuel_to t	share of electricity production from oil, gas and coal in gross electricity production, %;
2	tfec	final energy consumption, TJ;
3	ren_el	production of electricity from renewable sources, GW;
4	ren_en_cons	consumption of electricity from renewable sources, TJ;
5	ren_en_tfec	the share of renewable sources in final energy consumption, %;
6	ren_el_totel	specific share of renewable sources in gross electricity production, %;
7	get_el_score	electricity availability index on a 100-point scale;
8	rel_trans_score	reliability of electricity supply and transparency of tariffs on a 100-point scale;
9	el_price	price of electricity, US cents per 1 kW;
0	D_el_price	a fictitious variable that takes the value 1 if the price of electricity is above average, 0 - otherwisey.
Indicators of economic freedom (on a 100-point scale)		
1	free_score	general index of economic freedom;
2	prop_rights	index of protection of owners' rights;

3	gov_int	index of state intervention in the economy and the share of the public sector;
4	gov_spend	the share of government spending in total consumption;
5	bus_free	business freedom index;
6	mon_free	index of monetary freedom;
7	tra_free	freedom of trade index;
8	inv_free	investment freedom index;
9	fin_free	index of financial freedom.
Indicators of climate and geographical location		
0	sun_hours	average annual number of hours of sunshine;
1	D_sun_hour	a fictitious variable that takes the value 1 if the number of sunny days in the year is above average, 0 - otherwise.

6 EXPERIMENTAL STUDY OF THE EFFECTIVENESS OF THE PROPOSED APPROACH

The objectives of the experimental study of the developed software package are:

1) checking the functionality of the software package, no errors during its execution;

2) analysis of the effectiveness of methods for accelerating the method of uneven coatings in the case of one or more criteria.

The experimental method is a system of methods for consistent and most effective implementation of experimental research.

The methodology includes:

1) Defining the purpose and objectives of the experiment.

2) Planning and evaluation, which consists of the following tasks:

- analysis of the usage context, collection of information.
- creating a SOFTWARE development plan based on ISO 9241-210: 2019: Ergonomics of human-system interaction-Part 210: Human-oriented design for interactive systems.

3) Development of SOFTWARE requirements. At this stage, a study of users and usability aspects is carried out, on the basis of which a specification of the requirements of the future system is later compiled. The methods used at this stage are designed to collect information about the user interface, users, their tasks, and the environment in which they are performed.

4) Development of software design and engineering, which includes: design guides, paper prototypes, heuristic and expert evaluation, parallel design, storyboard, prototype evaluation, templates.

5) Implementation and programming. This stage includes choosing a programming language, programming style rules, and developing quick prototypes.

6) Testing and evaluation of the software product

Based on the proposed method, the main and secondary characteristics that affect the process under study were established. Mathematical models and calculation schemes of the process are analyzed. Methods for processing and analyzing experimental data are selected. The results of the experiment are summarized in tables, graphs, and formulas.

The current state of the electric power system of Kazakhstan was tested on the basis of developed mathematical models. The production and consumption of electricity in Kazakhstan are studied, and mathematical models of stabilization, optimal control, and stability of the electric power system are developed. Numerical solutions were obtained using multistep Adamas-Bashford and Adams-Moulton methods and graphical results were shown.

Below are screenshots of the results:

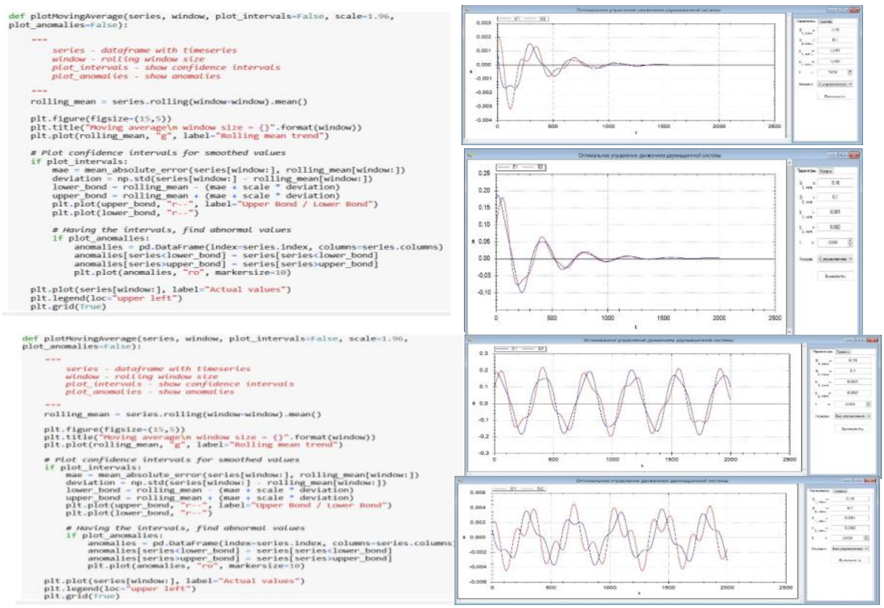


Figure 37 - Graphs of the function δ_1, δ_2 and S_1, S_2 without control

Figure 38 - Graphs of the function δ_i and S_i at 1=30

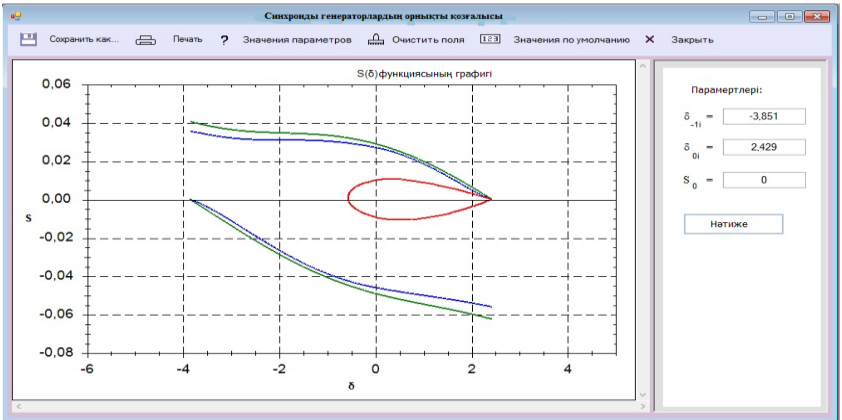


Figure 39 - Stability of synchronous generator motion

Analysis of scattering diagrams (figures 40-41) shows the presence of directly proportional linear stochastic relationships between electricity consumption and GDP per capita, population growth and aging. A complete list of significant linear stochastic dependencies is presented in the correlation matrix in figure 39. It is noteworthy that such indicators as the price of electricity, the share of industry in GDP have little impact on electricity consumption.

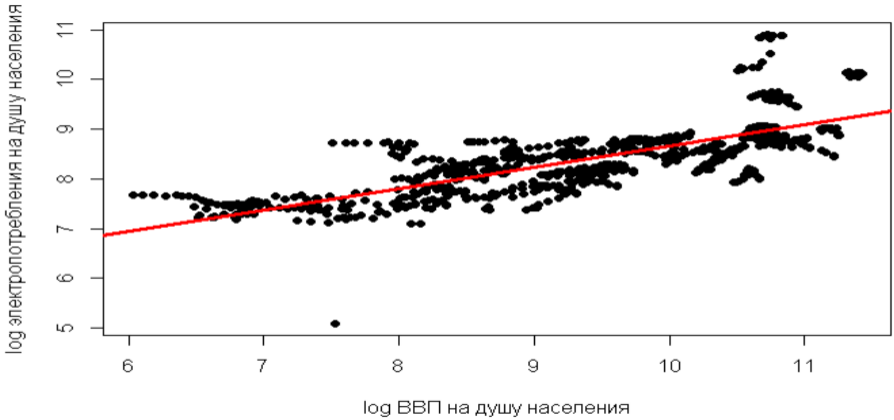


Figure 40-Dependence of electricity consumption on GDP per capital

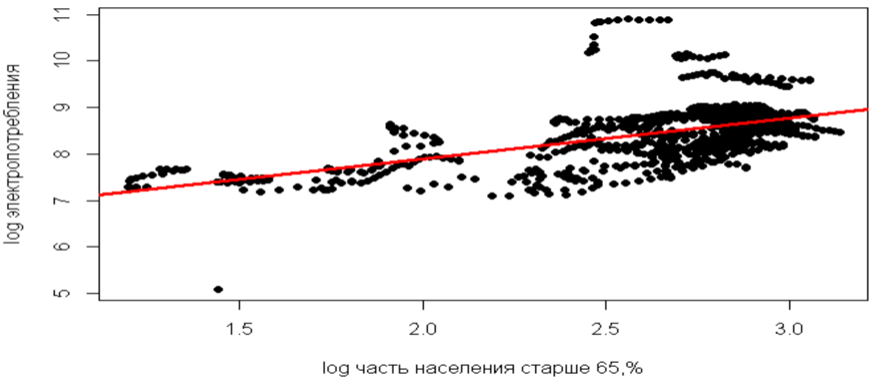


Figure 41-Dependence of electricity consumption on population aging

Source: software implementation in R according to data [5]

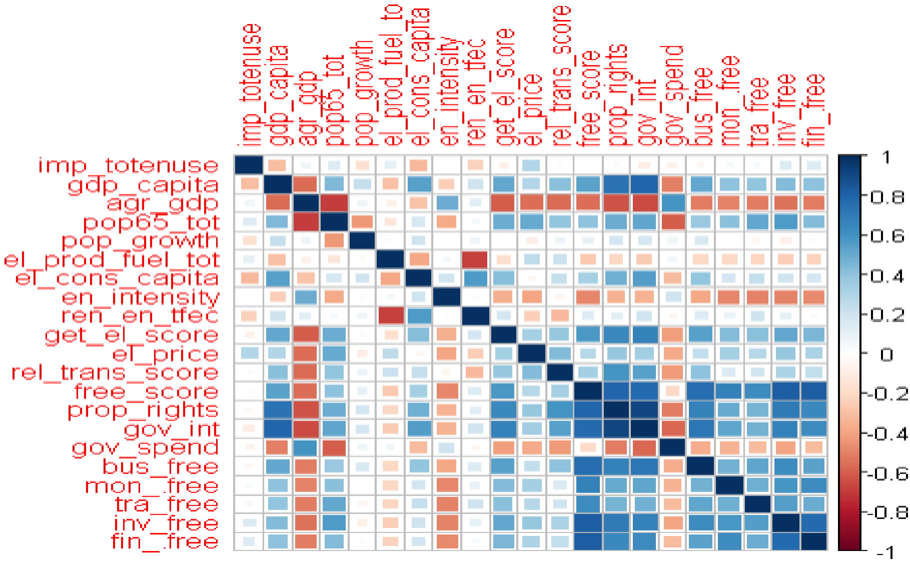


Figure 42-Correlation matrix

Source: software implementation in R based on data [5]

The next step is to study the causal relationships (causality) between variables based on the Granger test [12].

Based on the results of the above tests and statistical analysis, a basic linear regression model was built for pool data on electricity consumption:

$$\log(el\_cons\_capita_{it}) = 4.39 + 0.28\log(gdp\_capita)_{i,t} + 0.16\log(ren\_en\_tfec)_{it} + \\ + 0.38\log(gov\_\mathrm{int})_{it} - 0.11\log(imp\_totenuse)_{it} - 0.17D\_sun\_hour1 + \xi_{it}$$

All variables are significant for $\alpha = 0{,}05$.

Adjusted coefficient of determination $R^2 = 0.687$

F-statistics = 351.8 for degrees of freedom *df* = 795, p < 2.2 e-16.

