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Methodological Foundations for Modeling the Processes of Combining Organic Fuel Generation Systems and Photovoltaic Cells into a Single Energy Technology Complex

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Abstract: The needs to reduce the imperfection of theoretical and methodological approaches to value and regulate the processes of applying the methods of transactional energy are substantiated. The concept of combining organizational, economic and mathematical models to improve technical, technological and information methods for the effective integration of renewable and traditional energy facilities has been formulated. This determined the goal of forming a digital platform for machine-to-machine automatic processing of transactions. The creation of the platform contributes to solving a number of research tasks including development of schemes for the use of photo and thermoelements for energy generation in distributed energy and control of electrical and thermodynamic parameters of equipment in sensors of its diagnostics and use in electric drives of actuators of the Industrial Internet of Things. The use of big data and data science tools is aimed at achieving a number of practical results. Firstly, the differentiation of the composition of capacities and sources in the complex of hybrid energy facilities has been expanded, secondly, possibilities of modeling has been increased. Furthermore, the results of investigation are the model of integration and balancing regulation in the transactional energy platform of the Center for the Coordination of Interest in Complex Objects.

Keywords: energy transactions; internet of energy; photovoltaic cells; thermoelements in the energy technology complex (ETC); big data and data science tools; approximation of step functions of the jump processes

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1. Introduction

1.1. Relevance of the Topic and Purpose of the Work

The relevance of improving the assessment and regulation of the efficiency of the processes of combining generation of hybrid organic fuel and photovoltaic cell systems increases in the conditions of combining renewable and traditional distributed energy sources. The hybrid composition of its facilities complicates the cycle of processes for measuring and auditing its condition and optimizing the quality parameters of energy production and consumption processes according to the criteria of energy, environmental and economic efficiency (3-E efficiency).

Currently, there are several industrial and energy facilities in particular that do not have a full connection with each other. Such objects should include, first of all, micro-networks. These are connections between distributed energy facilities and consumers. Small-scale power sources operate dispersed with centralized power systems. In addition, small-scale energy facilities can be installed at industrial enterprises as autonomous energy sources. In this case, there are also difficulties in transferring excess electricity to the centralized power system [1,2]. It should also be noted that enterprises located in continental and subarctic climates require heat to cover the needs for heating, ventilation and hot water supply. It is very difficult to combine small-scale energy facilities, enterprises, and private consumers of heat and electricity within the framework of standard technological schemes [3,4]. In this case, the goal of the study is to develop new methodological approaches to creating a single energy technology complex with a dispatching and control system based on neural network technologies and the Internet of Things.

1.2. Literature Review

To identify the degree of scientific and practical development of the research problem, the following actions are necessary [5,6]. Firstly, the identification of the subject and objects of study in accordance with the keywords is needed; secondly, the definition of the database and its limitations is identified. Furthermore, the establishment of criteria for evaluating sources is shown and quantitative assessment of the qualitative characteristics are presented. In this section, we will present an analysis of the key works on the research topic.

Szalavetz points out the need for digitalization, automation and upgrading among global value chain-factory economy actors [7]. This can reduce the risks of using renewable energy in individual countries, according to Li et al. [8]. The special significance of solar photovoltaic power generation is proved by Hosenuzzaman et al. [9]. Design solutions in this direction are offered by Alsayah et al. [10]. One of the key concepts of solar energy development was proposed by Sampaio and González [11].

The radical nature of the necessary changes in these directions corresponds to the conditions of the singularity of development. Many forecasts confirm the well-known methodological proposals of Lalu and Meyer, that favor creating biosimilar management structures of "live" organizations [12,13]. They note that holacratic flexible (agile) methods of creating self-governing teams of different profiles are effective of the spiral dynamics model of the so-called "turquoise enterprises". However, Mitreva et al. have proved that the inclusion of even such competent personnel in the control and regulation system does not completely solve the problems of managing complex systems [14]. This is especially true in relation to the quality of control of thermodynamic parameters of power and technological installations. The inclusion of the human factor in the control system leads to a low speed and reliability of regulation, according to Pisar and Bilkova, since it does not correspond to the context of Industry 4.0 [15]. Despite their practicality, they are more applicable in the design and engineering field. This narrows the applicability of such methods in the formation of ETC (Energy Technology Complex). More concrete forecasts for the development of intellectual resources can be found in forecasts by Oseledets [16] and Ji [17]. They describe an increase in the number of digital and network companies such as "Amazon". They expect growth by 2035 of the capabilities of computer systems and artificial intelligence in assessing their computing power. They will exceed the total analogous potential of the human biological system. Peskov claims that growth of high-tech and high-tech engineering services in the innovation ecosystem in the modern conditions of the Russian Federation, universities of types 2.0 and 3.0 prevent them from being drivers/challenges for the development of industry, mainly of industrial type [18]. At the same time, the scale of their transformation into educational and scientific 4.0 complexes is growing with universities that are distinguished by a high degree of globalization of education and the use of new educational methods using big data methods. Currently, a number of researchers have recognized the need for the use of training digital simulators (doubles) in virtual or real cognitive methods to apply the data science approach for solving practical problems of the post-industrial economy and energy [19,20]. In such a digital economy, it is necessary to use open educational platforms based on large databases [21]. Especially they are necessary for analyzing the possibilities of advanced combination of resources based on the organization of ETC with the inclusion of objects of distributed energy, other multipurpose productions and participation in projects of such transformation of research and educational complexes of type 4.0 [22,23]. The considered methods solve a complex of problems of the organization of processes of high-tech development with use of integration of the diversified resources. However, assessing their overall compliance with the concept of combining methods to ensure 3-E efficiency, we can note their insufficient focus on solving these research tasks.

In the period 2014–20, there was a significant increase in the number of publications on the relationship between new business models and sustainability of development in the areas of combining methods and resources of a diversified composition in the conditions of technology singularity [24,25]. The combination of organizational and technical methods in the complexes of objects is considered as a necessary condition for ensuring the sustainability of long-term development. Thus, Brixner et al. called this condition the "new tecno-organizational paradigm" [26]. This experience extends to innovative business models in sociology and research opportunities [27,28]. Researchers such as Cainelli et al. [29], Khalfallah and Lakh [30] and Chen et al. [31] justify the role of knowledge in the diversification of organizational impacts to reduce costs in industry to ensure competitive advantages. Brito et al. [32] and Bagis, et al. [33] prove the increasing importance of new competencies when implementing them in the management quality improvement system.

The need to use the Internet of Management Artifacts, for example, Internet Of Things and the new Architecture for Business Models is justified by Rocha et al. [34]. Asif [35] and Hipp and Binz [36] write about the possibility of including new tools in the structure of management quality methods. The significance of our proposals for tools of big data and data science and their inclusion in the cyclic model of integration of scientific and educational resources and production is confirmed by the research of Xiao et al. [37], Casalet and Stezano [38], Clegg [39] and Wang et al. [40].

The creation of a platform for planning the processes of joint functioning of objects of the hybrid economy is determined by the need to increase its 3rd efficiency. This follows from the works of Zeng et al. [41]. The transition to these planning tools involves the modeling of abrupt and evolutionary cyclic transition processes [42]. It is also necessary to coordinate the joint work of different energy sources. According to Liu et al., [42,43] special conditions are required for the regulation of traditional and renewable energy sources. Such possibilities were investigated by Wang et al., [44] and Yang et al. [45]. Wang and Zhang [46] and Yang et al., have proved the potential for increasing efficiency in creating conditions for complementary combination of hybrid system resources [47].

The ongoing research in the field of application of energy technology complexes and neural network technologies in the energy sector is focused on regulation [48]. The paper proposes to take into account the world experience based on the obtained experimental data, to combine the calculation methods and to introduce adaptive weight coefficients for them. The authors studied the combustion of organic fuels and have experience that allows us to evaluate the reliability of the results of neural network forecasting in this area [49]. New approximation methods were also used by the authors [50]. For a similar combustion problem, the authors have a theoretical basis for research [51]. Combustion process research is conducted by scientists from many countries. The most complete understanding of the preparation of coal dust in thermal power plants can be found in [52]. One of the main conditions for efficient and high-quality fuel combustion is to take into account its composition, which is confirmed by the mathematical models of the authors [53]. In addition, the presence of sufficient air as an oxidizer affects the quality of combustion, which the researchers have noted [54].

In [52], the topic of approximation of the obtained results was raised for the first time, which was later reflected in the already mentioned work. It should be noted that the existing programs give an idea of the distribution of the fields of temperatures, velocities and concentrations, which are connected by known dependencies, but the accuracy and reliability of the results obtained do not always meet the criteria necessary to start designing an energy technology complex.

The research of such authors such as Rosendahl supports the theory of weak methodological security of heat transfer processes in high-temperature installations and energy technology complexes, and this researcher together with Mandø published an article with his own mathematical model [55]. In [56], Asotani and his co-authors also consider the model of combustion fuel mixture with air, and the proposed mathematical model corresponds well to [55], as well as to some of the authors' proposals [57]. The mathematical models proposed in the review do not contradict each other, as well as the fundamental laws of physics, and heat transfer in particular.

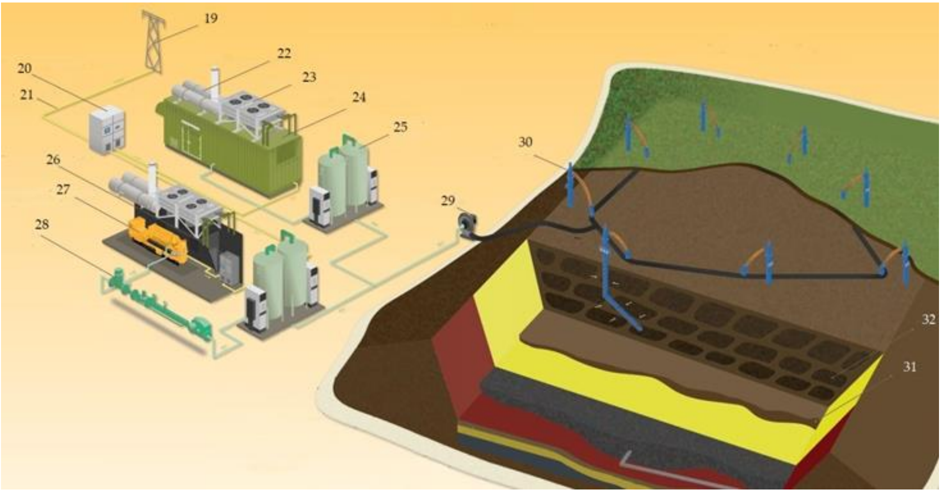
1.3. Proposed Scheme

In this section, the authors present the developed technological scheme, for which a new methodological framework will be applied in the future. The combination of technological systems based on organic fuel and renewable energy sources is not uncommon, however, their combination in a single energy complex with a control and management system based on neural networks and micro-electric networks is used for the first time. In addition, the methodological base includes methods for approximating piecewise linear functions, which allow us to evaluate the effectiveness of technical solutions and optimize the process of choosing the most appropriate solution.