To solve the problem, we used a robust covariance matrix to obtain effective estimates of coefficient errors

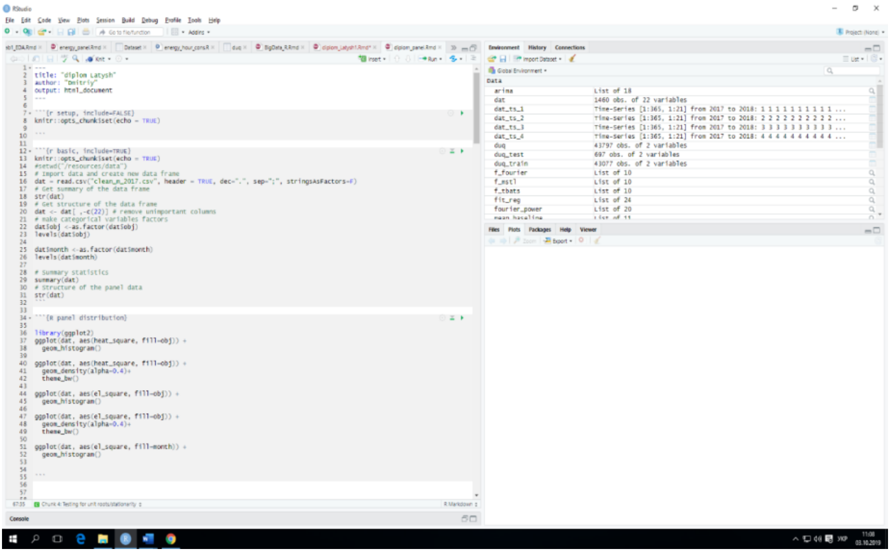


Figure 43-Power system forecast by day

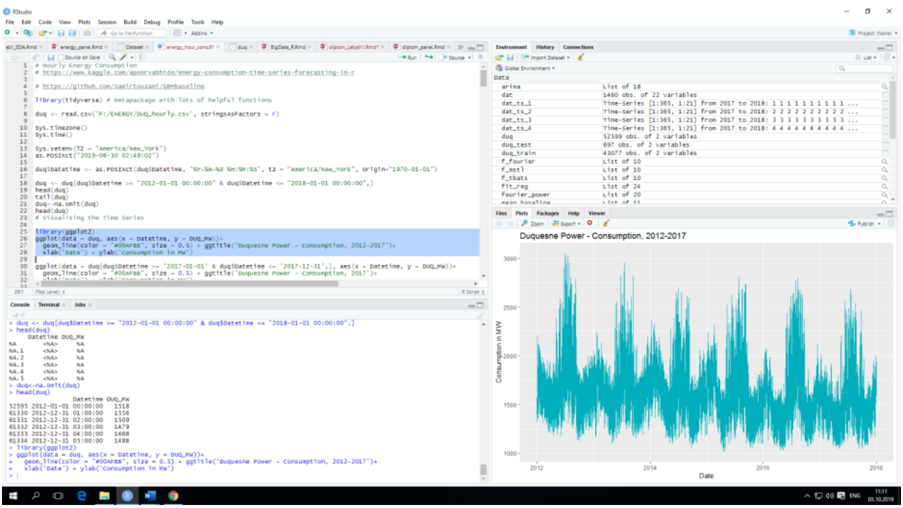


Figure 44-Visual inspection of power consumption time series points, considering possible sources of data changes, including weather, holidays, daily, weekly, and monthly frequency

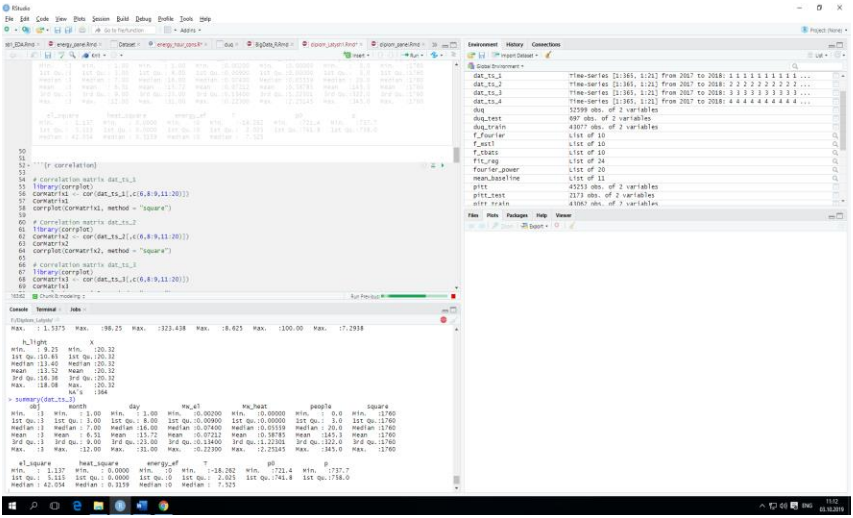


Figure 45-Data by day, week, and month

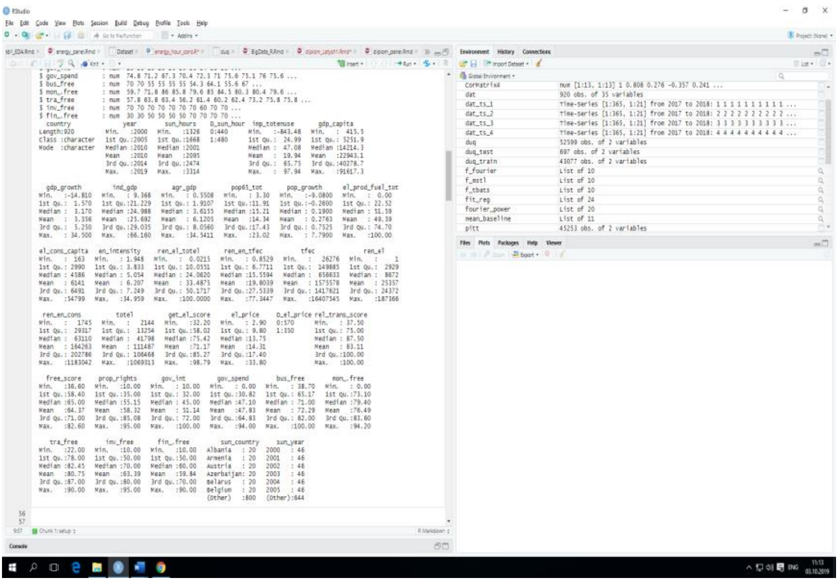


Figure 46- data by age

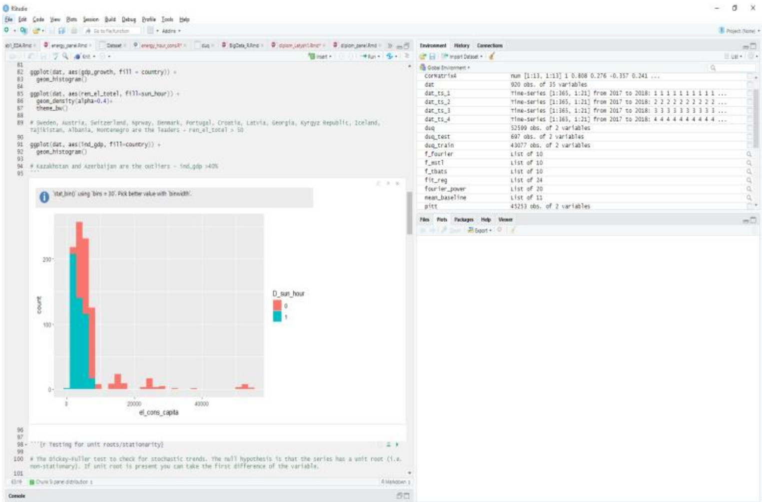


Figure 47-data on sunny days

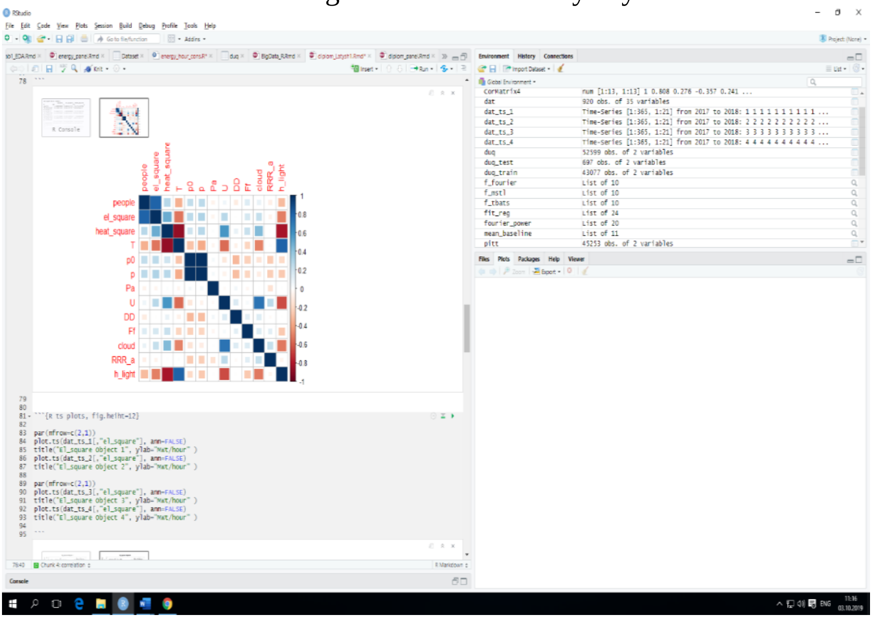


Figure 48-Correlation matrix

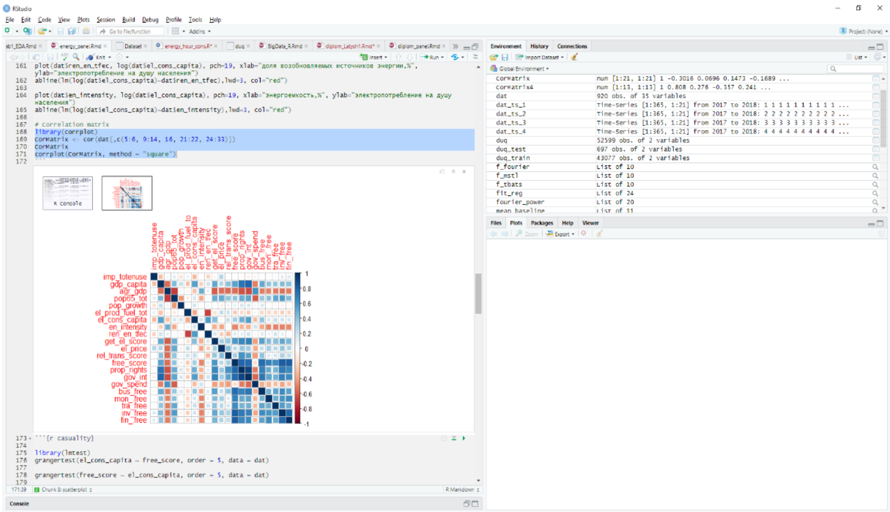


Figure 49-Correlation matrix

7. THE AUTOMATED SYSTEM FOR SHORT-TERM FORECASTING AND MONITORING OF ELECTRICITY CONSUMPTION IN EDUCATIONAL INSTITUTIONS

7.1 Scientific and methodological foundations for the organization and construction of the automated system for short-term forecasting and monitoring of electricity consumption in educational institutions.

The humanity has always strived for increasing the comfort level of its existence. A generations of people saw the way to this through providing themselves with material goods, technologies that reduce the amount of labor invested in the production of goods. However, along the growth of the population, the need for additional products to meet the growing needs of humanity increases too. The main resource for expanding the production and the provision of services remains the material reserve of the Earth's Environmental Systems. Reserves of primary mineral resources are limited. Biological resources are also exhaustible. According to the statistics, the annual increase in reproducible biological resources that can be used in public production makes about one percent, and the dynamics of the annual growth of the world gross product shows an average increase of about 2-3% during the crisis-free period. The development and dissemination of information technologies in the modern world is associated primarily with the increased use of energy. Moreover, although the alternative methods of energy generation (first of all electric one), alternative to traditional technological processes, have been dynamically developing in recent years, but energy generation by processing primary fossil fuels remains dominant in the energy sector. One way or another, this is due to the use of chemical oxidation reactions with the release of a large amount of heat for its further use in energy transformations. Unfortunately, traditional technologies for electricity generation cannot provide a high degree of beneficial use of the generated heat at the stage of its conversion to electric one. In addition, the side chemical compounds and substances, that are formed and released at power plants, appear in the environment as emissions and cause a negative impact on the state of the biosphere that is followed by further warming of the atmosphere. Humanity, in pursuit of its own comfort, increases its power-to-weight ratio, increases energy consumption and it, in turn, causes a catastrophic deterioration of the conditions of its existence. The society cannot stop the production because it cannot stop the consumption. The way out of this situation is seen through the use of technologies which will allow to reduce the input amount of materials, provide the lowest possible use of energy and reduce the irrational expenditures.

Improving the efficiency of the use of primary energy resources and energy is one of the urgent problems of the humanity and the Ukrainian society in particular. The reduction of the use of electric energy is possible due to the implementation of purely technical measures into technological processes (industry, transport, utilities and public sector institutions) and this should mainly be achieved by using new energy-efficient equipment. The second, but no less important factor, is the development and implementation of organizational and technical measures relating to the operation modes of enterprises and institutions, the organization and coordination of electricity and heat consumption regimes and electricity consumption regulation. The solution of the problem of improving the energy efficiency of technological processes is, first of all, the reduction of the electric energy consumption. Given the existing technologies for electric energy generation in Ukraine at thermal and nuclear units of power plants, the reduction in consumption is connected with a reduction in electricity generation, and, consequently, with a decrease in emissions of greenhouse gases and other pollutants into the atmosphere. That is, any production or other process (even if it does not generate waste that are harmful for the environment) which uses the electricity, always has a negative "environmental footprint". On this basis, the problem of efficient and economical use of electric energy has become national one in any country. Its solution also lies in the plane of creating mathematical models of electricity consumption and its forecasting, and systems for monitoring current electric energy consumption. Such systems are aimed at organizing commercial control of determining consumption amount for further financial calculations between consumers and electricity generating enterprises. Given the influence of various factors in the current planning of the components of electricity consumption, affecting the electricity consumption, also affects the forecast balances of the energy system, the planning of the functioning of the entire fuel and energy complex of the country. Control of electricity consumption should be constant (periodic or continuous) in order to timely influence current deviations (inconsistencies). Deviations are considered as non-compliance with certain amount of electricity consumption in the technological process at the current moment, or in other period. On this basis, there arises the issue on developing a system (algorithms) on comparing the indicators of current electricity consumption with predefined conditions for this production process. These pre-calculated values should correctly characterize the energy state of the current collectors systems, considering all possible regulated energy consumption. In addition, the correctly calculated indicators of energy consumption, as well as the normative ranges of their changes should serve as control basic values of the diagnostics system for the technical condition of current collectors units. Now these problems are being solved by creating Automated System for Commercial Accounting of Power Consumption (ASCAPC) and determining the standard indicators of the specific electricity consumption per unit of product, service providing, etc. The primary link of the ASCAPC is the electricity meters. Most often, they are installed in places where it is possible to organize commercial accounting, which will ensure its reliability and completeness with minimal costs for its arrangement. Such an approach does not always meet the goals of providing full operational control over the energy consumption of current collectors. In addition, ASCAPC mainly records only current electricity consumption without the function of analyzing the compliance with standard indicators, and even more so, without recording the inconsistencies. These problems should be solved by the creation and functioning of automated systems for short-term forecasting and monitoring of electricity consumption by current collectors and their systems with the possible organization of recording current energy consumption data on-line with their analytical support for calculating and comparing control data of current consumption amount, energy efficiency of technological processes.

The analysis of publications that highlight the results of research and suggestions on the use and development of monitoring systems of electricity consumption shows a big number of authors. Moreover, almost everyone offers to use ASCAPC as a tool to improve the efficiency and streamlining of the electric energy use [1]. The authors [2] point to the minimal impact of the "human factor" during the collection, transmission and processing of information while using automated systems for monitoring electricity consumption, as well as the efficiency of their functioning. The sources [3], [4] indicate the need for using economic and mathematical methods for forecasting electricity consumption (exponential smoothing, neural network methods). Most authors proceed from the fact that the existing ASCAPC systems do not fully address the problem of increasing the efficiency of electricity consumption. The issues on accounting of all current factors while determining standard indicators of electricity consumption remain problematic. The authors [1] propose to transform automated electricity consumption metering systems into developed information structures (metering and information systems) that can collect and analyze data («smart metering systems»). V. Kaplun and V. Borovyk argue that operation of control systems of energy efficiency involves a comparison of actual energy consumption with planned or standard ones. [6] consider the principles of construction and operation of the «Automated Electricity Management System» created at the Kyiv National University of Technologies and Design. In their opinion, specific indicators obtained by a statistical analysis of the functioning of engineering networks and operating conditions of educational buildings and residencies (hostels) should be as the key criterion for assessing the energy efficiency of energy consumption systems. The specific indicators of electricity consumption, referred to the reduced area of educational buildings and the reduced student population or the average monthly number of students living in residencies (hostels) are key ones for assessing the energy saving potential of the university and forecasting electricity consumption levels in the near future. Rationing and control over the electric energy consumption under the prevailing operating modes of electrotechnical equipment should be carried out according to the final performance indicators, which will make it possible to organize adequate forecasting of the specific electricity consumption by higher education institutions and will allow the effective implementation of energy conservation measures. However, [6] does not take into account the information of the class schedule, the results of energy inspections of buildings and their premises, which can be used for creation and implementation of the algorithms for calculating the forecasted electricity consumption. Thus, the methodologies for determining control (basic) indicators of energy consumption in technological processes remain problematic.

Energy information systems should include two main functions: monitoring current energy consumption and determining the indicators of forecast energy consumption for a predetermined period. The second function is the most problematic in terms of the correct determination of energy consumption limits. Currently the results (arrays) of statistical studies are used for their calculation. Calculation algorithms do not always take into account the continuous-variable factors of influence on the electricity consumption. But they can be significant. Such a situation may affect the interpretation of energy consumption results and personnel actions or testing the technical state of equipment. For example, according to [5], a general standard for the operation of the lighting system in educational institutions was determined as 250 hours per year and this standard is to be used for calculating energy consumption limits by the lighting systems of the institutions. This approach is very general and does not take into account many factors (features of the functioning of institutions, climatic conditions, etc.). Also, this methodology does not stimulate personnel to save energy. Based on this, to construct a mathematical model of the electricity consumption of the institution, it is necessary to clarify the methodology for calculating the values of regular energy consumption, which would take into account short-term changes in the technological process and external changing conditions for its use. In addition, the modeling of electricity consumption should be based on the initial data, which correctly characterizes the processes of energy consumption. It is rather complicated task to determine them and this is often impossible without differentiating general indicators of electricity consumption. The use of improved methodologies for the formation of the «spectrum» of electricity consumption, which combine the calculation, statistical methods for modeling, should increase the accuracy of determining the components of electricity consumption by individual systems and the forecasting accuracy.

As already noted, at present, the construction of existing forecasting and monitoring systems for electricity consumption is mainly based on statistical information arrays or standardized indicators and does not take into account a number of current factors affecting energy consumption. The suggested system for the automated calculation of forecast electricity consumption by current collectors takes into account their installed capacity, operation modes and conditions using mathematical models for determining electricity consumption.

To obtain the necessary initial data for the further determination of the control (basic) values of electricity consumption, it is proposed, as the first stage, to conduct energy inspections of buildings, equipment and other technological means using instrumental research methods. It is possible to take into account the influence of climatic factors on the amount and nature of electric energy consumption by analyzing an array of statistical data, accumulated over a period, on the meteorological observations and current and forecast information on the weather conditions of the area (territory) where the institution (enterprise) is located. It is suggested to determine the nature of electricity consumption by current collectors based on the analysis of their operation modes, taking into account the structure of the elements of the technological process (production, educational process, etc.). The automation of the process of calculating the limit indicators of forecast electricity consumption is suggested to carry out by using the capabilities of computer technology and the creation of algorithms and programs of existing packages. Combining and visualizing the results of current monitoring of electricity consumption and the corresponding forecast, evaluating their non-compliance is proposed to carry out according to the developed algorithms using mathematical modeling methods, which allows to create automated complexes for short-term forecasting and monitoring of their electricity consumption.

The analysis of the functioning of the technological processes of any industrial enterprise, educational institution or other institution indicates the common components of the overall structure of electricity consumption. According to a defined consumption structure, current collectors can be classified by the systems where they are used. They are as follows:

1. artificial lighting systems for premises where the basic and support technological processes are carried out;
2. energy supply systems for buildings and processes, as well as their maintaining;
3. systems for providing administrative activities and daily living needs;
4. systems for supporting the processes of logistics activities;
5. systems for carrying out the basic technological process and the support processes.

By the functional area, the artificial lighting systems provide general, local and emergency lighting. Their use should provide the necessary sanitary and hygienic level of the lighting of workplaces and other premises for the execution of certain processes. If there is necessary level of lighting, the operation of current collectors of such systems is inadvisable. The amount of electric energy consumed by them should be determined by the actual $P_{ligh.actual}$ (or installed $P_{ligh.instal}$, if their values coincide) electrical capacity and the period of the technological process $t_{ligh.}$., during which the lighting is lower than the required level. The length of the period $t_{ligh.}$ is affected by the duration of the technological process, its length and climatic conditions. The influence of climatic conditions can be considered by using the *climate coefficient* $c_{c\lim}$ Based on these conditions, the amount of electric energy which should be consumed by current collectors of general and local artificial lighting systems can be calculated by the following formula:

$$A_{lig.} = P_{lig.actual} \cdot t_{lig.} \cdot c_{c\lim} \tag{7.1}$$

The coefficient $c_{c\lim}$ can take a numerical value 0 or 1 depending on the lighting level. If the lighting level is sufficient then $c_{c\lim} = 0$ if not, then $c_{c\lim} = 1$. Current operating period $t_{ligh.}$ of the current collectors of lighting systems can be determined and controlled using the lighting sensors. Estimated forecast period can be determined by considering the short-term weather forecast and the available array of statistical data on the dependence of lighting indicators on the environmental meteorological conditions (cloud cover, day length, season, etc.) in rooms where the corresponding technological process is carried out. For example, for an educational institution, the algorithm for determining the amount of electricity, consumed by the lighting system of classrooms, where lectures, practical or other classes of the educational process take place should be based on formula (7.1). That is, using the results of energy inspection of the premises, the lighting systems of the rooms are certified. The installed capacity of electricity $P_{ligh.instal}$ is determined by lighting level (natural and artificial ones). To determine the length of the periods $t_{ligh.}$, it is necessary to use the class schedule, which indicates the type of classes, the location, time and length (in hours).

Based on the analysis of statistical data of past periods and using short-term forecast indicators of future meteorological conditions, the need for the operating of artificial lighting systems during a particular period of next day for each classroom is determined (i.e. the value of $c_{c\,\mathrm{lim}}$ is determined (1 or 0)). The block diagram of this algorithm is given in Fig. 50.

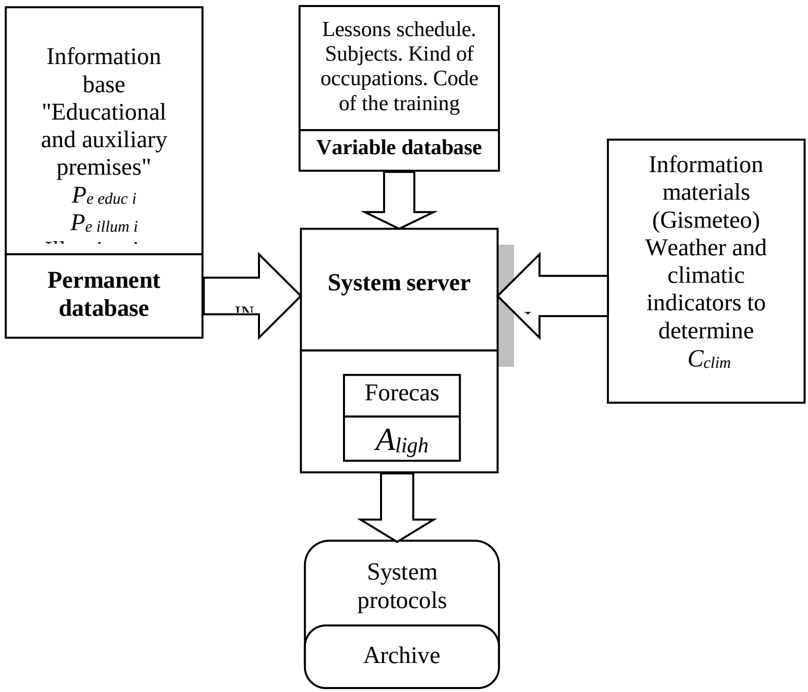


Figure 50 The block diagram of the algorithm for calculating the forecast limit of electricity consumption by lighting systems

The amount of forecast electricity consumption of artificial lighting systems in common areas $A_{lig.com.cjrrid.}$ (corridors, toilets, stairs, etc.) should be determined by a similar algorithm, but some features should be taken into account. The standard level of lighting of such rooms is much lower than for classrooms. While calculating, in many cases, it is possible to exclude the influence of cloud cover during daylight hours, and while determining $t_{ligh.}$,it is possible to focus on the minimum values of lighting, the institution's operating schedule (working hours during the day) and calendar indicators of daylight hours. The operating time of the lighting system will consist of two components: from the opening of the institution to the standard lighting value (first half of the day) $t_{ligh.1}$,and from the moment the lighting becomes lower the standard level until the end of the working day and the personnel leave the building (second half of the day) $t_{ligh.2}$. Then the calculation of the forecast electricity consumption by artificial lighting systems of common areas should be determined by the formula:

$$A_{lig.com.corrid.} = P_{lig.1actual} \cdot t_{lig.1} + P_{lig.2actual} \cdot t_{lig.2} \tag{7.2}$$

where $P_{ligh.1actual}$ and $P_{ligh.2actual}$ – installed or actual electrical capacity of the current collectors of artificial lighting system which operate in the first and second half of working day of the institution. If $P_{ligh.1actual} = P_{ligh.2actual}$ and it can be presented as $A_{lig.com.corrid.}$, the formula (7.2) can be presented as follows:

$$A_{lig.com.area.} = P_{lig.comarea} \cdot (t_{lig.1} + t_{lig.2}) \tag{7.3}$$

If there is no natural light in the toilets, then based on the analysis of the research conducted on an array of statistical data, it is advisable to take the duration of one visitor's stay there on average 7-10 minutes, i.e. about 0,16 hours. However, for most educational institutions and industrial enterprises, such planning of toilets is quite rare and is not considered in our further calculations.