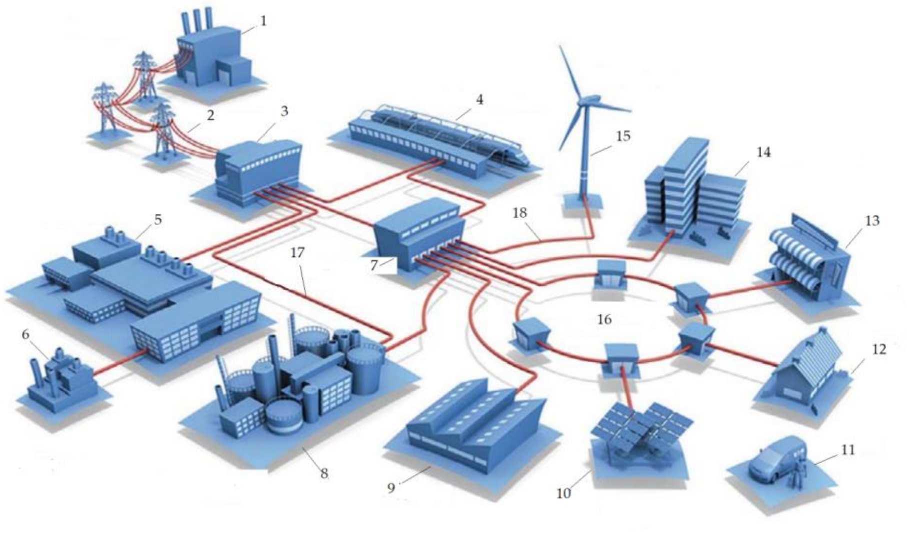
The mutual transfer of heat and other complementary material products based on the conclusion of contracts for energy and other transactions is assumed by the following types of main objects of the macro-network of the formed energy technology complex (ETC) in Figure 1: I—a medium or large industrial enterprise-a consumer of two types of energy; II—a landfill of solid household and industrial waste (SHIW) as a source of biogas for micro-grid facilities; III—a micro-network that includes small industrial, agricultural and other small enterprises, households and residential buildings with the ability to produce heat and electricity using renewable resources of heat pumps, biogas microturbines, solar and wind; IV—a power plant that produces heat and electricity, a district or local boiler house (separate or as part of another object of the economy) using traditional resources; V—an object considered as a storage of heat and electric energy (for example, it can be large-capacity helium batteries and biogas resources of the SHIW landfill; VI—a scientific and educational center for research, development and sales of innovative projects to improve the 3-E efficiency of these objects for the introduction of innovations in heat power and heat engineering.

The proposed composition of the main objects includes a smaller number of complementary objects of the microgrid II–V. The goal is to organize the economic, machine and physical interaction of producers and consumers of electric and thermal energy with the execution of contracts. To do this, it is necessary to form the structure of the micro-network and transform some of its objects for the possibility of implementing energy transactions on the Internet of Energy and Things. The main objects of type III in the micro grid are the following: 6-elements of distributed generation, including small power generation and 7-distribution substations; 10-objects using renewable solar energy resources; 11-service services for diagnostics and routine repairs of equipment; 12-households and residential buildings with power generation capabilities; 13-micro grid control center with new economic transaction capabilities; 14-commercial buildings with local boilers; 15-wind power facilities. To implement physical interaction, the following are required: 16-transformer substations that reduce the voltage for physical interaction of objects; 17-low-voltage power consumption and excess energy transmission lines; 18-high-voltage transmission lines of generated electricity by small-scale power facilities; 19-high-voltage transmission lines of electricity generated by microturbines of local objects of the hybrid network of the SHIW landfill of object II.

In crisis situations, for example, when renewable energy resources are insufficient, reserve capacities and technical means of traditional energy are needed: 1-a station that centrally produces the predominant share of electric and thermal energy using traditional (non-renewable resources) as part of micro—grid objects of type IV; 2-high-voltage power transmission lines and 3-main substations for converting electricity parameters to implement physical interaction in the micro-grid. Additional sources of energy of lower quality and reliability can be considered objects of types II and V: microturbines of the local boiler house at the SHIW landfill; thermal energy storage in the form of systems of the following environmental protection elements: 22-release of combustion products into the environment and filters for their purification, 23-cooling of liquid and solid waste in energy generation processes, 24-solid waste containers, 25-preparation of biogas for useful use, 26-management of waste sorting in containers, 27-biogas generator sets, 28-biogas supply networks, 29-pumps, 30-wells for collecting biogas, 31-insulating layers of SHIW storage, 32-storage cells for unused waste.



(a)



(b)

Figure 1. Diagram of the macro network of separately functioning main objects of a single energy technology complex; (**a**) composition of the main objects; (**b**) Center for Coordinating the Interests of Hybrid Network Objects (CCI).

These capacities make it possible to ensure the reliability of energy supply to the main consumers of objects of type I of the macro grid of the ETC: 5-industries of the metallurgy type, 8-engineering type, and 9-other industrial objects. To regulate the economic, machine-to-machine and physical relationships and interconnections in the micro-network of complementary objects and the macro-network of a single ETC, it is necessary to create a coordinating structure of the Center for Coordinating the Interests of Hybrid Network Objects (CCI). The Center should make decisions on the organization and regulation of economic relations and physical relationships using objects 20 (control system for parallel operation of lines) and 21 (control signal transmission lines for machine-readable interaction with the exchange of signals).

Methodological support of type VI in infrastructure object 4 is developed by structures such as research and educational centers for the development and sale of innovative products. It is necessary for the organization of a unified and high-tech approach to solving the problems of increasing 3-E efficiency while reducing the imbalance of interests of traditional and renewable energy facilities in the ETC.

The scheme is characterized by a number of weaknesses: excessive imbalance of interests of micro-and macro-network objects due to the lack or insufficient regularity of network relationships between producers and consumers; low flexibility and efficiency of regulation of mutual transfers of capacity or energy. This leads to unjustified investments in new energy facilities with a low level of use of the installed capacity of existing ones. Independent solution of problems of low efficiency of processes by individual objects is carried out mainly by methods of modernization of a limited number of types of their heat engineering due to a lack of investment resources.

Taking into account the heat and energy orientation of the study, we have identified the maximum indicators of energy and environmental efficiency of separate functioning of objects of type III-V (Table 1).

Table 1. Maximum average indicators of energy and environmental efficiency of separate functioning of macro grid objects of type III–V, % [1–6].

Energy Efficiency Indicators	Centralized Generation of Electricity and Heat from Natural Gas	Gas-fired Biogas Plant	Installations Using Renewable Solar and Wind Resources	Photovoltaic and Thermoelectric Panels for Energy Generation
Thermal efficiency	55.00	40.00	-	-
Wind energy usage ratio	-	-	35.00	-
Conversion rate of solar panels	-	-	-	18–28

The standard composition of monitoring and control sensors does not register or change the imbalance of energy and environmental efficiency goals of facilities. The existing variety of them (Table 2) does not allow us to evaluate the 3-E efficiency and regulate the processes of objects. It is necessary to include microgrid objects in the Internet of Energy and Things system to organize transactions taking into account the mutual transfer of capacity by consumers and producers.

Table 2. Composition of some control and measuring devices for assessing the energy and environmental efficiency of separately functioning macro grid objects of type I–V.

Names of Control Devices	Thermal Power Plant	Gas-Fired Biogas Plant	Installations Using Renewable Solar and Wind Resources	Photovoltaic and Thermo Electric Panels for Energy Generation
Thermocouples	+	+		
Valves	+	+		
The inverter			+	+

In addition, these devices are not included in the unified process control system based on the results of monitoring the electrical and thermodynamic parameters of equipment of all manufacturers and consumers of I–V facilities. Common in practice sensors for diagnosing the state of heat and power plants and heat engineering do not use the capabilities of the Industrial Internet of Things (IoT) and Energy. Autonomous regulation of renewable and traditional energy sources does not provide high-tech processes of machine-to-machine and physical interaction of objects. This leads to an increase in the problems of insufficient 3-E efficiency of thermal power plants operating in a network with solar and wind energy sources. In a number of regions of the world with a similar composition of facilities, therefore, environmental protection opportunities are reduced with insufficient use of the installed capacity of power plants. The inflexibility of regulating the interaction of such hybrid energy facilities also reduces the economic efficiency of investments in projects to reduce the energy intensity of the Russian economy. It is several times higher than in countries with a developed knowledge economy [6].

To increase the reliability of assessments of the interaction of objects I–V of the hybrid ETC system being formed, a new set of advanced digital processes of control and supervision technical tools is required. The quality parameters of regulating the consistency of interaction between the differentiated composition of macro-network objects should be increased in cyclic processes.

Modern energy-saving methods of industrial energy development should be largely determined by the factors of the new industrial revolution. The main factor in accordance with the topic of the article is the need to take into account the effects of the Industrial Internet of Things and Energy in physical systems with cybernetic properties. The corresponding direction of high-tech development determines the choice of the organizational and economic paradigm of the analog-digital representation of methods for integrating objects and combining research methods. The methods are applicable to information technologies of distributed (cloud) resources to achieve a competitive level of innovation. Forecasts of the developed countries of the European Union show the growing advantage of renewable energy: by 2050, it is expected to provide up to a third of electricity needs with solar energy resources, and up to 65% with wind energy resources [6]. The joint use of diversified resources of hybrid energy facilities is a prerequisite for ensuring the effective sustainability of the development of energy systems. This determined the purpose of the study of the possibilities of using advanced digital processes of control and supervision in the transactional energy platform and the network of a single ETC of hybrid objects. It is necessary to solve the problems of regulating the processes of increasing the 3rd efficiency at the stages of the cycle, which differ in evolutionary and abrupt types of changes in the quality of the control parameters. This makes it necessary to use a large database (big data methods) for the organization of advanced digital processes of control and supervision.

The analysis of the existing results of the study of automatic control systems and telemetry allows us to draw conclusions about the insufficient degree of their perfection. The systems are characterized by relatively low reliability due to the lack of backup channels for converting control actions and automatic diagnostics. The possibilities of the systems' influence on the quality parameters of the organizational-economic, machine-to-machine and physical interaction of energy producers and consumers and related complementary products of hybrid energy facilities are insufficient. This does not allow us to radically reduce the cost of primary fuel and environmental pollution in the emerging energy technology complex.

2. Materials and Methods

2.1. Methodologies of Modeling Processes Combining Generation of Hybrid Systems on Organic Fuel and Photovoltaic Cells in a Single Energy Technology Complex Assessment and Regulation

Achieving the goal of improving the quality of regulatory parameters in the study is proposed to be implemented in the concept of combining organizational, economic and mathematical models for the application of a system of information and technical and technological methods according to the criterion of maximizing 3-E efficiency. This defines the emergence of a new organization architecture using the information technology capabilities of the IoT and Energy and. Advanced digital processes of control and supervision are needed to implement the interaction of micro-and macro-network objects using transactional energy methods in a single hybrid-type ETC. The new architecture and structure involves a radical expansion of the range of autonomous sensors with a long service life, sensors-meters of various process parameters and other elements of cybernetic purpose. All these devices must be connected by a telemetry data network, partially shown in Figure 1. The high importance of such technical means of the digital economy is confirmed by a positive assessment of the results of the study of the prospects for the complementary use of resources and energy distribution in the conditions of the modern industrial revolution [21]. The effectiveness of their use has been proven to reduce repair costs, increase uptime, and reduce the need for personnel to synchronize processes with dispatchers. The article solves the problems identified by the lack of compliance of technologies and methods for the development of distributed hybrid energy with the factors of the industrial revolution. The insufficient degree of integration of objects I–V of industrial energy with the resources of scientific and educational objects of type VI for the organization of high-tech development of the macro-network of ETC in the knowledge economy is revealed. At many domestic enterprises of industrial heat and power engineering, evolutionary methods of modernization of individual elements of equipment with a low level of innovation of technologies and results prevail. Investment decisions on new construction and technical re-equipment projects are often made without modeling the processes of transition to technologies and organizational methods of energy saving based on the factors of the new industrial revolution [22].