Amount of electric energy consumption by emergency lighting system $A_{lig.com.emerg.}$ are suggested to be determined by traditional calculation which considers installed capacity of its current controllers $P_{lig.com.emerg.}$ and the operating time within 24 hours $t_{ligh.emerg.}$ in accordance with the applicable rules and regulations:

$$A_{lig.emerg.} = P_{lig.emerg.} \cdot t_{lig.emerg.} \tag{7.4}$$

The operating of the general lighting system and local lighting determine electricity consumption by the lighting system of administrative, accommodation and support premises. It is suggested to determine the amount of electric energy consumption $A_{ligh.com.ad\min.}$ by analogy with formula (7.3), which considers the installed capacity of current collectors $P_{ligh.ad\min.}$ and the operating schedule of the institution within 24 hours. The operating time of the lighting system will consist of two components: from the beginning of the working day of the department of the institution, or the presence of personnel in the room, until the standard value of lighting (the first half of the day) $t_{ligh.ad\min.}$ and from the moment when the lighting level becomes lower than the standard level until the end of the working day and when the personnel leaves the rooms (the second half of the day $A_{lig.com.ad\min.}$) $t_{ligh.ad\min.}$

$$A_{lig.ad\min.} = P_{lig.ad\min.} \cdot (t_{lig.1ad\min.} + t_{lig.2ad\min.}) \tag{7.5}$$

The calculation of the amount of electric energy consumption during the educational process should be carried out taking into account the values of the installed capacity of current collectors $P_{educ.}$, that are involved into the operation of educational technologies (computers, accessories, multimedia projector, operating models, other equipment) and the period of time $t_{educ.}$ during which they are used for a particular class and in a particular classroom. Based on the results of the certification and defining the list of current collectors, the power-to-weight ratio of the classroom should be determined, i.e. the installed capacity of the current collectors involved in the educational process. The time of their use depends on the type of classes (lecture, seminars, etc), as well as on the course and its subject. In order to simplify the algorithm for the automated calculation of forecast amount of electricity consumption, it is advisable to use the relative value c_{load}, the time of use of the current collectors $t_{educ.}$ to the total (calendar) time of the class $t_{calend.}$ which is calculated as the load (use) coefficient by the formula:

$$c_{load.} = t_{educ.} / t_{calend.}$$

Then the estimated amount of electrical energy consumption by the current collector during the class $A_{educ.}$ is determined by the following formula:

$$A_{educ.} = P_{educ.} \cdot t_{calend.} \cdot c_{load.} \qquad (7.6)$$

To calculate the forecast amount of electric energy consumption it is necessary to:

Step 1 – to determine the code of classroom *j (j = 1…n)*;

Step 2 – to determine the list of current collectors in that classroom, their installed capacity $P_{i\ educ.}^{j}$, where *i* – number of current collector from the classroom list *j (i = 1…n*);

Step 3 – to determine the codes of academic disciplines which are to be conducted in classrooms *j* and the types of classes (lectures, seminars, etc);

Step 4 – to determine the list of current collectors with capacity P_i^j, that are used at a particular class by particular academic discipline, to determine their load coefficient c_{load} ;

Step 5 – using formula (6) to calculate the amount of electricity consumption by *i-th* current collector $A_{educ.i}$ and by the available list of current collectors for classroom *j* to determine the total estimated amount of electricity consumption $A^c_{educ.j}$ during conducting classes on a particular academic discipline:

$$A^c{}_{educ.j.} = \sum_{i=1}^{n} P_i^j{}_{educ.} \cdot t_{calend.} \cdot c_{load.i} \tag{7.7}$$

Based on (7.7), the total daily amount of electric energy consumption $A_{educ.j}$ (excluding electricity consumption for lighting) while conducting classes in classroom *j* should be determined as the sum of the amount of consumption at each class according to the schedule:

$$A_{educ.j.} = \sum_{c=1}^{n} A^c_{educ.j} \tag{7.8}$$

Alternatively, to unify the databases and simplify the automated calculation of electricity consumption, it is considered to be possible, and in some cases advisable, to add the load factor to the algorithm (the basic formula (7.6)) of calculation *the load coefficient of total installed electrical capacity of the current collectors* $c_{load.P}$ *at the classes.* It characterizes the share of the use of the total installed electrical capacity of the current collectors of the classroom at classes. Depending on the type of classes, it is calculated as the ratio of the total installed electrical capacity of the current collectors that are used at this class to the total installed electrical capacity of the current collectors of the classroom (except for the artificial lighting system).

In order to clarify the length of the period of the current collectors operation at the classes and to simplify the calculation (formula (7.6)) of electricity consumption, the algorithm can be added by *the coefficient of use of the total installed electrical capacity of the current collectors at the classes* $c_{load.t}$ It characterizes the time of the total installed capacity of electricity of the current collectors of the classroom at the classes on this academic discipline.

Depending on the type of class, it is calculated as the ratio of the period (in hours) of the current collectors operating (electricity consumption by them) during this class according to the duration of the lesson (in hours) according to the schedule. Based on this, formula (7.6) can be presented as follows:

$$A_{educ.} = P_{educ.} \cdot t_{calend.} \cdot c_{load.P.} \cdot c_{load.t.}$$

In many cases, the main technological process of studying in classroom should be preceded by support preparatory processes (storage and preparation of specimen, equipment setup processes, etc), which are carried out in separate rooms. The calculation of the daily amount of electricity consumption during such processes $A_{educ.\sup p.j}$ (excluding the electricity consumption for lighting) should take into account the installed electrical capacity of the equipment $P_{i educ.\sup p.j}$, that is used to carry out the support process, its load factor $c_{load.i}$ and the duration of the process $t_{calend.}$. Mostly, the execution of support processes coincides in time with the working schedule of the institution, so their duration $t_{calend.}$ should correspond to the length of the working day. The daily volume of electricity consumption for carrying out the support processes outside the premises (excluding electricity consumption for lighting) should be calculated by analogy with (7.6). The total daily electricity consumption during support processes should be calculated by analogy with (7.8):

$$A_{educ.\sup p.j.} = \sum_{c=1}^{n} A^{c}_{educ.\sup p.j} \qquad (7.9)$$

The forecast amount of electric energy consumption by energy supply systems of buildings and processes, as well as their support (water supply, heat, sewerage, etc.) $A_{energy.\sup p.j}$ should be calculated based on the installed electricity capacity of their current collectors $P_{i.energy.\sup p.j}$ and the operation period $t_{j.calend.}$. By analogy with previous calculations, in this case, it is advisable, to use their load factor $c_{load.ienergy.\sup p.}$. The total estimated daily amount of electricity consumption by energy supply systems of buildings and processes is calculated by analogy with (7.9):

$$A_{energy.\sup p.j.} = \sum_{j=1}^{n} A_{energy.\sup p.j} \tag{7.10}$$

The estimated forecast of the amount of electric energy consumption by the current collectors of the units, which provide the administrative activities, and domestic needs of the institution $A_{ad\min.j}$ should be calculated based on the installed electrical capacity of their current collectors $A^{j}_{i.ad\min.}$ and the operation period $t_{j.calend.}$. It is also advisable to use their load coefficient for the calculations $c_{load.i.ad\min.}$. The total estimated daily amount of electricity consumption by the current collectors of the units, which provide the administrative activities and domestic needs of the institution, is calculated by analogy with (7.10):

$$A_{ad\min.} = \sum_{j=1}^{n} A_{ad\min.j} \tag{7.11}$$

The amount of forecast consumption of electric energy by the current collectors of the outdoor lighting system $A_{light.out}$. is suggested to be calculated on the basis of the installed total electrical capacity of its current collectors $\sum_{i=1}^{n} P_{light.out.i}$ where n – their number and calendar period of system operation $t_{calend.}$. Despite the seasonally variable period of daily use of external lighting, while calculating it is advisable to use the load coefficient $c_{load.light.out}$, which should be variable depending on the season, length of daylight hours and should be calculated by the formula: $c_{load.light.out} = t_{light.out} / t_{calend.}$, where

$t_{light.out}$ - standard, or adopted the daily period of operation of the outdoor lighting system.

Then:

$$A_{light.out} = \sum_{i=1}^{n} P_{light.out.i} \cdot t_{calend.} \cdot c_{load.light.out} \qquad (7.12)$$

According to the current repairs schedule of buildings and systems, their preparation for work in the autumn-winter period, the educational institutions should carry out activities to their implementation. Planning of labor, material and energy costs should be carried out taking into account the duration of the work, a list of current collectors that are used in such technologies and their installed capacity of electricity. It seems appropriate, in addition to the estimates for the performance of these works, to develop a separate specification, which should reflect the list of current collectors with a certain installed electric capacity and the period of use. Planning of amount of electric energy consumption during repair should be carried out while developing a calendar schedule of work execution. The forecast amount of daily electricity consumption for these types of work should be taken into account while forming a short-term forecast limit for electric energy consumption by an institution or its unit. According to this limit, the further recording of the amount of current electricity consumption is carried out.

By analogy with (7.12), it should be calculated as follows:

$$A_{repair} = \sum_{i=1}^{n} P_{repair.i} \cdot t_{calend.} \cdot c_{load.repair.i} \qquad (7.13)$$

Where A_{repair} - forecast amount of daily electricity consumption for this type of work performed, $\sum_{i=1}^{n} P_{repair}$ - the sum of the installed electrical capacity of the *i-th* current collectors that should be involved in the performance of work in the forecast calculation period, $c_{load.lrepair.i} = t_{repair} / t_{calend.}$ - load coefficient of the *i-th* current collector.

It is advisable to divide the amount of forecast electric energy consumption by their structure while carrying out the work related to the execution of orders of third-party organizations. For example, they can be divided into activities in office premises (with use of office equipment) and in production rooms where technological processes connected with the manufacture of material products (manufacturing of various products, carrying out repair work, etc.), with use of industrial equipment, are carried out. According to such structure, it is proposed to carry out the element by element calculations: daily electricity consumption during the lighting system operation $A_{light.agreed.}$ and office equipment (computers and other devices) $A_{office.dev.agreed.}$ as well as industrial equipment consumption $A_{indust.equip.agreed.}$ which should be calculated by analogy with (7.3) and (7.5), using the formula:

$$A_{light.} = \sum_{i=1}^{n} P_{light.agreeg.i} \cdot (t_{light.1ad\min.} + t_{light.2ad\min.}) \tag{7.14}$$

Where $\sum_{i=1}^{n} P_{light.agreeg.i}$ - the total installed capacity of the current collectors of the lighting system located in separate rooms used to execute the orders of third-party organizations;

$$A_{1office.dev.agreed.} + A_{indust.equip.agreed.} = \sum_{i=1}^{n} P_{office.dev.apreed.i} \cdot t_{calend.} \cdot K_{zoffice.dev.apreed.i} +$$

$$+ \sum_{i=1}^{n} P_{indust.equip.agreed.i} \cdot t_{calend.} \cdot K_{zindust.equip.agreed.i}$$

Where $\sum_{i=1}^{n} P_{office.dev.apreed.i}$ - total installed electrical capacity of current collectors of office equipment used while executing orders of third-party organizations, - load coefficient of the *i-th* current collector of office equipment used while executing orders of third-party organizations; $\sum_{i=1}^{n} P_{indust.equip.agreed.i}$ - the total installed electrical capacity of the current collectors of industrial equipment used in the execution of orders of third-party organizations, – load coefficient of the *i-th* current collector of industrial equipment used while executing orders of third-party organizations.

In order to simplify the construction of an algorithm for calculating the forecast amount of electricity consumption by artificial lighting systems, it is suggested to connect them by structure and in time with the class schedule. Then it is advisable to consider in parallel and simultaneously the operation of lighting systems in classrooms, in the rooms where the support processes are carried out, in common areas, in administrative and accommodation premises, as well as outdoor lighting systems. For this purpose, the daily operating time of the institution should be divided into periods corresponding to the duration of classes and breaks between them. As a rule, the class schedule is constructed with the indication of the discipline title, type of class, name or number of the room, time and date of the class. It is also necessary to add information (as basic) about the installed capacity of the room lighting system $\sum_{i=1}^{n} P_{light.i}$. The estimated climatic coefficient $c_{c\lim}$ should be determined for each period of classes according to the schedule and in accordance with climatic conditions (length of daylight hours) on the date of their conducting. Similar to the above mentioned, an algorithm for calculating the forecast electricity consumption of other lighting systems mentioned can be constructed. The amount of forecast electricity consumption by lighting systems of premises, where the orders of third-party organizations are executed, can be calculated by the given sequence, or (if the premises are functionally and organizationally separated from the main activity of the institution) according to aggregated indicators, taking into account their $\sum_{i=1}^{n} P_{light.i}$ and $c_{c\,\mathrm{lim}}$, as well as taking into account the duration of the working day. The calculation of the forecast daily amount of electricity consumption by emergency lighting systems should be calculated in accordance with current labor protection standards and taking into account the design features of the building and the institution's working schedule. The total forecast daily consumption of electricity by lighting systems should be calculated as the sum of the mentioned components.