Technical and technological models should describe the dynamics of the physical interaction of objects of the hybrid network of the complex being formed. Taking into account the scientific and practical results of the research, the article examines in detail the possibilities of improving the 3rd efficiency of hybrid energy micro-grid facilities [1–5]. The predominantly heat-energy nature of the study determines the geographical limitations on the scale of the complex being formed: objects II-V can be placed at distances of no more than 25 km (the maximum possibility of network physical interaction according to the permissible 3rd efficiency of heat transfer). The micronet is formed as part of the ETC and implements the subject of scientific research in the design development of an innovative idea for the formation of a local market for energy sales and other results of the complex's activities that are of value to their producers and consumers. Advanced digital processes of control and supervision of heat and electric energy production and consumption are studied in detail on the example of a microgrid. Such processes are effectively implemented and recorded in the form of energy transactions in the Internet of Things and Energy system using the information and analytical tools of big data and data science. The material complementary products obtained from the accumulated resources of SHIW, as well as the results of scientific and design developments, can also be evaluated in the model of the cost-effectiveness of processes using standard methods for estimating their cost.

The object of the study is the formation of a macro-network and a micro-network as part of the ETC, which provides such processes of control and supervision of the production and consumption of heat and electric energy with the organization of economic, machine-to-machine and physical interaction of objects of type I–V (Figure 1). The creation of information and physical capabilities for their joint functioning requires improving the quality of control parameters and dispatching high-tech processes of integration of hybrid energy facilities. The implementation of the research concept is aimed at ensuring the 3rd efficiency of the dynamics of processes in terms of reducing anthropogenic loads on the environment. For this purpose, a combination of resources and technologies is proposed based on the integration of individual industrial and household energy installations into the ETC (Figure 2).

As an object of research, a micro-grid is defined as part of a single ETC and the following composition of hybrid distributed energy facilities: II-a landfill of accumulated SHIW, as a source of secondary combustible resources (biogas and other material waste for further processing) and additional fuel for a local boiler micro-network; III-heat-power installations of the type of heat pumps that use the property of the thermodynamic cycle of converting heat into work using water vapor. Such an organization of energy production is proposed for agricultural facilities (for example, greenhouses, livestock farms, grain dryers, root crops and fruits, small enterprises of other industries, trade, etc.), households and residential buildings with the ability to generate energy and transfer its surplus to the network. They require the production of heat in the form of hot water, as well as electricity using microturbines that use the accumulated biogas resources of the SHIW landfill. At the same time, it is proposed to exchange energy transactions with the conclusion of energy transactions on the Internet of Energy and Things. This requires thermal and electrical networks for physical connections to objects of type 4 and 5 (district and local boiler houses and energy storage). At the same time, the processes of control and supervision of energy transactions should be carried out using the big data and data science tools.

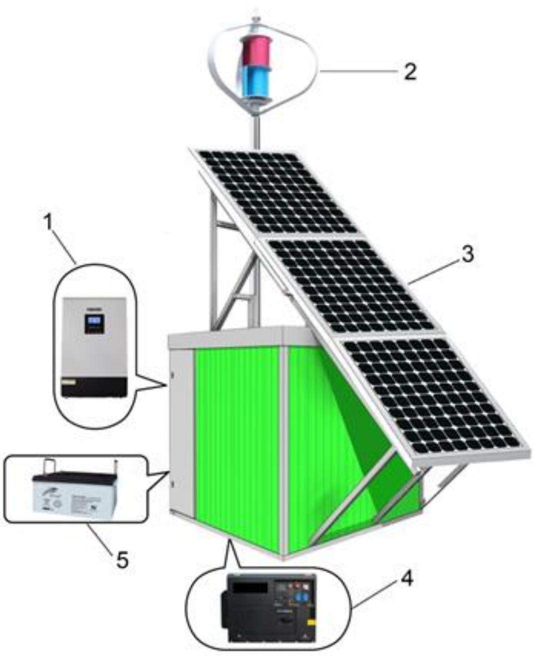
Hybrid systems may include, for example, organic fuel and photovoltaic cells combining heat and electrical generation. The use of alternative solar energy increases the energy independence of consumers. The autonomy allows you to sell the excess electricity produced in the micro-grid of the object III of the macro-grid of the ETC. Such a micro-network combines the functions of an autonomous and network, providing a backup power supply.

With sufficient insolation, the solar panels 3 generate electrical energy and feed it to a hybrid inverter that converts it for the needs of consumers. Unused electricity from the inverter goes to the batteries (object V in Figure 1), and when they are fully charged, to the network for sale if there is a contract with the network company. The criterion for making such a decision is the excess of the tariff for the sale of electricity of the tariff for the purchase from the network. When the situation is reversed, it is better to save energy in the batteries to use it in the evening. In the case when the energy storage is already fully charged, and the generation capacity exceeds the current consumption, it is advisable to sell at any price. It is possible to underutilize the capacity of traditional energy and reduce the 3rd efficiency in the long term due to unjustified investments. If there is insufficient insolation, the solar cells do not work at full capacity. The missing energy will be supplied from the helium accumulators of the Type V facility, local installations using the biogas resources of the SHIW landfill, or centralized macro grid facilities. When setting up the automation of the multifunctional inverter 1, you can make priority decisions on the choice of a backup power source according to the criteria of maximum autonomy of the micro-network. This meets the criteria of its energy and economic efficiency with sufficient insolation during the year. Figure 2 shows the options for the joint operation of traditional centralized and distributed hybrid energy facilities. They involve combining different sources of generation hybrid systems on organic fuel, wind energy and photovoltaic cells in a single ETC.

Micro-networks embedded in a hybrid power system should be evaluated according to the criteria of the regulatory quality of energy and the reliability of the functioning of existing distribution and high-voltage networks. Energy flows (generated electric and thermal energy, heat of the heated heat carrier with the use of renewable resources) have losses. The proposed methodology is aimed at reducing them in the processes of generation and transportation to consumers.

Figure 2 shows a diagram of interacting objects in a hybrid microgrid. It allows you to combine the possibilities of generating energy with the use of renewable resources in solar panels and diesel generators. In addition, the exchange of such types of energy with the traditional energy facilities indicated in Figure 1 is taken into account. The organization of joint work is possible with the impact on the control system in the CCI according to the criteria for improving the reliability and 3rd efficiency of the distribution of energy flows.

Figure 3 shows a variant of the composition of microgrid objects that we selected to study the reliability of solar panels and determine the effective operating modes of a diesel generator. Such systems have recently been regulated by predictive regulation based on neural network algorithms. The parameters of hybrid installations are monitored using the organic part of the micro-grid, which includes diesel generators or local means of generating electric and thermal energy. Renewable resources, for example, installations that use solar and wind energy, are controlled minimally and operate mainly in automatic mode.



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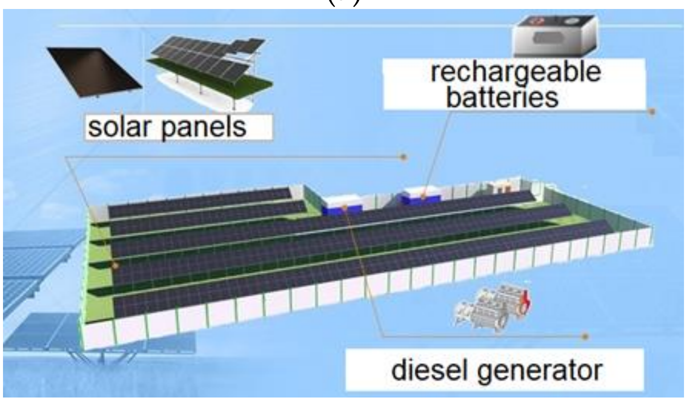

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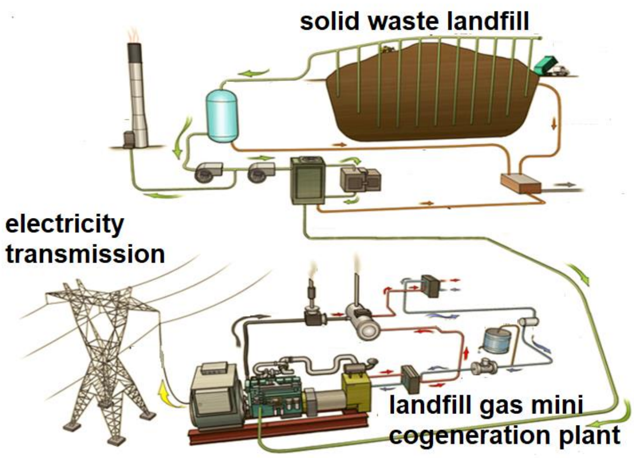

(c)

Figure 2. Diagram of jointly functioning objects.of the hybrid distributed power grid: (**a**)—joint operation of installations 2,3,4: 1-multifunctional inverter; 2,3-installations using wind and solar resources; 4-diesel generator; 5-helium batteries. (**b**)—joint operation of solar panels and diesel generators, (**c**)—generation of heat and electricity using biogas resources from the SHIW landfill.

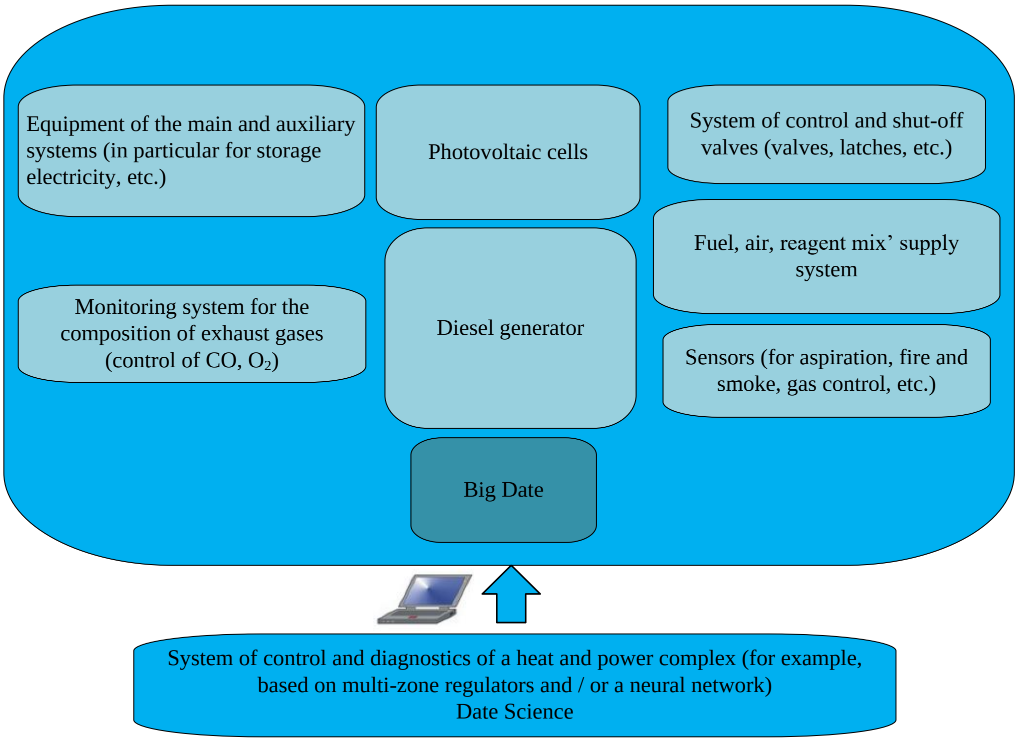

Figure 3. Composition of objects and elements of the micro-network of objects in the energy technology complex.

Standard control and measuring devices and automation are not able to increase the efficiency of the plant in the long term. It is necessary to use neural network algorithms that allow you to collect big data data, process it and make predictive control in the processes of mainly machine-to-machine interaction of micronet objects. This requires special mechanisms for combining management methods to coordinate the interests of traditional and renewable energy facilities.

The standard composition of monitoring sensors does not register an imbalance of energy and environmental efficiency goals, macro-and micro-grid objects. The technical implementation of advanced monitoring and dispatching processes requires the use of photo-and thermo-elements in the sensors and actuators of the IoT system to include micro-grid objects in the Energy Internet system. It is necessary to supplement them (Table 3) to assess the 3-E efficiency and regulate the processes of objects operating in the microgrid, taking into account the mutual transfer of capacity and energy transactions in the Internet of Energy system. The use of sensors for temperature, pressure, and concentration of combustion products is justified. This is required to assess the quality of energy transmission and the completeness of energy use. The controllers should be used in conjunction with multi-zone controllers. Software systems based on neural network algorithms should be able to process a large array of data and select the weight coefficients of the controlled parameters. Therefore, Kosko neural network algorithms are suitable for these purposes [1–5]. SCADA systems are designed for process control. All additional devices should be included in the control system of the dynamic simulator mechanism for combining methods of joint energy generation developed by us and presented in the article. The micro-networks in the ETC should use additional sensors of the IoT (Internet of Things) system and the Internet of Energy, built into the control and control systems of technological processes.

To organize economic relationships in the form of user transactions, they must be represented by digital assets that confirm the mutual transfer of capacities or products of producers and consumers. This is made out by signed contracts, documents of their verification and payment on the basis of inter-machine interaction of objects.

Table 3. Name of processes of production and consumption of heat and electric energy and additional types of control and measuring devices for control and supervision assessment of the 3-E efficiency of interconnections of micro-grid objects.

Additional Instruments and Control System	Power Plant	Gas-Fired Biogas Plant	Wind Power Plant	Photovoltaic Panels (Data for 2021)
Temperature, pressure, and concentration sensors	+	+		+
Controllers	+	+		+
Software systems based on neural network algorithms	+		+	+
SCADA aystems	+			+

Processes whose parameters change abruptly or exponentially are particularly difficult to account for and model. This makes it necessary to use special mathematical software, used, for example, to represent the processes of signal transmission. Such features determine the additional use of tools for deeper analysis and digital modeling of Data Science processes [7,20]. It is based on providing real-time control and regulation using deep machine learning neural network algorithms using artificial intelligence. Similar processes are applied by us for regulation of the 3-E efficiency in power installations of objects of a micro-grid of ETC. At the same time, there is often a decrease in the stability of development processes due to abrupt changes in the processes during the transition to a new structure of interrelations of objects in the complex. Improvements of the radical type are also distinguished by the singularity (unusual) of the processes of transition to new technologies, methods of analysis and regulation of processes. It can be expressed in exponential, hyperbolic, and even jump-like (for example, sawtooth waveform), changes in indicators-properties of 3-E efficiency at zero or minimum transition time to their new level.

To ensure the sustainability of the proposed processes of control and supervision, it is necessary to form a model of a dynamic simulator of a mechanism for combining management methods for coordinating the interests of traditional and renewable energy facilities (Figure 4).

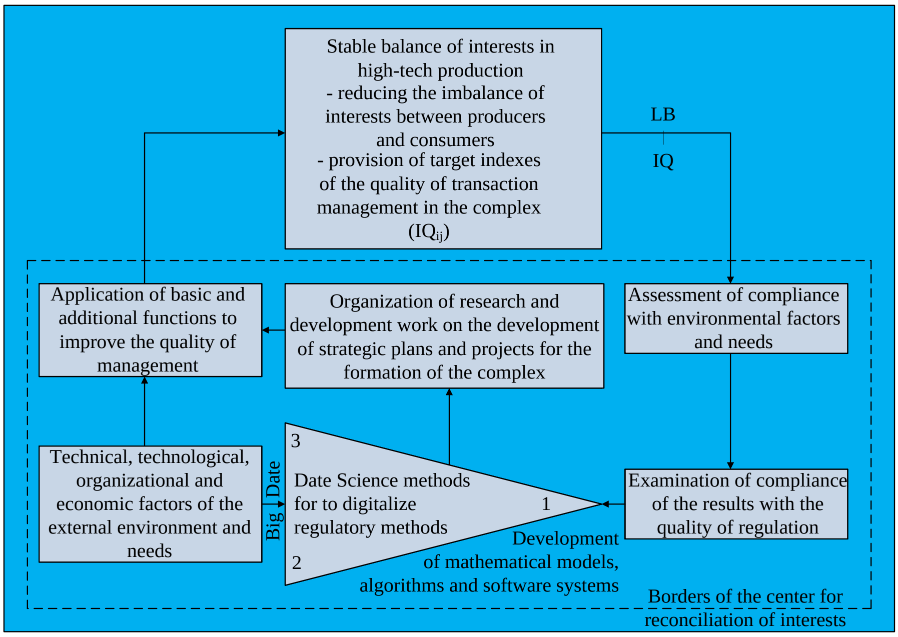

Figure 4. Control system of the dynamic simulator of the mechanism of combining methods of joint energy production.

The level of the balance of interests is ensured by the regulation of the quality indices of the regulation parameters according to the above criteria. The corresponding resulting indicators are evaluated by well-known approaches to thermodynamic modeling of the processes of increasing energy and environmental efficiency for separately functioning objects II-V of renewable and traditional energy (Table 4).

Table 4. Methods, parameters used and results of the analysis of calculations of the 3-E efficiency in the conditions of joint operation of objects 2–5 of the microgrid.

Types of Objects	Advantages	Disadvantages
Heat pumps	The ability to work on almost any type of low-potential energy	High service cost
Photovoltaic cells	Application in any climate	Complexity of maintenance
Wind-Powered installations	Variety of installation types by environmental factors	Wind speed and nature protection restrictions
Diesel generators	Easy maintenance and independent of environmental factors	High fuel consumption
Microturbines using accumulated biogas resources	High speed and fast output to the rated operating parameters	The efficiency depends on the gas composition
Local heat and power networks	Use in any area, including remote areas	Low power quality
Complex lines that combine all the previous ones	Use of all types of energy sources	Complexity of the control system

Calculations show significant increases in the 3-E efficiency in the organization of interaction of objects of type II–V in the ETC. An additional increase in the indicator is achieved in terms of integration with an object of type VI. A radical improvement in the quality of parameter control is provided by the mechanism proposed in the article. To do this, it is necessary to use the process of control and supervision of energy transactions and increase the focus of technologies and methods on the rational organization of the cycles of the formation of ETC. The possibilities of contractual transfer of facilities' capacities to each other can be realized by three types of interaction: organizational and economic (development of models and projects for combining methods and resources, execution of contracts for energy transactions and contracts for research and design development and their author support); machine-to-machine (monitoring of energy quality parameters and other commodity results of activity and data exchange); physical (creation of thermal and logistics networks for the implementation of transactions). At the same time, the imbalance of these interests often grows. The research concept can be implemented using the methods of the methodology of integration-balancing regulation of the three specified types of interactions of the objects of the formed complex. Its methods are most effectively implemented on the basis of energy transactions on the Internet of Energy using the tools of big data and data science [20]. The data science toolkit is characterized by the ability to radically improve the efficiency of decision-making in real-time machine-readable estimates for concluding the necessary energy transactions on the Internet of Energy. In practice, there are interrelated subsystems and the main stages of the methodology for developing the appropriate platform. First, an organizational and economic platform for energy transactions on the Internet of Energy is being formed with an assessment of the quality of the parameters of regulation of the 3rd efficiency in the conditions of separate operation of objects (see Figure 1). Further, special mathematical software is adapted for modeling and algorithmization of actions for solving problems of combining resources in the platform. Secondly, projects are being developed in the technical and technological areas of combining micro-and macro-network objects of a single ETC. Then the application of existing or adaptation and development of computer programs for transactional energy on the Internet of Energy based on machine learning methods for modeling and evaluating the progress of projects is justified (see Figure 4).

Artificial intelligence neural network technologies make it possible in real time for several days (not months, as previously) to implement a cycle of activities for the development and experimental implementation of projects for high-tech resource combination based on the organization of transactions in the network of ETC objects. At the same time, the advanced capabilities of multivariate and multi-criteria analysis in such a digital platform are implemented without primary filtering of the source data. The method increases the depth and durability of business intelligence based on a series of operational solutions, without filtering the data. The use of neural network algorithms of deep machine learning provides the possibility of obtaining a machine-readable signal transmission control system at the output of the developed system, while increasing the speed and reliability of evaluating and regulating the parameters of interaction between ETC objects. Third, comparative thermodynamic calculations are carried out to assess the 3-E efficiency of two options: in the scheme of the process of control and supervision of separately functioning distributed energy facilities of the hybrid type (see Figure 1 and Table 2); in the energy transaction platform for organizing the interaction of microgrid objects after the completion of the subsequent stages of the development of organizational, economic and mathematical methods.

The development of organizational and economic models and methods of coordinated interaction of macro-and micro-grid objects is aimed at creating analog models that describe the processes for the formation and development of ETC. The combination of methods and integration of resources is supposed to be carried out in the transactional energy platform as an Internet of Things and Energy system. It is a high-tech basis for the functioning of the newly created coordination structure of the CCI network of complementary ETC objects. The criterion for improving the quality of the process of control and supervision for regulation should be the maximization of the 3-E efficiency of the use of traditional and renewable resources by methods of their integration. Therefore, the purpose of the Center is to use additional functions of monitoring and dispatching the processes of regulating commodity-money relations between producers and consumers of a diversified composition of energy and material products. In order to ensure the consistency of the interests of these objects in these three types of interaction, in addition to energy flows, logistics flows should also be taken into account. In this case, it is the sale of the results of research and design work and their author's support for the operational implementation of business ideas in the areas of work of object V in projects to improve the 3-E efficiency of hybrid energy. At the same time, for the registration of energy transactions, the following should be determined and taken into account: sales and consumption of electric and thermal energy (taking into account the use of storage devices) of different quality parameters; complementary products formed when using diversified resources of renewable and traditional energy; provision of transactional services to energy producers and consumers (including households). Thus, two types of markets are formed and regulated, which are geographically limited by the physical possibilities of capacity transfer and other results of the ETC activity: a macro-network (see Figure 1) with an unlimited scalable market (electricity and research and development); a micro-network (see Figure 2) with local markets (mainly thermal energy, by-products, or secondary products, small amounts of electricity). Micro-networks are formed to increase the 3-E efficiency of interaction of hybrid distributed energy facilities located at distances of no more than 25 km.

To achieve a compromise of goals within the boundaries of the platform, an analog model of a macro network of objects consisting of two pyramid-shaped functional blocks has been developed (Figure 5). The arrows in the model show the rational direction of the processes of forming the platform and network in the cycle of changes with evolutionary changes from a low level of quality of the parameters of control and dispatching processes in the technologies of separate functioning of objects (quadrant 1) to its increase in the integration of individual objects (quadrant 2 in cycle 1). Next, in quadrant 3, there is a leap-step transition to a high level of 3-E efficiency of combining organizational methods and technologies. The stabilization of the achieved level of quality of parameters for regulating the interaction of traditional and renewable energy facilities in the new platform structure is achieved in quadrant 4 or in the next cycle.