The adjustment of the amount of daily electricity consumption by lighting systems with considering the current climatic and meteorological situation is suggested to be calculated by further adjustment of the values $c_{c\,\mathrm{lim}}$ for the i-*th* period of the educational process. Such calculation should be performed every day based on actual indicators of the meteorological situation of the previous day. That is, while generating protocols for an automated forecasting and monitoring system for electric energy consumption by lighting systems, it is possible to generate arrays of information on a short-term estimated forecast, information on adjusted daily consumption according to the actual meteorological indicators and, using information on current consumption, information on actual deviations of real electricity consumption from the calculated one for making effective management decisions of effective management of electricity consumption.

It is obvious that the forecast estimated amount of electricity consumption should be calculated as the sum of certain components. Considering that the current collectors of the lighting system is one of the key consumers in the educational institution, therefore, based on the analysis of the accuracy of the weather forecast, it seems advisable to determine 24 hours as a period of short-term forecasting.

The working schedule of the educational institution is mainly subordinated to the technologies of the educational process, which is regulated by the class schedule. Thus, for the formation of profiles of daily forecast amount of electricity consumption, it is suggested to take the structure of energy consumption by time of classes conducting as a basis. The key information blocks which future will form the database for calculating the forecast limit of electricity consumption should be as follows: the room data sheet with an indication of its number, the installed capacity of the current collectors of the lighting system, the installed capacity of the current collectors of the educational process; passport of the academic discipline, with an indication of its title, type o classes, installed capacity of the current collectors that are used for this type of activity, load coefficient of the current collectors during the class; class schedule, which should contain information on the calendar date, periods for conducting classes, title of the discipline, location of the lesson conducting, the reference value of the climate coefficient for each period of the lesson depending on the date. Climate coefficient refinement should be carried out in automatic mode taking into account the forecast and current meteorological situation, which is estimated by using the information of the local weather station (available on the Internet). A graphical interpretation of the key information blocks of the algorithm for calculating the forecast amount of electricity consumption during the educational process is given in Fig. 51.

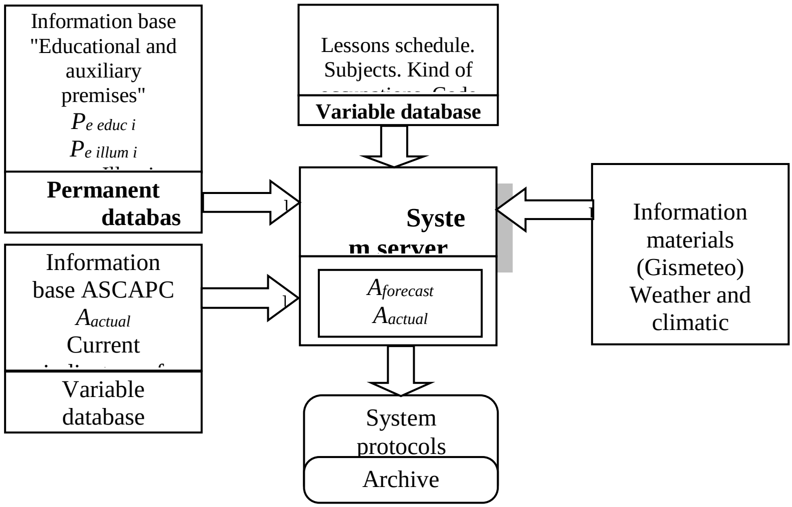


Figure 51. The block diagram of the information blocks of the algorithm for calculating the forecast volumes of electricity consumption during the educational process

To simplify the algorithm for calculating the amount of forecast electricity consumption by the lighting system of administrative, accommodation and support premises, it seems advisable to define basic duration of the periods of the lighting system operating $t_{ligh.1ad\,\min}$ and to be a multiple of (or correspond to) periods of the classes schedule.

An integral indicator of the results of calculating the forecast amount of electricity consumption by the above components should serve as a benchmark for the amount of electricity consumption for the next day. This value can be taken as the estimated limit of electricity consumption for the current collectors of a building, institution. The main difference from the existing limits defined by the current regulatory documents, which summarize large amounts of statistical information of a general nature, is the fact that based on the results of the energy inspection of particular rooms, it is possible to consider the specific features of the educational and support processes, climatic and weather conditions while determining the adjusted forecast amount of electricity consumption of a particular educational institution. The suggested algorithm (mathematical model) for determining the amount of electricity consumption is quite simply integrated into the computer-aided calculation system using modern computer technology and can be used as a basic platform in the formation of an automated system for short-term forecasting and monitoring of electricity consumption by current collectors of electrotechnical complexes and systems of business entities.

However, the described model should be only (although a key one) a part of an integrated automated system for monitoring the current electricity consumption of a separate facility, building, institution. Another component of the system should be a system of automated continuous-time recording of electricity consumption. For this purpose, it is possible to use the technical and organizational capabilities (as basic ones) of the existing ASCAPC system, the elements of which exist and operate in almost every institution. That is, a further algorithm for the system operation should be based on the current combination of information arrays of short-term forecasting and real electricity consumption with the possibility of analyzing and comparing them on-line with the elimination of the possibility of recording distortions due to the possible influence of the human factor.

The combination of the elements of automated forecasting with monitoring of real electricity consumption allows to carry out the accurate and detailed planning of schedules and amount of electricity consumption in order to quickly manage electricity consumption processes and eliminate inconsistencies in order to increase the energy efficiency of the electrical capacity using. As a result, it will lead to the reduction of the costs for electric energy consumed by the building, reduction of CO_2 emissions into the environment.

The combination of the automated short-term forecasting function of electric energy consumption by current collectors (calculation of the estimated amount of electric energy consumption), which is based on the forecast indicators of meteorological conditions (determined by the weather station's information arrays or weather sites and get into the system via the Internet), a variable information array of classes schedule of the institution (the key technological process) and a permanent database of the electricity installed capacity of the current collectors, that are used in a particular room, and the possibility of using the information arrays of the Automated System for Commercial Accounting of Power Consumption (ASCAPC) of the institution, which are combined into the algorithm of the automated information system to determine the amount and schedules of electric energy consumption, comparing with them the profile of real current consumption "on-line" provides additional opportunities to make timely the effective management decisions with the aim to efficiently use electric energy.

The total forecast electricity consumption should be calculated (in kWh) as the sum of the determined components. They should be formed by the periods of the day, the corresponding class schedules and the working hours of the support units, forming the electricity consumption profiles of the building. Data can be generated in the form of tables and graphs of forecast consumption for the next day. The algorithm of the system allows to make adjustments to the results of the forecast calculation at the end of the current period, if there are significant changes in the variables of the initial data connected with a change in the class schedule or a change in meteorological conditions.

Using current ASCAPC data on electricity consumption, the system algorithm allows to reproduce a picture of real electricity consumption and its profile in the form of tables and graphs, as well as to compare the values of the forecast electricity consumption with the real current ones on-line, or with values of any period.

This method for automated short-term forecasting and monitoring of building electricity consumption allows the real-time determination of the current state of electricity consumption by buildings and analysis of deviations of actual electricity consumption from the forecast limit by using modern information technologies for processing and analyzing monitoring data and, as a result, provides the manager with operational analytical information for making decisions. The method includes a system for automated short-term forecasting and monitoring of electricity consumption in buildings and powerful analytical tools for processing monitoring results. This contributes to the transition to electronic document management, the formation of current information on electricity consumption on-line for maintenance staff, and the simplification of the work of the manager in terms of decision-making regarding energy conservation measures in the institution.

7.2 «Spectrum» of electricity consumption and methods for its components analysis

Amount of electric energy consumption, which are recorded by metering devices, usually determine the total consumption by current collectors, which are powered by the mains at the input of which the metering station is equipped. The key tasks and function of an automated commercial metering system for electricity consumption is to record the amount of electricity that "has passed" through the meter during a certain period. The derivative of this function is the calculation of other quantitative indicators of electricity consumption. That is, in any case, these indicators are integrated ones for all current collectors of the mains, if they are not equipped with additional metering devices. Under such conditions, the direct use of system protocols for the detailed study and analysis of the operation of current collectors, the mechanisms of systems and technologies is limited. The energy flow must be detailed according to the consumption components in order to conduct a detailed analysis of electricity consumption. That is, it is necessary to divide it into elements to create a «spectrum» of the components of electric energy consumption.

The analysis of the «spectrum» of electricity consumption by the buildings of the educational institution is presented by case study of the most typical educational building for a higher educational institution, where educational, laboratory, support, administrative and accommodation rooms of the departments of general technical, electrotechnical, financial and economic areas are located.

According to the results of the energy inspection, the nature and profile of energy consumption, which is recorded by the metering systems ASCAPC, it is advisable to divide the day into the periods as follows:

1 – Nighttime: from 00.00 to 8:00 a.m. (beginning of the working day) with a discreteness of the period for determining the amount of electricity consumption of one hour;

2 – Day study period: during which the key and support technological processes of educational activity are carried out with a discreteness in the period for determining the amount of energy consumption, which corresponds to the duration of one class (from 8:00 a.m. to 21.00 p.m.);

3 – Evening period: from 21.00 p.m. to 00.00.

Associated processes of the functioning of the building which consumes electrical energy is associated with the operation of the equipment of the cantina that is located in the building; round-the-clock functioning of the information support system (servers) located in the building, current collectors of the heating network of the building operating during the heating season, periodically operating current collectors of outdoor lighting the territory near the building, etc.

It is advisable to determine the profile of such an electric load and the schedule of the electricity consumption amount by analyzing the energy consumption on holidays and weekends, when no educational and support processes are conducted in the building. Let’s call this element of electricity consumption as “noise” or «background» electricity consumption. It always accompanies the functioning of the building 24 hours and its value is quite constant. As for our case, the selected component of the “background” electricity consumption is on average 2 kW by capacity. It is tracked in each of the three defined day periods.

During the heating period, the building heating system switches to so-called standby mode of operation in order to conserve thermal energy, when personnel is not in the building in the evening and night hours. According to this mode, the temperature of the coolant in the heating system decreases according to the corresponding schedule and, accordingly, the air temperature in the rooms decreases. To create comfortable conditions for the staff on-duty, who stay in the building for 24 hours, local electric heaters are used in the duty rooms. Therefore, during periods 1 and 3 the operation of electric heaters in local premises is an additional element of the “spectrum” of electricity consumption. In our case, this component is 0,4...1,0 kW by capacity. This situation is justified from the point of view of energy conservation, since keeping the temperature of indoor air in the building’s premises at a constant level for 24 hours during off hours, entails an additional average consumption of thermal energy of about 0,27 Gcal/day. The additional use of local electric heaters requires an additional electricity consumption of about 10 kWh per day. Bringing these indicators to the monetary equivalent of the amount of payment for the indicated energy resources shows the advantage of implementing such activities as 1:15,6 in favor of local electric heaters.

The consumption of electric energy by the current collectors of the outdoor lighting system is observed in the evening hours (period 3). According to the results of the analysis of electricity consumption profiles, lighting is switched on according to a schedule that is consistent with climatic conditions and length of daylight hours. This component usually makes about 1 kW in terms of electricity consumption. Exceptions are the periods of large holidays, when the territory is decorated with additional illumination.

The results of differentiation of the daily profile of electricity consumption by the indicated components make it possible to present the “spectrum” of the electricity consumption by its elements and periods of the day. The graphical interpretation of the components of daily electricity consumption is given in fig. 53 and numerical values are given in table 7.1.

Table 7.1. – The components of daily electricity consumption by current controllers of building of educational institution (according to the averaged data from October to March)

Period, hours, minutes	Actual total consump-tion,kWh	Const.components of actual consumption «background», kWh	Consumption by lighting during educational process (estim.), kWh	Consumption by gadgets during educational process (estim), kWh	Consumption by gadgets, lighting, and support processes (estim.), kWh	Consumption during educational process (estim.), kWh	Outdoor lighting, other processes, kWh
0 - 1	2,495	2,0	0	0	0	0	0,5
1 - 2	2,308	2,0	0	0	0	0	0,3
2 - 3	2,038	2,0	0	0	0	0	0,4
3 - 4	2,238	2,0	0	0	0	0	0,3
4 - 5	2,1	2,0	0	0	0	0	0,1
5 - 6	5,026	2,0	0	0	0	0	3,0
6 - 7	6,148	2,0	0	0	0	0	4,1
7 – 8.15	6,264	2,0	0	0	0	0	4,26
8.15 – 9.50	12,872	2,1	4,656	5,546	0,57	10,202	0
9.50 – 11.25	18,504	3,16	0	7,264	8,08	7,264	0
11.25 – 12.45	20,333	3,16	0	7,214	9,959	7,214	0
12.45 – 13.25	5,324	1,0	0	0	4,324	0	0

13.25 – 15.00	20,032	3,16	0	6,647	10,225	6,647	0
15.00 – 16.35	17,807	3,16	7,84	4,742	2,065	12,582	0
16.35 – 18.00	13,560	3,16	2,848	4,092	3,48	6,94	0
18.00 – 19.25	5,949	3,16	0,54	0,494	0	1,034	1,755
19.25 – 20.45	3,727	3,16	0	0	0	0	0,57
20.45 – 22.00	2,739	2,0	0	0	0	0	0,74
22.00 – 23.00	2,700	2,0	0	0	0	0	0,70
23.00 – 24.00	2,99	2,0	0	0	0	0	0,99

The performed differentiation allows a more detailed analysis of the electricity consumption amount for 2 days.