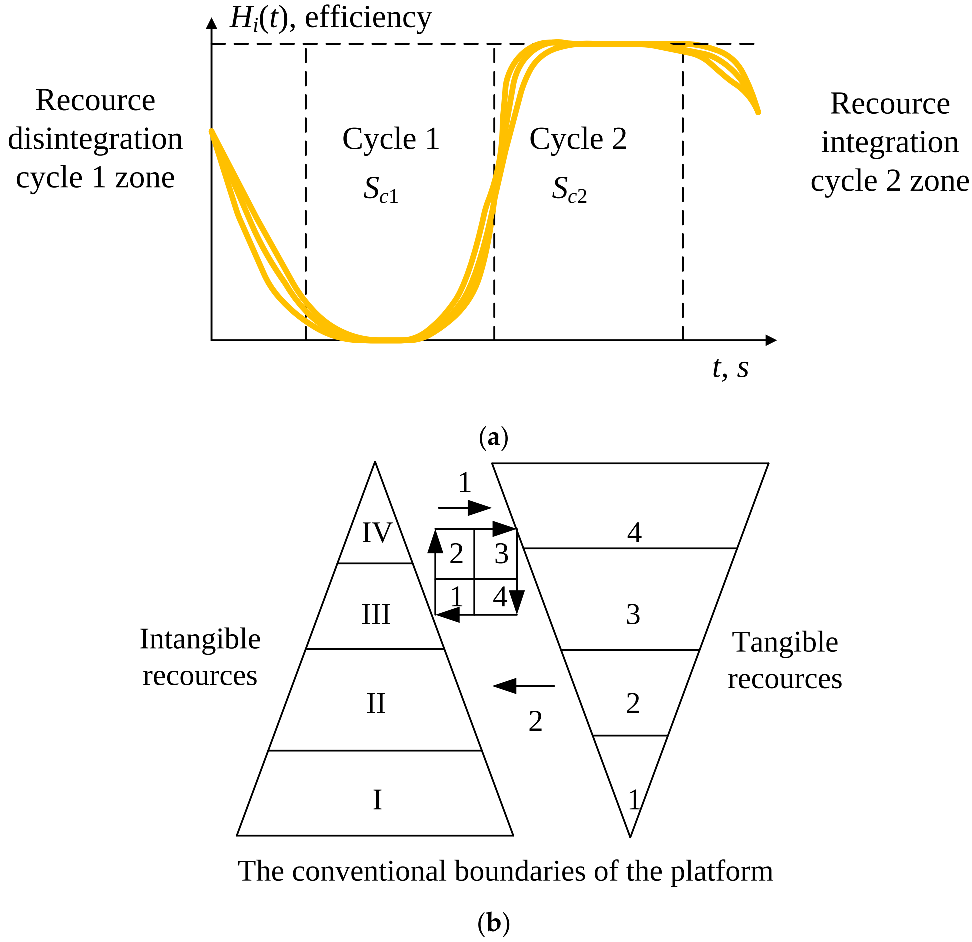

Figure 5. The model of integration-balancing regulation in the transactional energy platform (modified by [21]), $H_i(t)$ is 3-E efficiency (dimensionless unit), t is the cycle time (seconds); (**a**) zones of cycles; (**b**) the conventional boundaries of the platform.

The structure of the platform shows the interaction of blocks. The left pyramid represents the sequence and direction of the application of additional functions of control, evaluation, analysis, coordination of interaction with objects of type 6 (see Figure 1). This is necessary for making decisions on changing the quality parameters of regulating the processes of improving technologies and methods. The goals of increasing the 3-E efficiency by the methods of the post-industrial knowledge economy are taken into account. The transfer of technologies and methods is the result of sales and author support of scientific and design developments. This increases the speed and efficiency of implementing business ideas in the areas under study in distributed hybrid energy projects. The right pyramid corresponds to the impact of material resources when selling technologies of four levels of novelty and 3-E efficiency.

To assess and regulate the processes of the impact of resource types, the analog model is combined with a quantitative display of curves on the graph of changes in the 3-E efficiency (H) over the cycle time (t). The three types of curves are further justified by mathematical proofs. They reliably represent the processes in cycle 1–4. The left pyramid defines the direction and sequence of" I–IV " technologies and methods of using intangible resources of separately existing objects of education (level I), basic research (II), applied science (III), design development of equipment and business models of organizational methods of combining and their author service (support of implementation processes) (IV). The lack of constant cooperation or project interaction with separately functioning energy facilities leads to insufficient efficiency of their transformations. This use of the capabilities of individual objects of a low-tech type in the context of the disintegration of resources corresponds mainly to the industrial type of economic development. This is shown by the decrease in efficiency in cycle 1 and by the area ratio S of cycles 1 and 2 in Figure 5.

The standard model of the direction and sequence of "I–IV" improvement of economic and organizational interaction of objects does not fully correspond to the challenges of the post-industrial knowledge economy. Therefore, it is proposed to integrate resources of non-material and material types within the boundaries of an effective platform and micro-network of high-tech development of distributed energy. The right pyramid represents the "4-1" pattern of direction and sequence of actions. It is distinguished by the use of the most developed high technologies and tools of Data Science, which dramatically increase the 3rd efficiency of processes in the context of the integration of objects II-V in the micronetwork of ETC (level 4). Arrow 1 shows the direct effects of these additional functions when using large databases for digital modeling based on artificial intelligence, the Internet of Things, and energy. In order to improve the quality of regulation of the enterprise's relationships in the next cycle of high-tech transformations or to stabilize the achieved level of efficiency, a decision is made on the need to use more knowledge-intensive and innovative energy-saving technologies in the formed platform and micro-network: 4-business models, technical means and methods of low-quality parameters of control and dispatching processes in technologies of separate operation of objects that maintain or reduce the achieved level of 3-E efficiency; 3-the use of separate tools and methods for improving the quality of control parameters and dispatching processes in technologies for integrating separately functioning objects at the beginning of the formation of a micro-network and a macro-network of ETC; 2—the use of a full set of tools of control and supervision to ensure a leap transition to a high level of 3-E efficiency by combining the maximum number of organizational methods and technologies; 1—means of stabilizing the achieved level of quality of parameters for regulating the processes of interaction between traditional and renewable energy facilities in the new structure of the platform. Levels 1 and 2 are provided by the use of additive technologies of the digital industry based on digital doubles, the Internet of Things and other SMART technologies using artificial intelligence. Such high technologies should be transferred to the education system at level I to transfer the experience of their practical application and start a new development cycle.

Special additional resource integration management functions implement direct links (arrow 1) that have planned, regulatory, coordinating, or project impacts of data science tools. Feedback loops (arrow 2) implement the function of monitoring the results of high-tech development of objects in the complex. This allows you to more fully use the platform's information networks for resource integration.

At the second stage of the implementation of the research concept it is necessary to justify and adapt mathematical methods for describing evolutionary and leap processes combining and applying Data Science tools in the specified development cycle.

For this purpose, the application of a new method of approximation of a generalized function of the form of a delta function by analytical functions is justified [58]. It is established that they adequately allow to solve theoretical and applied problems of representation and analysis of the specified dynamics in relation to modeling of processes of interaction of objects of the formed ETC. The delta function can be defined by a functional of the following form [58]:

$$\delta(x) = \begin{cases} +\infty, \ x = 0, \\ 0, \ \forall x \neq 0, \end{cases} \tag{1}$$

with:

$$\delta(x) = \begin{cases} +\infty, \ x = 0, \\ 0, \ \forall x \neq 0, \end{cases} \tag{2}$$

It is not difficult to see that for any n the area of the figure under the graph of such a step function is equal to one. We find the values of the coefficients of the Fourier series on the segment, taking into account the theorem on the average value of a certain integral:

$$a_0 = \frac{1}{\pi}\int\limits_{-\pi}^{+\pi} \delta_n(x)dx = \frac{1}{\pi}\int\limits_{-1/n}^{1/n} \frac{n}{2}dx = \frac{1}{\pi}; \tag{3}$$

$a_k = 0$, by virtue of the parity of the function;

$$b_k = \frac{1}{\pi}\int\limits_{-\pi}^{\pi} \delta_n(x)\cos kx dx = \frac{1}{\pi}\int\limits_{-1/n}^{1/n} \frac{n}{2}\cos kx dx = \frac{1}{\pi}\cdot\frac{n}{2}\cdot\frac{2}{n}\cos(kx^*) = \frac{\cos(kx^*)}{\pi}, \quad x^* \in [-1/n,\ 1/n], \tag{4}$$

Since the delta function is $\delta(x) = \lim\limits_{n\to\infty}\delta_n(x)$
and, noting that $x^* \underset{n\to\infty}{\to} 0$
find $b_k = \frac{1}{\pi}$
Therefore, the expansion of the delta function into a Fourier series on the segment [−π,π] has the form:

$$\delta(x) = \frac{1}{2\pi} + \frac{1}{\pi}\sum_{k=1}^{\infty}\cos(kx). \tag{5}$$

For a finite series, we have an approximate relation:

$$\delta(x) \approx \frac{1}{2\pi} + \frac{1}{\pi}\sum_{k=1}^{n}\cos(kx). \tag{6}$$

It is established that the selected segment [−π,π] does not reduce the generality of our reasoning. Using variable substitution, the results are generalized to the case of an arbitrary segment. It is found that even with a significant number of harmonics (in our case n = 1000) the approximation error is very high. This shows the Gibbs effect [3], even though the delta function is non-negative. The minimum value of the constructed approximation is negative and is—69.182. Moreover, with an infinite increase in the number of terms in the approximating Fourier series, the minimum value of its sum tends to $-\infty$. This corresponds to the statement proved earlier [59] about the possible infinitely large error in the approximation using the Fourier series. In other words, the approximation by Fourier series, even with an infinite number of terms, does not correspond to the original delta function at all.

The Gibbs effect leads to extremely negative consequences of using the partial sum of the trigonometric series as an approximating function for solving mathematical modeling problems, for example, in the study of periodic transformation processes of technical systems. The use of a sequence of step functions does not allow for the proper representation of the derivatives of the delta function, which are also generalized functions. The problem is that step functions have discontinuity points at which they are not differentiable in the mathematical sense. Therefore, to represent the derivatives of the delta function, you need to use an approximating sequence of analytical functions that have derivatives of any order.

To construct such a sequence, we use the fact that the delta function is a derivative of the function O. To construct such a sequence, we use the fact that the delta function is a derivative of the O. Heaviside function, or the unit jump function. It determines the estimates of the 3rd efficiency (H) by factors x of improving the quality of control parameters over time [58,59]:

$$H(x) = \begin{cases} 1, \ \forall x > 0; \\ 0, \ \forall x < 0. \end{cases} \tag{7}$$

It is proposed to approximate the Heaviside function with a sequence of functions of the form:

$$\mathrm{H_n}(x) = 0,5(1 + f_{\mathrm{n}}(x)) \quad (8)$$

where the sequence of recursive functions $f_{\mathrm{n}}(x)$ is defined by the relation:

$$\{f_{\mathrm{n}}(x)\ |f_{\mathrm{n}}(x) = \sin((\pi/2) \cdot f_{\mathrm{n}-1}(x)),\ f_1(x) = \sin x;\ \mathrm{n} - 1 \in \mathbf{N}\ \} \subset \mathbf{C}^{\infty}[-\pi/2,\ \pi/2]. \quad (9)$$

It can be proved that the sequence $f_n(x)$ converges in norm to a function $f_0(x)$ in space L_2 [0,π/2].

This allows us to make the assumptions shown in Figure 5 by graphs of three consecutive approximations. We interpret them as the effects of the proposed increase in the number of additional quality functions of the control parameters from 9 to 11. This addition will allow you to evaluate and regulate transactions in a more complex macro-and micro-network of hybrid energy facilities. The values of A can model the increasing degree of impact of the quality parameters of the regulation of the processes of combining resources, which are taken into account when changing the planned indicators in the CCI at the stages of the development cycle [59].

$$\mathrm{H_9}(x) = 0,5(1 + \sin(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(x)))))))))))$$
$$\mathrm{H_{10}}(x) = 0,5(1 + \sin(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(x))))))))))))$$
$$\mathrm{H_{11}}(x) = 0,5(1 + \sin(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(\mathrm{A}(x)))))))))))))$$

where $\mathrm{A}(x) = \frac{\pi}{2}\sin x$.

The thickness of the graph lines in Figure 6 increases as the number of the approximating dependence increases.

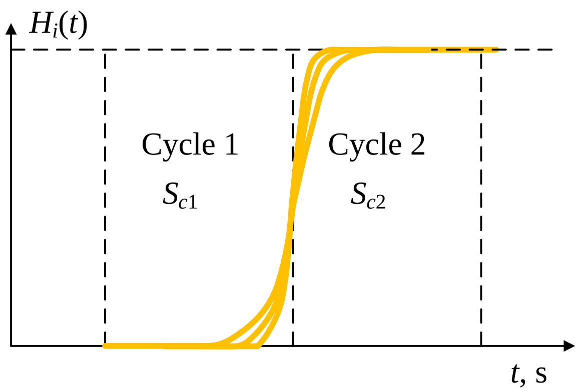

Figure 6. Graphs of approximations of the Heaviside function, simulating the processes of improving the quality of energy parameters during the transition to the microgrid and complex structures, $H_i(t)$ is 3-E efficiency (dimensionless unit), t is the cycle time (seconds).

Figure 7 shows the dynamics of the efficiency of energy generation and transmission processes by the factors of interaction between traditional and renewable energy facilities. The energy efficiency indicators of the hybrid complex of small distributed energy (solar panels in combination with a diesel generator from the type III objects) are taken into account according to Table 1. The maximum corresponds to the working conditions as part of the micro-grid of the ETC. The dynamics is explained by the fact that in the interval of 15...20 months, there are factors that affect the efficiency of solar panels (winter and summer time) after reaching the maximum efficiency, its sharp abrupt decrease occurs.

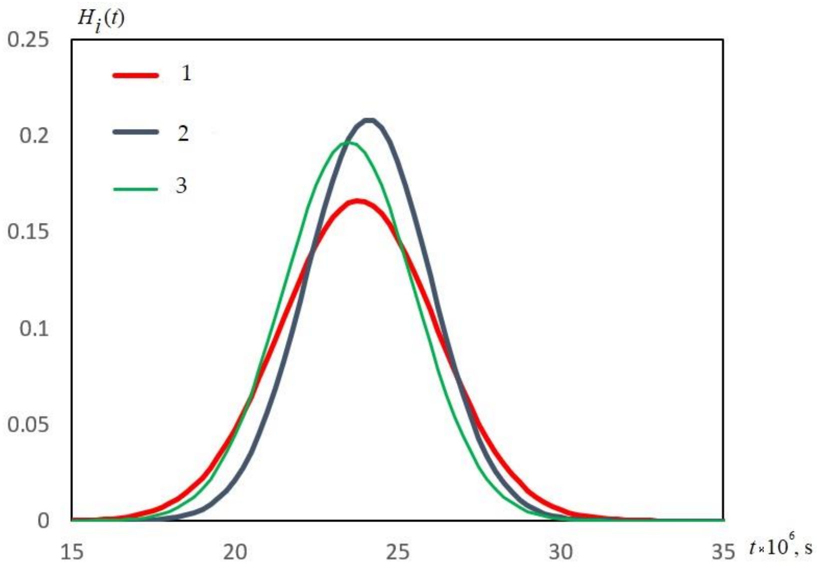

Figure 7. Dynamics of the efficiency of energy generation and transmission processes by factors of interaction between traditional and renewable energy facilities:1—small distributed energy; 2—interaction of microgrid objects in accordance with the developed methodology; 3—large centralized energy, $H_i(t)$ is 3-E efficiency (dimensionless unit), t is the cycle time (seconds).

The average indicator of the energy efficiency of a diesel generator separately operating for electricity generation and water heating as part of a large energy complex that uses traditional resources (for example, a central power plant from type IV facilities) is represented by an estimate of the maximum value according to Table 1. The maximum corresponds to the conditions for joint operation of objects as part of a micro-grid of ETC. The dynamics is explained by the fact that in the interval of 15...20 months, there are factors that affect the amount of heated water (winter and summer). After reaching the maximum efficiency, there is a quite understandable decrease in it.

An integrated approach to the organization of economic, machine-to-machine and physical interaction of objects in accordance with the developed methodology provides a significant increase in the 3rd efficiency (Table 5).

Table 5. Improving the 3-E efficiency in terms of quality control parameters of processes control and supervision of interaction of microgrid objects.

Performance Indicators, %	Number of Interacting Objects			
	2	3	4	5
Energy, Loss reduction	1.5	2.0	3.5	5.0
Environmental, reducing the amount of emissions into the atmosphere	5	8	12	15
Economic, reducing the cost of heat and electricity	0.8	1.6	2.5	3.5
Improving reliability	4	7	13	16

Using expressions for the first derived approximations of the Heaviside function, we obtain successive approximations $\frac{dH_9(x)}{dx}$, $\frac{dH_{10}(x)}{dx}$, and $\frac{dH_{11}(x)}{dx}$ for the delta function. Their graphs are shown in Figures 5 and 6. With a sufficiently large number of nested and regulating functions, we obtain an approximating function $\frac{dH_{18}(x)}{dx}$ that fully corresponds to the function of the original function. Such a function can simulate processes that correspond to the high quality of the control parameters and the maximum 3-E efficiency.

Consequently, the proposed approximation methods give a much more accurate approximation of the delta function than the Fourier series. Moreover, the accuracy of the approximation can be increased to an arbitrarily large degree by increasing the number of nested functions. The height of the approximation peak (the amplitude) can be determined by the integral condition in the definition of the delta function. To do this, we differentiate the approximating functions of the considered sequence $\mathrm{H_n}(x) = 0,5(1 + f_\mathrm{n}(x))$ and obtain in Figure 8 the mapping of the processes of applying 9, 10, and 11 functions. Thus, the increase in the speed of applying the quality parameters of regulating the processes of interaction of micronetwork objects in the CSI of the complex is modeled by increasing the number of additional regulators [58]:

$$\frac{\mathrm{dH_n}(x)}{\mathrm{d}x} = \frac{\pi^{\mathrm{n}-1}}{2^{\mathrm{n}}}\prod_{\mathrm{k}=1}^{\mathrm{n}-1}\cos\left(\frac{\pi}{2}f_\mathrm{k}(x)\right)\cdot\cos\ x \tag{10}$$

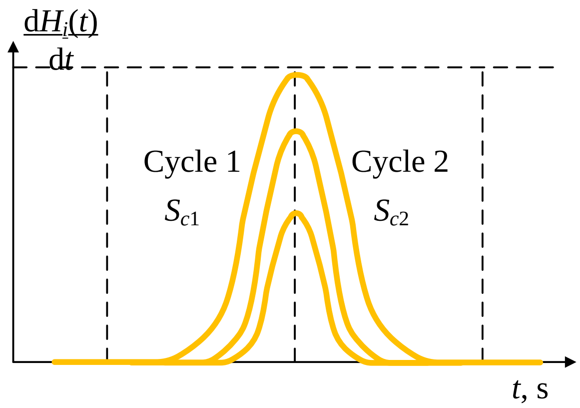

Figure 8. Graphs of delta function approximations for modeling the speed of processes for improving the quality parameters of transaction regulation, $H_i(t)$ is 3-E efficiency (dimensionless unit), t is the cycle time (seconds).

Substituting in the resulting expression for the derivatives $x = 0$, taking into account the parity of the function δ, we find the value for the height of the peak of the approximating functions $\mathrm{H_n}(x)$. Thus, it is proposed to assess the maximum degree of impact of the quality parameters of regulation. At the same time, the maximum levels of 3-E efficiency and balance of interests of traditional and renewable energy facilities in the micro-grid are achieved [58]:

$$\mathrm{A_n} = \frac{\pi^{\mathrm{n}-1}}{2^{\mathrm{n}}} \tag{11}$$

The average reliability indicator—the probability of failure-free operation of small distributed power equipment with traditional and renewable resources (for example, a wind-powered installation) from the composition of type III objects) is represented by an estimate [58,59] using Equation (12):

$$P = 1 - \frac{r}{N}, \tag{12}$$

where r is the number of failures at the time of operation (use) of the installation, N is the number of elements at the beginning of the use of wind energy.

The main advantages of using this indicator in calculations are two factors. First, the probability of failure-free operation is evaluated, taking into account all the factors that affect the reliability of the elements. Reliability assessment is carried out according to the criterion of the maximum indicator P. Secondly, the probability of failure-free operation is determined in the reliability assessment of complex systems consisting of more than one element. The dynamics shown in Figure 9 is explained by the fact that in the interval of several months of operation of the installation, environmental factors, such as weather conditions, act. The average reliability indicator is the probability of failure-free operation of a large power plant that uses traditional resources (for example, traditional energy facilities of type IV). At the same time, the calculation is carried out according to the same formula, but the number of elements in the composition of large energy facilities is immeasurably greater, so the probability of trouble-free operation is not significantly reduced. This occurs after reaching the maximum reliability during the warranty period. Further, the probability of trouble-free operation is sharply reduced.

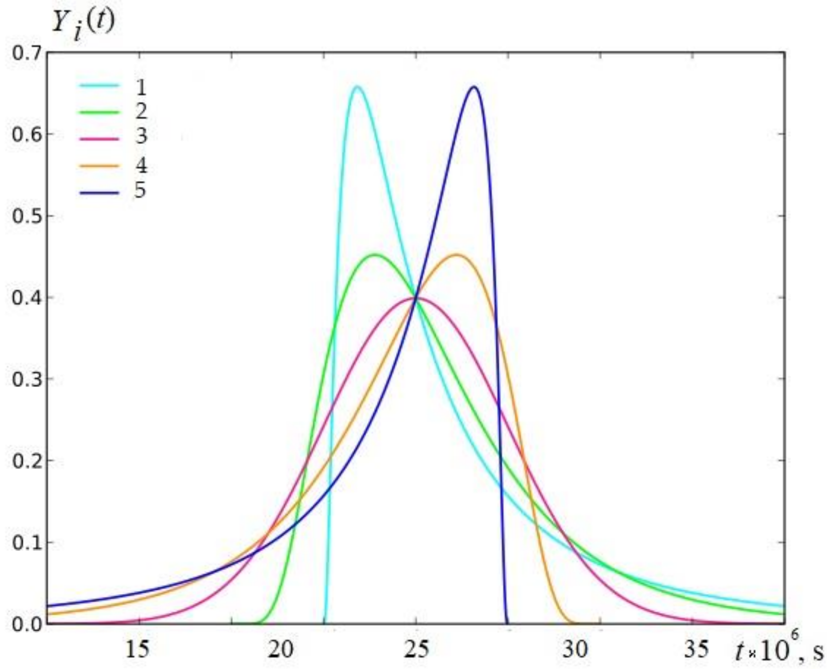

Figure 9. Dynamics of equipment reliability indicators by the factors of interaction between traditional and renewable energy facilities: 1—large and 2—small energy using traditional resources; 3—distributed energy and 4-other hybrid energy facilities; 5—interaction of micro-grid facilities in accordance with the developed methodology, $Y_i(t)$ is dependability (dimensionless unit), t is the cycle time (seconds).

An integrated approach to the organization of economic, machine-to-machine and physical interaction of objects in accordance with the developed methodology provides a significant increase in reliability. Indeed, the tools of the control mechanism of the dynamic simulator of the mechanism for combining methods of joint energy generation, the Internet of Energy and things provide advanced diagnostics of equipment failures and opportunities for author supervision during its life cycle. This significantly increases the 3-E efficiency of the joint operation of micro-network objects. In absolute terms, for example, the gains in energy and environmental efficiency are determined as follows (the results of the calculations are summarized in Table 5).

Since we have approximated the generalized functions by analytic functions, after differentiating them, we can find derivatives of any order and degree of accuracy. The constructed graphs of successive approximations of the first, second, and third derivatives of the delta function are proposed to be used to model the speed of the processes of digital control and dispatching advanced digital processes of control and supervision in a dynamic simulator of the mechanism for combining methods for coordinating the interests of complex objects (see Figure 3).