As already noted, the daytime study period is the time of day during which the key and support technological processes of educational activity and other processes, associated with the scientific and economic activities of the institution, are carried out. Despite the fact that the main activity during this period is the educational process, which is regulated by the class schedule, it is advisable for the convenience of electricity consumption analysis to divide it into time intervals with discreteness, which corresponds to the duration of one class.

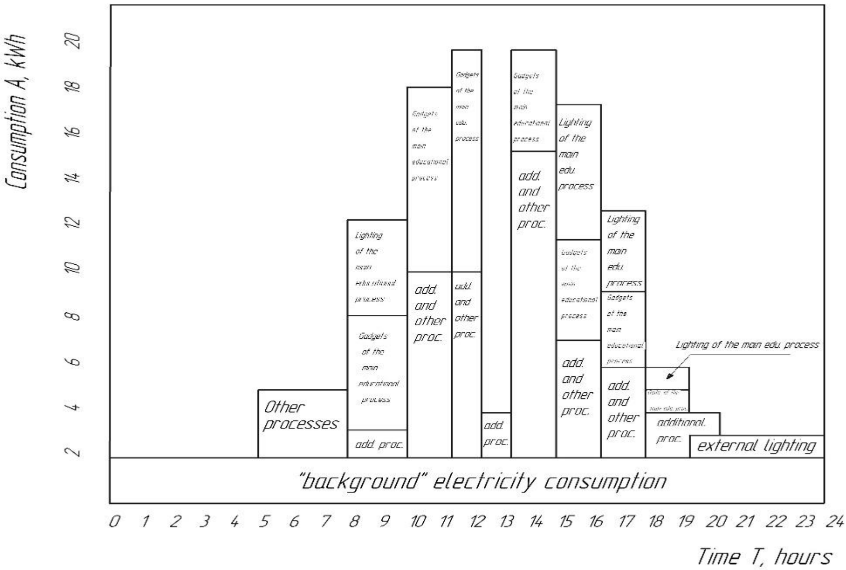


Figure 53 – The «spectrum» of electricity consumption by its elements and periods of the day

The «background» electricity consumption is observed during this period. That is, the current collectors of the uninterrupted support systems for the functioning of the processes that are carried out in the building, as well as systems of energy and functional support of the building itself. That is, it can be defined among the total amount of electricity consumption as a constant while analyzing electricity consumption during this period. The results of the analysis of electricity consumption at the weekend are one of the confirmations of the quantitative assessment of such component of electricity consumption. If mentioned components are already separated from the total amount of consumed electricity, then the balance should include the amount of consumption during the educational, support and other processes. As the results of the analysis show, this component of electricity consumption takes about 2/3 of all electricity consumption in the buildings of educational buildings of higher educational institutions. Further differentiation of electricity consumption can be based on data of electricity meters, if there are installed in the building and record the electricity consumed by building systems. However, such an opportunity is more an exception to the general rule for educational institutions. In this case, it is advisable to further study the amount of electricity consumption and their modes by using the calculation method. This method uses predefined energy consumption constants by individual current collectors available in the premises and an algorithm for their use in appropriate periods. The most organized and regulated process at the university is the educational one. If current collectors used at a particular class and the class schedule are known, it is not difficult to make preliminary calculation of the amount of electricity consumption for any period of the educational process. Given that all other processes, one way or another, are consistent in time with the training, it is advisable to consider them by intervals of classes during the working day of the institution.

It is advisable to consider the electric energy consumption by current collectors, which are used in the educational process, by two components of the consumption «spectrum»:

- electricity consumption by current collectors of the lighting system of educational classrooms where the educational process is carried out (lamps);

- electric energy consumption by current collectors of devices that are used at classes (multimedia projector, system units, monitors, laboratory equipment, etc.).

A specific feature of the algorithm for such calculations is the need to consider the operating mode of the lighting system of work places in classrooms. This situation is directly connected with the level of natural light. It is a variable parameter and depends primarily on the length of a day (climatic and geographical parameter), as well as on meteorological factors (cloud cover, etc.). Considering the changes in the length of the day and the lighting in the premises during certain hours of the day does not cause any particular difficulties. It can be forecasted for any period. Regarding variable meteorological factors, the task is more complex and requires a fairly accurate short-term weather forecast. Considering that lighting systems in classrooms can have only two energy modes – «on» and «off», then the algorithm for calculating the energy consumption amount should be constructed taking into account these two modes. It is suggested to describe the energy modes using the weather (climatic) coefficient. Depending on these factors, it can take one of two values – «1» or «0». That is, the calculation of the forecast electricity consumption is performed taking into account the installed electrical capacity of the current collectors of the lighting system and its energy modes.

Forecast amount of electric energy consumption by current collectors of devices and gadgets used at classes should take into account two specific features of their use. The quantity and completion of such devices can vary significantly for each class, therefore, in calculation algorithm it is advisable to use the electricity capacity constant (for example, the total installed capacity of the current collectors located in the room) of the gadgets. It is suggested to take into account the share of their use through the capacity use (load) factor at class. The define the time of gadgets use during the class remains a problematic task. It is also proposed to determine it by introducing a variable indicator into the algorithm – the coefficient of used time (the load coefficient of gadgets at class by time). This coefficient has to characterize the share of the period at class during which the current collectors operate and consume electrical energy.

Having a class schedule and using the calculation algorithm it is not difficult to accurately determine the forecast electricity consumption amount for any period of the working day. For example, table 2.1 shows the results of the calculated differentiation of electricity consumption by class and out-of-class periods.

To determine and evaluate the component of electricity consumption in the «spectrum» in support processes, it is possible to use the calculation method, by analogy with determining the amount of electricity consumption during the educational process. But it is very difficult to do. In spite the fact that the beginning and the end of the working day is clearly regulated for staff, it is difficult to determine the day amount of electric energy consumption by a detailed calculation method. The uncertainty of the results is associated with the need to take into account the influence of a number of factors. The creation and functioning of a mathematical model require the use of large resources and it is not always justified. A more acceptable way to determine this component of the "spectrum" is to calculate the remainder that is formed after extracting from the full amount of the «spectrum» the values of electricity consumption by the current collectors of «background» electricity consumption by outdoor lighting systems, other processes and educational process systems together with lighting systems in the educational process. At the same time, dividing the electricity consumption into components of the lighting systems operation for support processes and equipment, used in support technologies, remains problematic. This issue can be solved by a detailed analysis of this component. At the same time, to calculate the forecast consumption by current collectors of lighting systems, it is possible to use a technique similar to the calculation method in the educational process.

The accumulation of statistical data on the components of the "spectrum" of electricity consumption makes it possible to use other methods of modeling energy consumption processes while forecasting consumption amount in the future.

Thus, it should be noted that the main steps of the methodology for determining the components of the «spectrum» of electricity consumption in the educational buildings should be as follows:

- step 1 – using the ASCAPC database, to determine the integral profiles of the daily consumption of electric energy by the current collectors located in the building, to determine the time "step" of the profile (during the classes that are conducted according to the schedule, it should match the duration of the class, in other periods of the day it is desirable to bring it up to one hour);

- step 2 –to analyze the profile of electricity consumption by the building's current collectors at weekends in order to determine the «background» electricity consumption by the building's life support systems, the systems of outdoor lighting of building and the surrounding area;

- step 3–to determine the "background" electricity consumption as the remainder of the difference between the integral and the "background" consumption, determine the profile of the total electricity consumption by the current collectors during the educational and support processes;

- step 4 – using the materials of energy inspections of the premises of the educational building, to conduct the energy certification of the current collectors located in the premises as well as to determine their installed (or actual) electrical capacity in kW by dividing the classrooms into educational and support ones; to determine the current collectors of the lighting system according to an additional list, to calculate their integral installed electrical capacity;

- step 5 – according to the list of academic disciplines for which the educational process is conducted in accordance with the class schedule, materials of energy inspection to determine the list of current collectors that are used in classrooms while studying the discipline at certain type of classes, to determine their integral installed (or actual) electrical capacity ;

- step 6 – according to the data obtained during steps 4 and 5 to calculate the amount of electricity consumption by the current collectors in the classes in accordance with the class schedule, meteorological and climatic conditions, separately highlighting the electricity consumption by the lighting systems of the classrooms and gadgets used in the educational process;

- step 7 – after determining the profile of the total electricity consumption by the current collectors in the educational and support processes (step 3), it is suggested to identify (minus) the tariff electricity from the current collectors that are involved in the educational process (lighting system and gadgets), which allows to obtain the profile of the current consumption by current collectors used in support processes;

- step 8 – to conduct a calculated analysis of the electricity consumption by current collectors of support processes, dividing them by the lighting system, etc.

- step 9 – draw up a «profile» of electricity consumption by components in accordance with a defined form and conduct an appropriate energy, financial and economic analysis of electricity consumption.

The calculation of the "spectrum" of the electricity consumption profile can be quite simply automated using modern computerization tools with the previous preparatory work listed in the above-mentioned steps.

The analysis of the components of the «spectrum» of electricity consumption shows that, as a percentage, the average amount of electricity consumption by the current collectors in the building of the educational building are divided according to the following systems:

- «background» consumption is about 36 %;
- consumption in the educational process is about 32 %,

including: lighting systems is about 39 %;

- gadgets is about 61 %;
- consumption by an outdoor lighting system and other processes is about 1 %;
- consumption during support processes is about 32 %.

As the above mentioned data show, the consumption of electric energy in the educational process is about 32 % of total consumption. Other consumption relates to the execution of supporting processes.

It should also be noted that the electric energy consumption amount are different in different periods of the day. They are the largest during working hours and the maximum consumption occurs during daylight hours, even though the lighting system does not work.

An analysis of the electric energy consumption amount by lighting systems indicates a significant share in the total electricity consumption by current collectors of current technologies of the key educational process. The energy «background» of electricity consumption is also quite significant.

The described methodology for the analysis of electricity consumption allows to determine the energy efficiency of processes that are carried out in educational institution by comparing the calculated current indicators of specific electricity consumption with standard ones both for the institution in general and for individual technological processes. The constructed profiles of actual and forecast electricity consumption by current collectors of systems and processes is the basis for decision-making on further development of measures to increase their energy efficiency, a real assessment of the feasibility of implementation based on calculated economic indicators.

This methodology allows to combine elements of calculation algorithms, statistical databases, as well as current and archived data of instrumental measurements (including ASCAPC data) to form a «spectrum» of electricity consumption amount for further analysis and making relevant current and future managerial decision.

7.3. Implementation of solar electric energy generation with the location of solar panels on the enclosing structures of educational buildings

The organization of electric energy generation processes for the needs of educational institutions and the use of enclosing structures on buildings of educational institutions as mounting supports for solar panels is a very forward-looking activity.

The electric energy generation by solar power plants for the needs of technological processes in educational institutions is conditioned and restrained by the schedule peculiarities of the educational process, which is most subject to all other technological processes, as well as conditions and possibilities of solar panels on the territory or facilities. Current legislation regulates the general conditions for the panels location on the external surfaces of buildings.

The attractiveness of the potential application of solar electric energy generation for at least partially satisfying the requirements of an educational institution is also explained by coincidence in time of the generation and consumption schedules of electric energy.

Organizational, technical and climatic aspects of the use of solar electric energy generation installations in educational institutions.

According to the current legislation in Ukraine, the academic year in educational institutions is organized mostly from September 1 to July 1. Due to its climatic and meteorological features in the north and northeast of the country, this period is characterized by high cloud density for almost 4,5 months out of 10 months of the academic year. The results of observations show that the specific generation of electric energy during these 4,5 months is about 780 kWh/10kW of installed capacity of solar panels, i.e. the average daily generation in the «dark» time of year is about 6 kWh/10 kW of installed capacity of solar panels when they are stationary on the roof of the building. However, in the "bright" period of the academic year (September, October, part of March, April, May, June) the total average specific solar generation is about 6310 kWh/10 kW of installed capacity of solar panels, and the average daily generation is about 38 kWh/10 kW of installed capacity of solar panels. The maximum efficiency of solar panels is in July, August (average daily generation – about 48 kWh/10 kW of installed capacity of solar panels), however, during this period, educational institutions stop the educational process and electricity consumption is minimal. The peak of electric energy consumption coincides with the hours of maximum solar electric energy generation, see Fig. 54.

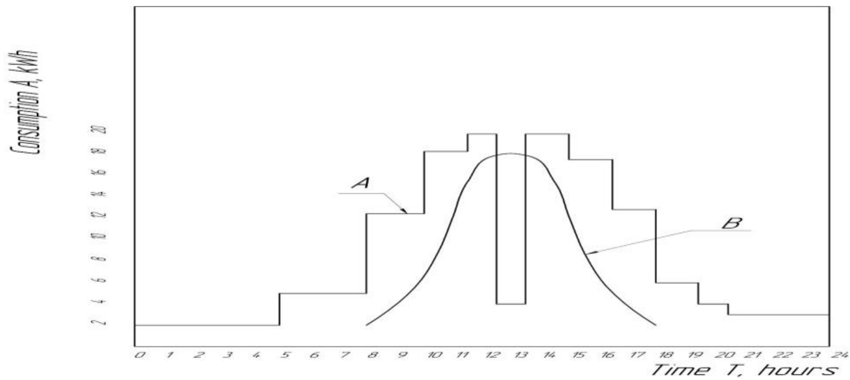


Figure 54. Profile of electricity consumption by the building of the educational institution and profile of its generation by solar panels by the time of day (A – profile of consumption, B – profile of generation)

If to pay attention to this fact and to plan the most power-consuming classes in hours of the maximum generation during scheduling (in the presence of solar generation), it is possible to «align» schedules (profiles) of power consumption during the educational process. Based on the possibility of placing solar panels on the building and considering the conditions of panels orientation in space for maximum electricity generation, using as much surface area of enclosing structures as possible, it is not difficult to determine the technical capabilities of solar power generation technology in the educational institution. It is also necessary to refer to the economic aspects of the implementation of such a measure, the organizational opportunities for electricity sale to supply companies in the event of a surplus of generated electricity in summer months.

In some cases, it is advisable to use solar panels on vertical surfaces of enclosing structures as a protective and finishing surface of facade insulation systems (on the principle of a ventilated facade). However, when determining the technical and economic rationale for such an action, it is first necessary to pay attention to the efficiency of solar panels, which in such conditions will not be located at the optimal angle to the Sun's rays.

Research results on the influence of the tilt angle of solar panels on electricity generation.

Solar panels work most efficiently when their surface is perpendicular to the Sun's rays, so the tilt angle to the horizon is one of the key parameters of the solar power station [12]. Another factor that affects the amount of electricity generation is the azimuth that is the angle between the Sun and the south. Currently tracking these parameters is not a difficult engineering task, but its implementation requires additional equipment and high financial costs, so most solar panels are located on open surfaces at certain angles and with a south orientation. The tilt angle depends on the latitude of the area in which the panels are located. When it is constant during daylight, the efficiency of electric energy generation is variable. To evaluate this effect, the coefficient of electricity generation k_g is used as the ratio of the value of the actual generation power P_{actual} (kW) to the nominal power of the panel $P_{manag.}$ (kW):

$$k_g = P_{actual} / P_{manag.}$$

This coefficient for a constant tilt angle is variable over time and depends on the actual tilt angle of the line connecting the observer and the Sun to the horizon.

The research to determine the dependence of the change in the coefficient k_g in time was conducted on a laboratory installation, which in automatic mode monitors the angle of the panel to the Sun.

To exclude the influence of the azimuth angle during the study, we defined the maximum value of P_{actual} at the *i*-th period of time and the optimal tilt of the panel, which provides the maximum generation of

P_{actual}. The deviation of the tilt angle of the panel was determined from the specified optimal angle. The research results are presented in Table 7.2.

Table 7.2. – The change in k_g when the tilt angle of the solar panel deviates from the optimal one

Deviation of the inclination angle	5^0	10^0	15^0	20^0	25^0
Calculated coefficient k_g	0,862	0,809	0,712	0,688	0,655

If, according to the optimal tilt angle of the panel, we take the coefficient value $k_g = 1$, then, when changing the tilt angle in the range from 0º to 25º, the coefficient k_g changes in the range from 1 to 0,655, which corresponds to the range of decrease in generation from a possible 100 % to 65,5 % in accordance with a change in the tilt angle of the panel from the optimal one at the *i*-th period of time. Based on the findings and calculations, the calculated coefficient k_g reduces to 0,172. The average value of the decrease in the electric energy generation, when the tilt angle of the solar panel changes from the optimal one in the range from 0º to 25º, is 17,2 %.

The indicated range of variation in the tilt angle of the panel can be considered as moderately acceptable in further calculations and studies, which corresponds to the design capabilities of solar panels placement on the external structures of buildings in the conditions of the northern climatic zone of the country.

The results of the analysis of solar power station operation in the climatic and geographical conditions of the northern region of Ukraine.

Further research on the solar power station operation was carried out using the collected source statistics.

The results of solar power station operation over the past three years with a nominal capacity of 10,2 kW placed on the roof of a building in Sumy (the northeastern region of Ukraine) were accepted for consideration and analysis. The orientation of the plane of the solar panels is south. To consider the architectural features of the building, the panels are placed on the same plane parallel to the roof with the tilt angle of 25º. The fastening of photovoltaic panels is stationary. The volumes of monthly electricity generation are indicated in Table. 7.3.

Table 7.3 – The generation of electric energy by a solar power station, kWh.

Months of the year	2017	2018	2019	Average per month
January	110	102	114	108,6
February	125	132	128	128,3
March	273	254	286	271
April	1398	1450	1419	1422,3
May	1580	1521	1590	1563,6
June	1652	1618	1666	1645,3
July	1393	1136	1486	1338,3
August	1524	1424	1707	1551,6
September	1094	1127	985	1068,3

October	583	465	781	609,6
November	194	132	251	192,3
December	73	54	88	71,6

The graphic interpretation of the distribution of average volumes of electricity generation by months of the year is presented in Fig. 55.

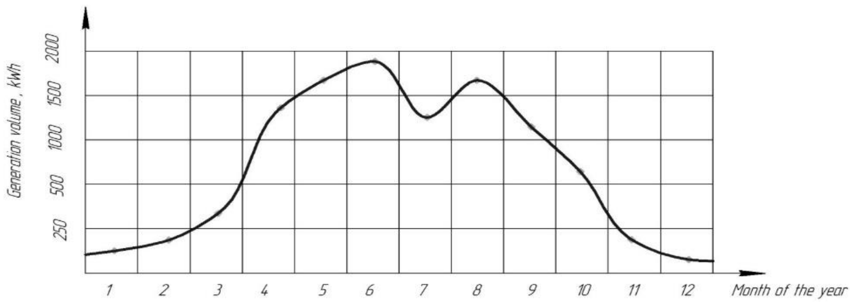


Figure 55. The distribution of average volumes of electricity generation by months of the year

The analysis of the results of the power station shows that, given the climatic conditions of Sumy, the generation in winter months is 10…15 percent of summer months. This is due to snow cover and cloudy weather during these months. Based on this, organizational and technical settings with a focus on efficient power station operation in winter is inappropriate. It is necessary to focus on the rational use of the solar power station in the period from the last decade of March to the second decade of November, so the main parameters of its adjustment should correspond to the geographical and climatic conditions of this period.

The analysis of statistics on the daily operation of the power station shows that the maximum instantaneous generation power is recorded at about 13 o’clock in the afternoon (in June it averages 9,2 kW in cloudless weather, in November – 6,2 kW under the same conditions). The period of active electricity generation in June is from 7.00 am to 7.00 pm, in November – from 8.30 am to 3.30 pm. Graphic interpretation of the daily change of instantaneous generation power is presented in Fig. 56.

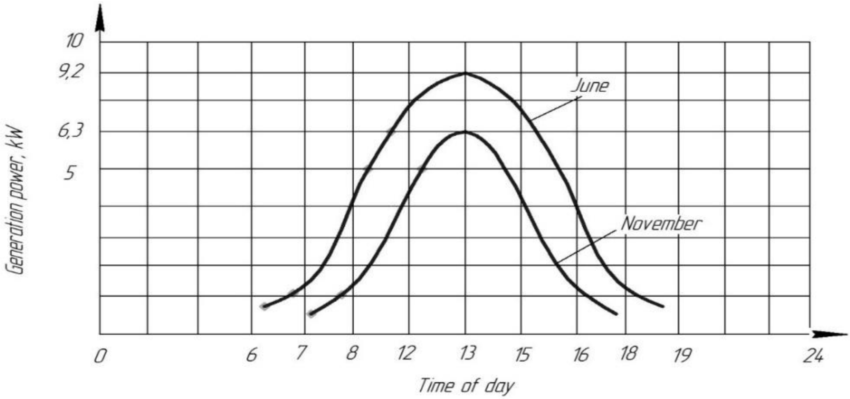


Figure 56. The schedule of daily change in instantaneous power of electricity generation

Under certain location conditions (based on the calculation algorithm according to the method [1]) the best tilt angle of solar panels in summer will be the numerical value of the latitude of the building, multiplied by 0,93 minus 21 degrees. In our case, it should be about 27º.

The comparison of findings (using a laboratory bench) of the change in solar generation power from the tilt angle of solar panels and the actual statistical data on the solar power station operation indicate the correctness of the algorithm of the method [7] and confirm the decrease in the calculated generation coefficient k_g within 3% with a deviation of the tilt angle of the solar panels from the calculated within 2º. This also corresponds to the trend data in Table 2.3.

Technical possibilities to increase the electric energy generation by a solar power station.

As already mentioned, these results were obtained under the condition of a stationary location of solar panels on the roof of the building.

However, the amount of solar radiation absorption entering the area of the solar panel (and as a result, the amount of electricity generated by the solar battery) depends on its orientation relative to the cardinal points, the tilt angle of the plane of the solar module relative to the horizon, the length of the daily period of daylight (if electricity generation by the module is possible). That is, the maximum efficiency (excluding the design features of the panel itself) of the solar module, in our case, should be determined by the initial orientation of the panels by geographical indicators, as well as tracking their changes during daylight with the possibility of adjusting the orientation of the panels in space and considering the coordinates of the Sun location in the *i*-th moment of time. It can be achieved by implementing special technical devices that automatically track the position of the Sun relative to the horizon and the sides of the world and allow you to orient the solar panels at any *i*-th moment of time.

Architectural and design features of most residential buildings of private construction allow the installation of such rotary devices (trackers) that should orient a separate solar panel in two planes: the azimuth and the angle of the Sun to the horizon.

The results of studies and observations of solar power station operation with an installed capacity of 10,2 kW in climatic and geographical conditions of Sumy city (average annual electricity generation of about 9800 kWh/year) show that equipping it with an automated system for adjusting the tilt angle will additionally generate about 1700 kWh/year. The total average annual electricity generation can reach 11500 kWh/year.

This result can be obtained under the condition of «landscape» arrangement of solar panels, i.e. the longer side of the panel should be located horizontally. This condition should be met to increase the use of the roof area for the position of the panels.

The area use factor K_s is calculated as the ratio of the area of placed solar panels S_p to the total area of the site of their placement S on the roof, or the walls of the building:

$$K_s = S_p / S \,,$$

and characterizes the potential value of the power installed on a certain plane of the power station.

Assuming a dense stationary arrangement of the panels on one plane parallel to the roof, the value of K_s will be close to one. That is, the area of the roof will be used as useful as possible.

When the panels are equipped with a track that changes their tilt angle to the horizon and its operation together with the rotation of the panels, shadow zones are created, which significantly reduce the electricity generation in the shaded areas of the panels. To solve the problem, it is necessary to place the solar panels at a distance from each other, which avoids shadow areas. The calculation shows that the position of the panels in compliance with this condition reduces the value of the area use factor by 18 %. This entails a reduction in the number of solar panels and, as a consequence, a reduction in the installed capacity of the solar power station provided that it is located on the same roof area.

Simple calculations show that in this situation the average amount of electricity generated by a solar power station per year should be about 9450 kWh. The comparison of power station operation providing stationary panel mounting on a certain roof area in one plane (subject to the tilt angle of the panels is 25^o) and using a tracker installation which monitors the tilt angle of the panels in accordance with the change in the Sun’s angle relative to the horizon, which shows that an increase in electricity generation does not compensate the loss of generation opportunities due to a decrease in the installed capacity of the power station located on the roof of the building.

When designing and carrying out assembly operations on the solar panels installed on the roofs of educational buildings or individual buildings, the main attention should be paid to the plane location of their installation relative to the horizon (mainly to the south) and compliance with the optimal angle of the solar panel relative to the horizon. Under these conditions, the amount of annual electricity generation mainly will depend on the area of solar panels located on the roof. The use of trackers, in this case, is not always justified, even from a technical point of view.