In the conditions of the functioning of the ETC micro-network, the results of the analysis of the processes in Figures 5–8 show that the manifestations of the Gibbs effect lead to extremely negative consequences of using the partial sum of the trigonometric series as an approximating function for solving mathematical modeling problems. This is established in the study of the dynamics of technical systems with the use of photo- and thermoelements for generation in distributed energy, monitoring of electrical and thermodynamic parameters of equipment (the scheme is given in Section 5 of the article). It is necessary to adjust the readings of sensors and the effects of electric drives of industrial Internet of Things (IoT) actuators when implementing the processes of physical interaction of complex objects.

The indicated Gibbs effect in the approximation of functions by trigonometric expressions determined a critical attitude to the proof of some theorems of the theory of signal transmission. New possibilities of correcting Kotelnikov's theorem, known in English literature as Nyquist's theorem, are revealed. When proving the theorem, V. A. Kotelnikov used the so-called integral sine, defined by the expression $\mathrm{Si}(x) = \int_0^x \frac{\sin t}{t} \mathrm{d}t$, to approximate the functions.

Based on the integral sine, he constructs a function $\mathrm{Si}(\mathrm{T}(\omega + \omega_1)) - \mathrm{Si}(\mathrm{T}(\omega - \omega_1))$, where ω is the argument, T, ω_1 some parameters.

It is stated that, with an increase T, this function tends to the limits shown in Figure 10a, i.e., we quote verbatim, it is equal to zero at $\omega > \omega_1$ and equal to π for $\omega < \omega_1$.

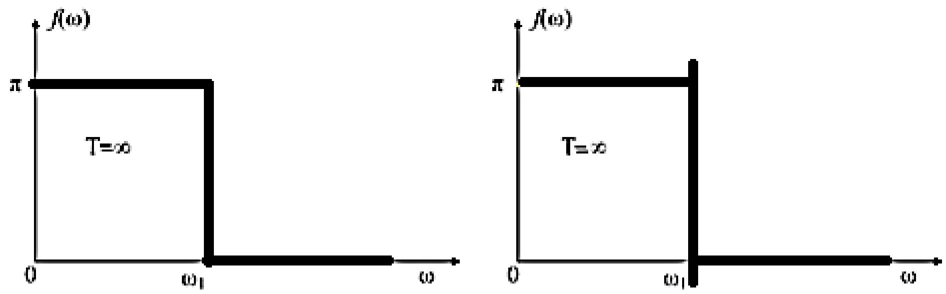

Figure 10. Graphs of the limit function in the Kotelnikov theorem, $f(\omega)$ is standard function (dimensionless unit), ω is the argument of standard function, for example dimensionless speed (dimensionless unit); (**a**) without Gibbs effect; (**b**) with Gibbs effect.

It is established that the graph of the limit function will have the form shown in Figure 10b. That is, for any, even arbitrarily large, but finite values of the parameter T, there will always be those $\omega < \omega_1$ for which the values of the function constructed by Kotelnikov will be different from π, and there will always be those $\omega > \omega_1$ for which its values will be different from zero. Moreover, it is important to note that this difference tends to increase not to zero, but to a certain number, approximately equal to 0.281 [58]. Therefore, in the practice of signal transmission, it is necessary to adjust their effects on the specified value of the coefficient, which we propose to call the Aliukov constant

2.2. Design of Methods of Combining Generation of Hybrid Systems on Organic Fuel and Photovoltaic Cells in a Single Energy Technology Complex Assessment and Regulation

The third stage of the study is to design the technical and technological composition of the equipment of manufacturers and consumers of the products of the formed ETC, the processes of which are justified by the results of modeling. This determined the need to develop an algorithmic scheme of the processes of the method of controlled improvement of the quality of control parameters according to the proposed criterion of increasing the 3-E efficiency. Decisions are made based on the following methodology (Figure 11). The algorithmic model defines the stages of the methodology of research and design of the transactional energy platform and the network of the energy technology complex of hybrid objects.

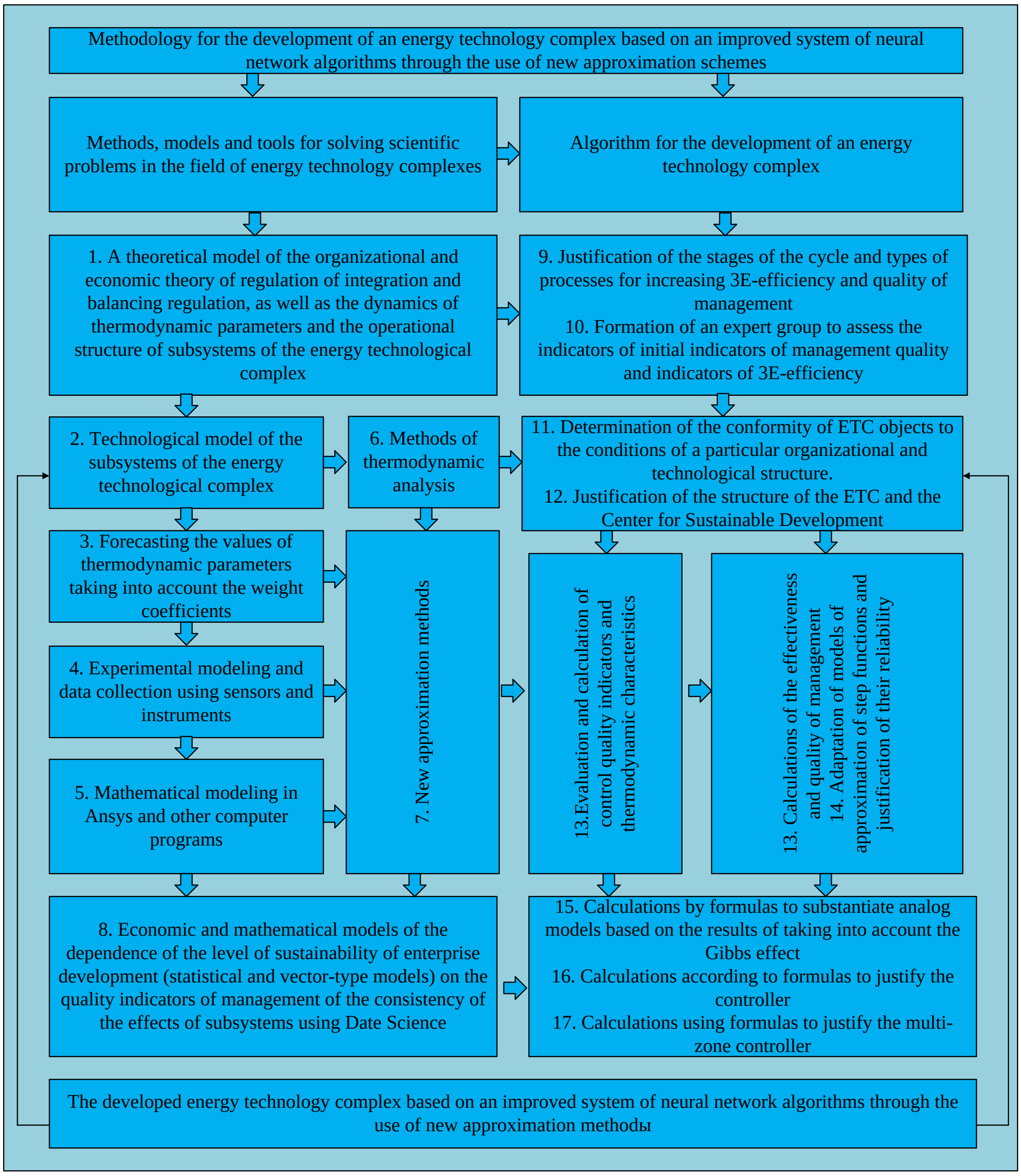

Figure 11. Algorithmic model of the methodology for improving the quality of regulation based on a combination of methods in the Center of Coordination of Interests of Complex Objects.

Determination of the initial assessment of the level of imbalance of efficiency goals (H) over time (x) of cycle 1 of the application of modernization and evolutionary changes in technology and organizational methods in the modernization processes (see Figures 4–6 in the ranges—0.20...0.00 radians. This is modeled by comparing the estimates of the areas of the zones S, which reflect the increase in speed in cycle 1 and its decrease in cycle 2. Therefore, the static criteria for improving the quality of control in finite increments of the indicator-properties have the following inequalities and relations [58]:

$$|H_i(x)x_{ts2}| \supseteq |H_i(x)kh_{ts1}|\frac{N_i(x)x_{ts2t2}}{H_i(x)x_{ts2t1}} \supseteq 1 \quad (13)$$

An increase in the area in cycle 2 or the value of the area ratio greater than 1 shows an increase in the quality of the control parameters in the space and time of innovative transformations. In addition, it defines the boundaries of the steps 1–4 of the cycle in

Figure 4 for the adoption and start of the implementation of the appropriate methods and processes. This is how the use of additional functions for the use of high-tech processes control and supervision is modeled: the transition from separate to joint operation of micro-and macro-network objects of the ETC.

Figure 11 shows an algorithm for developing and applying a methodology for improving the quality of energy parameters regulation according to criteria 3-E efficiency of joint operation of objects of the II-V microgrid. The objects are included in the objects of the macro network of the unified ETC and take into account environmental factors based on the integration-balancing methodology for organizing economic, machine-to-machine and physical interactions of objects. The methodology is applied based on the results of mathematical modeling of processes for improving the quality of regulatory parameters, based on new methods for approximating generalized functions. Steps 1–8 of the model correspond to the application of the methodology, organizational and mathematical models and methods of Section 3 of this article. Steps 9–17 present the practical application of the results of mathematical modeling of processes in Sections 3–5 of the article. For this purpose, the methods of physical modeling and error estimation of mathematical modeling are used.

The economic analysis of the quality of the process control parameters determined the need to display and model the conditional expansion of space and time for the application of processes control and supervision due to the high speed of regulation. The approximating trajectory of processes and results is shown in Figure 12 by the polyline A-B-C-D-E. It is established that at the beginning of the development of high-tech methods for implementing innovative results (these technologies for combining resources and ensuring the quality of energy parameters) in the formed networks of ETC, the level of economic efficiency of the systems decreases [20].

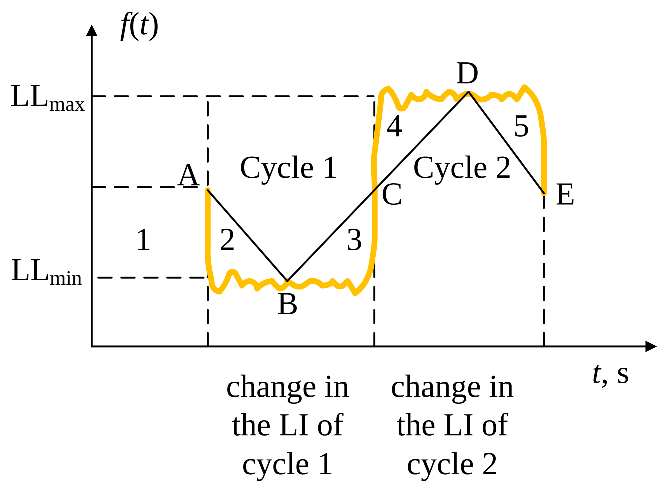

Figure 12. A model of the Gibbs effect in the parameters of the levels of efficiency of the use of control and supervision technologies in the network of the complex, where $f(t)$ is a function of the level of economic losses (EL)-dimensionless unit, t is the lifetime of equipment.