The use of a tracker system that would define the change in azimuth angle provided the position of the solar panels on the building's roof, is also associated with the problem of rational use of the roof area, and, consequently, with the amount of electricity generated. In addition, the results of research [8] confirm that the deviation of the azimuth angle of primary orientation of the panel plane within 15º to the east or west has almost no effect on the total average annual value of generated electricity.

The studies of literature sources [9] confirm the high efficiency of tracker devices use, provided that the placement of solar panels in one plane in a dense array. In this case, you can avoid shadow areas without reducing the occupancy of the panel area. That is, this scheme of location and orientation of solar panels relative to the Sun position during the daily period of active electricity generation is characterized by the maximum values of area use factors K_s and electricity generation k_g.

The legislative framework in Ukraine for regulating the location and solar power stations operation indicates the position of solar panels on the roofs and walls of buildings, without mentioning the possibility of their separation from the building. Given this fact, the use of tracker devices with the option described above may be questionable.

Increasing the amount of electric energy generated can be achieved by placing additional solar panels on the walls of the building [10]. The effectiveness of such a measure is also associated with determining the tilt angle of solar modules, the area use factors K_s and electricity generation k_g, the calculated numerical values of which can be a criterion for its evaluation.

The placement of panels on the walls of the building is limited by the predominant orientation of the outer surface of the wall to the south and its area, the space of possible installation of the panel, which is limited by the «protective» size of the deviation from the wall surface of the roofline (Fig. 2.7). This size for most buildings averages no more than 700 mm. It allows you to place the panel in the «magazine» version with an angle of at least 45º.

Based on the optimal value of the tilt angle of solar modules (in our case 27º) in hours of maximum daily activity of the Sun, and, consequently, the maximum electricity generation, the average electric energy generation of the power station with solar panels with an angle of 45º on the wall will be 0,704 of maximum possible.

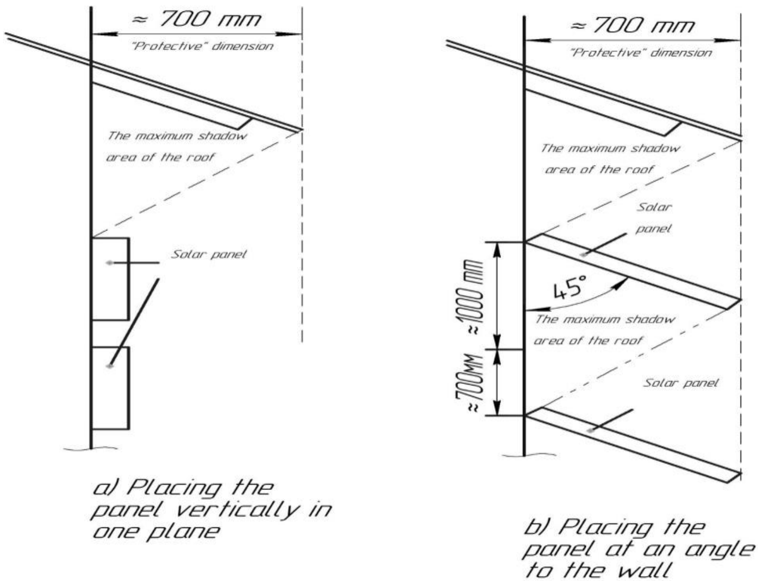


Figure 57. The layout of solar panels on the walls of the building

In addition, such a scheme for installing solar panels creates shadow zones on the wall plane, which must be avoided by placing the panels at a distance of about 1700 mm from each other. This feature reduces the area use factor to 0,58. That is, under such conditions, 42 % of the area cannot be used to place solar panels, and the total installed capacity of solar panels located on the wall will be less by almost 42 % compared to the option of placing panels vertically with one plane on the wall.

When placing the panels vertically in one plane, the area use factor of the wall area can be increased almost to one, which corresponds to an additional increase in the area of the location of the solar panels by almost 42 %. However, at the same time, during the hours of maximum daily activity of the Sun, the angle of deviation of the panel plane from the optimum will be about 63º, and, consequently, the average power generation of the power station will be 0,344 from maximum possible. Although in other periods of daylight hours, this angle will approach the optimum, a significant role in changing the generation power will play a change in the azimuth angle.

The total installed capacity can be increased by using the reserve of the area of «shadow zones» for additional panels placement. This measure can raise the total installed capacity by increasing the generation capacity to 0,488 from maximum possible. However, as can be seen from the comparison of calculation data, such a measure does not compensate for the decrease in generation capacity.

Placing solar panels on the wall of the building at an angle of about 45º gives an increase in electricity generation capacity during hours of maximum daily solar activity by almost 30 % compared to the option of placing panels vertically in one plane on the wall even if the wall area use factor increases almost to one.

Technical and economic aspects of implementing measures to regulate the tilt angle of solar panels.

The effectiveness of a solar power station operation when equipping the fastener system of solar panels with a one-turn tracker device (for tracking the optimal tilt angle of the panels) should be considered based on the conditions for a possible simultaneous increase in the average annual generation volumes, as well as its reduction due to a decrease in the number of solar panels placed on the roof.

As calculations show, such a contradiction negatively affects the solar power station efficiency and the efficiency of project innovations. Let’s discuss the use of a solar power station in a separate sphere or economic structure.

If it is possible to organize a solar power station operation in conjunction with the general regional power grid, the excess electricity generated flows and is calculated at a «green» tariff, which is 5,91 UAH/kWh. The average annual electricity consumption by the average economic structure is about 1750 kWh/year. As already mentioned, the average annual electricity generation under the condition of stationary placement of panels is about 9800 kWh/year, the amount of electricity «flowing» into the general network (9800 kWh - 1750 kWh) is 8050 kWh/year. In cash equivalent, it is UAH 47 575. After taxes, the household has a net income of almost UAH 38 300/year. Investments, in this case, amount to about UAH 280 000. Hence, the simple payback period of the project is about 7,3 years, subject to full monetary reimbursement of electricity consumed by this structure and neglect of the gradual in time solar panels efficiency reduction.

In the case of placing solar panels on the roof of the building by means of one-turn trackers to change the tilt angle automatically, the problem of shadow zones arises. According to calculations, its avoidance reduces the active area of electricity generation by 18%, which, under the same conditions of battery location, reduces installed capacity of the power station to 8,36 kW (by 1,83 kW). As already mentioned in the section, despite the increase in the specific generation rate, considering the loss of installed capacity, the average annual generation volume will be about 9450 kWh/year. The amount of electricity «flowing» into the general network (9450 kWh - 1750 kWh) is 7700 kWh/year. In cash equivalent, it is UAH 45,507. Excluding taxes, the structure has a net income of almost UAH 36 633 /year. According to this version of the technical solution, the investment volume will be almost the same UAH 280 000 with the exception of the cost of 7 solar panels (excluding «shadow areas») – UAH 29 400 (the average cost of one panel, considering the installation work, is UAH 4 200), i.e. the added cost of the tracker system is about UAH 140 000. That is, the total investment will be about UAH 390 600.

Hence, the simple payback period of the project is about 10,6 years, subject to a full monetary reimbursement of the consumed electricity and neglecting the gradual decrease in the efficiency of solar panels.

As you can see, under certain climatic conditions, the location of the building, its architectural features, the option of stationary location of solar panels on the roof without trackers is more attractive.

Technical and economic performance of the solar power station is also calculated under the condition of placing solar panels on the wall of the building with their vertical location (Fig. 2.7a) and placing the panel at an angle to the wall (Fig. 2.7b).

According to the version of Fig. 57, 20 panels with a total installed capacity of 5,2 kW are vertically placed on the wall. During the hours of the peak of solar activity and maximum electricity generation, the average power generation of a power station with such arrangement of solar panels will be 0,344 of the maximum possible, that is, 1,788 kW. Based on the total cost of the panels and possible added costs for their installation (about 20%), amount of required investment will be UAH 100 800.

According to the variant of Fig. 57b, there are 11 panels on the wall (considering the area of «shadow» zones). During the hours of the peak of solar activity, and, consequently, the maximum electricity generation of average power generation of the power station at the solar panels placement with an angle of 45º on the wall of the building will be 0,704 from maximum possible, i.e. 2,86 kW. Based on the total cost of the panels and possible added costs for their installation (about 20% of the cost), the amount of required investment will be UAH 55 400.

A comparison of calculation data shows that under certain climatic conditions, the location of the building, its architectural features, the option of a stationary position of solar panels on the wall at an angle to the wall according to the scheme of Fig. 57b is more attractive.

A comparison of operating results of power station with stationary panel mounting on a certain roof area in one plane (provided the tilt angle of the panels is 25º) and using a tracker installation, which monitors the tilt angle of the panels in accordance with the change in the angle of the Sun relative to the horizon, which shows that an increase in electricity generation does not compensate the loss of generation opportunities due to a reduction in the installed capacity of the power station located on the roof of the building.

When designing and carrying out assembly operations on the solar panels installation on the roofs of buildings, the main attention should be paid to the plane location of their installation relative to the horizon (mainly to the south) and compliance with the optimal angle of the solar panel relative to the horizon. Under these conditions, the amount of annual electricity generation will mainly depend on the area of solar panels located on the roof. The use of trackers, in this case, is not always justified, even from a technical point of view.

Placing solar panels on the wall of the building according to the option of their location at an angle of about 45º gives an increase in electric power generation during the peak of solar activity by almost 30% compared to the option of placing panels vertically in one plane on the wall even if the area use factor is increased almost to one.

Technical and economic calculations show that under certain climatic conditions of the northern part of Ukraine, the location of the building, its architectural features, the option of stationary location of solar panels on the roof without single-turn trackers is more attractive.

The comparison of calculation data shows that under certain climatic conditions, building conditions, its architectural features, the option of stationary location of solar panels on the wall with the tilt angle of the panels to the wall, according to the scheme of Fig. 57b, is more attractive.

CONCLUSION

In the course of the analytical review, the main provisions of the theory of modeling efficiency management systems and forecasting the use of electric energy by consumers were determined, which are based on assessing the regularity of the dynamics of time series of internal (technical and economic, structural, regime) and external (meteorological, environmental, energy, macroeconomic) factors, characterizing the system "generation - climatic conditions - energy consumption".

The principles of EES control in real time, as well as all levels of the automated control system, have been investigated. A control system for collecting data from lower-level devices and a SCADA system have been investigated.

The deterministic and stochastic components of time series are investigated. The stationary nature of the time series of the factors of its functioning has been established - the distributions of the stationary time series do not change with the time shift.

Two areas of research have been identified: forecasting electricity demand based on panel data by months (in the context of countries; regions of the same country; industries) and modeling the consumption of electrical energy by individual objects that have the appropriate equipment for measuring the consumption of high-frequency fixing electricity. It has been established that improving the quality of forecasts is an important stage in the combination of various modeling approaches (autoregressive, structural modeling, neural network forecasting, artificial intelligence methods), as well as the use of hybrid models. Based on the selected theoretical models, it is planned to develop scientific and methodological support for creating a multi-level control system for the processes of effective electricity consumption. Evaluation of the dynamics of demand for electricity and possible cause-and-effect relationships for different objects and levels, extrapolation and scenario analysis of the results obtained will allow to develop the main mechanisms of energy efficiency policy and the principles of their practical implementation.

A mathematical model has been developed for complex electric power systems. Controllability algorithms are developed using the multi-step Adamas-Bashford method. The analysis and assessment of significant factors influencing the forecast dynamics of electricity consumption volumes and the construction of multifactor regression and cointegration models are carried out.

In the course of the work, an intelligent information system for the EPS was designed and developed,

- UML diagrams and the structure of the database of an intelligent information system were created, requirements for the information support of the EES were formed, information models were created and IMS concepts were determined based on mathematical models,
- IoT technology was designed in electric power systems based on a mathematical model for an intelligent information system,
- a software complex for a multi-agent network and multi-layer machine learning IIS has been developed,
- designed and developed remote automated control, as well as monitoring IMS based on information technology,
- the dynamics, distribution, linear stochastic dependences and causal relationships of indicators of energy sectors in 46 countries of Europe and Central Asia were analyzed.
- the main provisions of the theory of modeling efficiency management systems and forecasting the use of electrical energy by consumers have been determined, which are based on assessing the regularity of the dynamics of time series of internal (technical and economic, structural, regime) and external (meteorological, environmental, energy, macroeconomic) factors characterizing the system " generation - climatic conditions - energy consumption ”.

The book studies the dynamics, distribution, linear stochastic dependencies and causal relationships of indicators of energy sectors in 46 countries of Europe and Central Asia. In the course of the study, the main provisions of the theory of modeling efficiency management systems and forecasting the use of electrical energy by consumers were determined, which are based on assessing the regularity of the dynamics of time series of internal (technical and economic, structural, regime) and external (meteorological, environmental, energy, macroeconomic) factors characterizing the system "generation - climatic conditions - energy consumption".

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