Therefore, the hypothesis of improving the quality of the parameters of regulation of high-tech processes of combining resources with the use of the methods and models of transaction organization proposed by us is valid. They make it possible to provide a zone of stability of the 3-E efficiency indicators in the estimates of economic loss reduction for several cycles. For its quantitative confirmation, analog-digital economic models of representation of management improvement processes are proposed. They use the well-known Gibbs effect in mathematics, which allows us to reveal the functional relationships of the indicator-the properties of the level of economic losses of the EL (the inverse value of efficiency) from the levels of innovation (LI) of the development of systems.

In each cycle, the zones of the minimum imbalance of goals in the estimates of the variability of the EL indicator are identified, depending on the LI technologies for combining resources that determine the development zones during the time period of cycles 1 and 2. In the cycle of evolutionary processes 1, methods of advanced investment are used in the subsystems for managing the integration of educational and research resources of objects of type VI (see Figure 1) with minimal and poorly regulated growth of the development index of the LI. In quadrant 2, the modernization or development of methods and technologies for the joint work of objects in the micro-network begins. At the same time, economic losses and costs are slightly and evolutionarily reduced due to the use of short-term effects of low-tech development of separately functioning objects outside the ETC (segment AB of the linear representation of the loss function).

Zone 3 of the development process is characterized by an increase in investment costs for personnel training and research in the areas of developing high-tech methods for combining resources. In this article, these are technologies and organizational methods for the joint functioning of microgrid objects) in the negative zone (−1...0), shown by the direct BC. The increase in economic losses is explained by the fact that each additional increase in the level of 3-E efficiency in the development of new technologies and methods reduces the severity of the consumer reaction in assessing the utility and cost of the formed hybrid energy networks. In practice, a number of technologies and products that differ in the level of innovation are usually mastered. They show a range of estimates from a jump in the levels of efficiency and innovation in the development of a new technology to gradual changes in the modernization of individual elements of the system. The low ratings in cycle 1 are also explained by the lack of recognition of the uniqueness of households and residential buildings by energy consumers. New consumer properties of the processes of physical interaction during joint generation, executed by transactions (in the period t_{c1}) are shown by negative estimates of the zones of increase in properties and the insignificance of the reduction in economic losses.

In cycle 2, a jump-like increase in the efficiency levels of technologies and organizational products is shown. Meaningfully, it is explained by similar reasons for the growth of economic losses in comparison with their value in cycle 1. This follows from the structural changes in Zones 4 and 5 in the creation of the CCI and the unified ETC. It is shown by the similar nature of the dependencies on direct AB and DE, BC and CD. Concretizing the hypothesis of the study, it can be assumed that the zone of compromise of the considered goals should be determined by balancing changes in the resulting property of economic losses in the specified range of estimates (−1...1). The stability of the zone boundaries should be regulated by additional functions in the special control system of the dynamic simulator of the method combination mechanism (see Figure 4). The mechanism provides joint energy production in the CCI, where the management of the matching effects on the indicators of the integrated application of investment, intellectual and research resources of long-term development is carried out. Such impacts are developed based on the model of the integration-balancing regulation methodology and are cyclically implemented in the transactional energy platform (see Figure 5). These processes are proposed to be modeled by mathematical functions of a stepwise form [58]. The evolutionary changes are described by a set of nested sinusoidal maps of these functions. Systems with step characteristics and functions are classified as essentially nonlinear structures. Despite the simplicity of step functions over sections, the construction of solutions over the entire domain of their definition requires the use of special mathematical methods. For example, the method of priming with linking solutions for sections and switching surfaces makes it necessary to overcome significant mathematical difficulties, quite often the solution is obtained in a cumbersome form.

The features of the organizational and economic relationships of a complex system allowed us to neutralize the negative manifestations of the Gibbs effect. So, if we take as members of the partial aggregate the levels of innovation of technologies, methods and products, then their number in the developing system is known and far exceeds dozens of levels. Therefore, the fact that the maxima and minima of the amplitudes of the indicator-property of the EL remain unchanged under the specified condition can be interpreted as the relative stability of the oscillation range during the cycle. This corresponds to an increase in the quality of the parameters of regulation of the efficiency of innovative development according to the criterion of reducing the imbalance of the goals of hybrid energy facilities in cycles 1 and 2 on the basis of the proposed methodology.

For relative error $\delta(x) = \Delta(x)/|f(x)|$, the proof is similar. Moreover, even with a fixed value $d \in \boldsymbol{R}$ $(d \neq 0)$ for any $M > 0$, you can choose a function $f(x) \in L_2[a,b]$ for which $\delta(x_0+0,d) = \Delta(x_0+0,d)/|f(x_0+0)| > M$. As such a function, for example, you can take a function that has $|f(x_0+0)| < \Delta(x_0+0,d)/M,\ f(x_0+0) \neq 0$. It is known that even on the set of continuous functions $S\,[-\pi,\ \pi]$, the Fourier series does not necessarily converge at every point.

New methods of approximation of step functions based on the use of trigonometric expressions in the form of recursive functions are proposed for modeling the processes of increasing the 3-E efficiency depending on the sequential increase in the number of objects of the ETC macro network (see Table 5) [59]. Let us consider, for example, in more detail the step function of economic losses f(x) = EL for an example of the application of Fourier series in the comparative analysis of the traditional decomposition and the representation of the proposed hypothesis. The Fourier series expansion of the function has all the disadvantages described above. To eliminate them [58], it is proposed to approximate the original step function by a sequence of recursive periodic functions (14):

$$\{f_n(x)\,|f_n(x) = \sin((\pi/2)\cdot f_{n-1}(x)),\ f_1(x) = \sin x;\ n-1 \in \boldsymbol{N}\} \subset C^{\infty}[-\pi,\pi] \tag{14}$$

The graphs of the original function (the thickened line) and its five successive approximations in this case have the form shown in Figure 13. They show a decrease in economic losses with an increase in the degrees of integration of the complex objects from one to five. As can be seen, even with relatively small values n, when using the iterative procedure (2), the graph of the approximating function approximates the original function (1) quite well. At the same time, the approximating functions obtained using the proposed method do not have the disadvantages of Fourier series expansion and the Gibbs effect. It is revealed that the functions $f_n(x)$ and $f_0(x)$ are odd and periodic with a period 2π. The functions $f_n(x+\pi/2)$ and $f_0(x+\pi/2)$ are periodic even. Therefore, it is sufficient to consider the sequence of approximating functions (6) on the segment $[0,\ \pi/2]$.

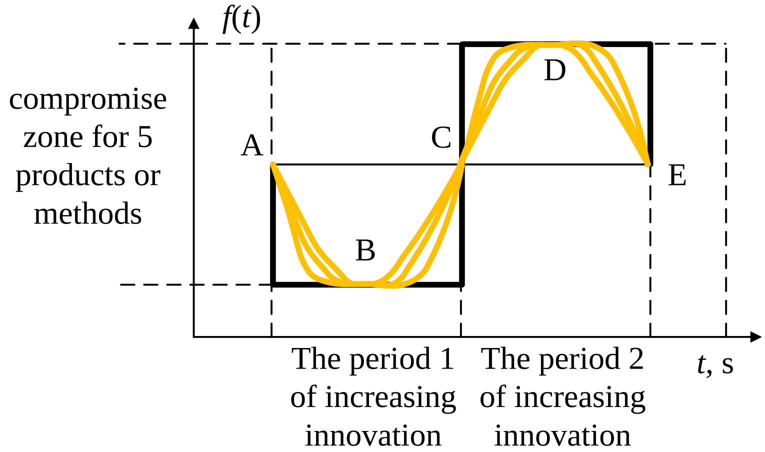

Figure 13. Modeling of the economic loss function and its five successive approximations by the five degrees of integration of the objects of the complex and the degree of combination of methods, where $f(t)$ is a function of the level of economic losses (EL)—dimensionless unit, t is the lifetime of equipment.

The continuity of the function of economic losses, determined by the levels of innovation of products, allowed us to establish quantifiable boundaries of the zone of compromise of the goals of microgrid objects. To do this, based on the results of differentiating the function according to Equation (1), the points of minimum B and maximum economic losses D must be determined. Thus, the boundaries of the zone of variability of the studied property of the economy of the joint development of objects, regulated by the control system of the CCI of the formed unified ETC, are also established.

Figure 14 shows the dynamics of the reliability indicator in assessing the probability of failures of equipment of energy facilities (for example, a combined source of electric and thermal energy on renewable biogas resources of the SHIW landfill from the composition of objects of type III) is represented by estimates of maximum values according to Table 1. The probability of failure increases over time and this requires monitoring using the capabilities of the IoT system. The sensors of the system set the parameters of the critical point, the appearance of the standard value of the probability of equipment failure. The inclusion of Ios actuators in the automatic actions eliminates the need for standardized regulations for the operation of microgrid installations.

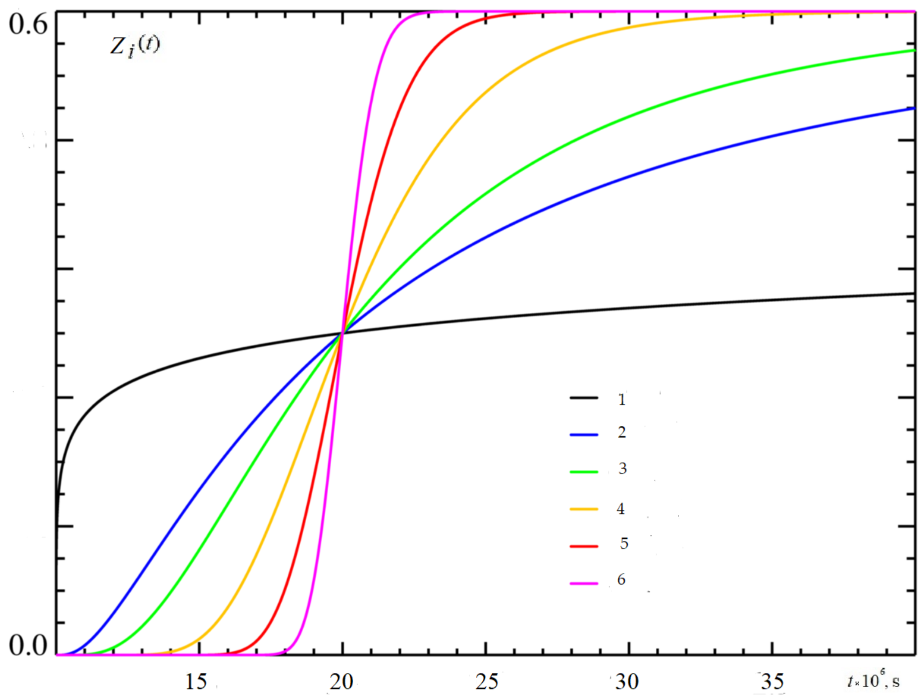

Figure 14. The dependence of the probability of equipment failure on the time of use of the facilities of the energy production complex: 1—large and 2—small energy using traditional resources; 3—distributed energy and 4-other objects of hybrid energy; 5—interaction of microgrid objects in accordance with the developed methodology; 6—use of neural network algorithms for hybrid complexes, $Z_i(t)$ is equipment failure probability (dimensionless unit), t is the cycle time (seconds).

3. Results

3.1. Results of Computer Simulation of Processes Combining Generation of Hybrid Systems on Organic Fuel and Photovoltaic Cells in a Single Energy Technology Complex

In the schemes of hybrid microgrid objects, various methods of combining the resources of organic fuel and renewable solar energy are used to calculate the 3-E efficiency. Photovoltaic panels are installed to reserve the generating capacity of the diesel generator. The efficiency increases if we use the results of computer modeling of the joint functioning of these objects.

Figure 15 shows the results of modeling the processes of increasing electrical power with an increase in the number of individual layers of a photovoltaic panel. In particular, the color shows the degree of heating of the layers under the influence of insolation.

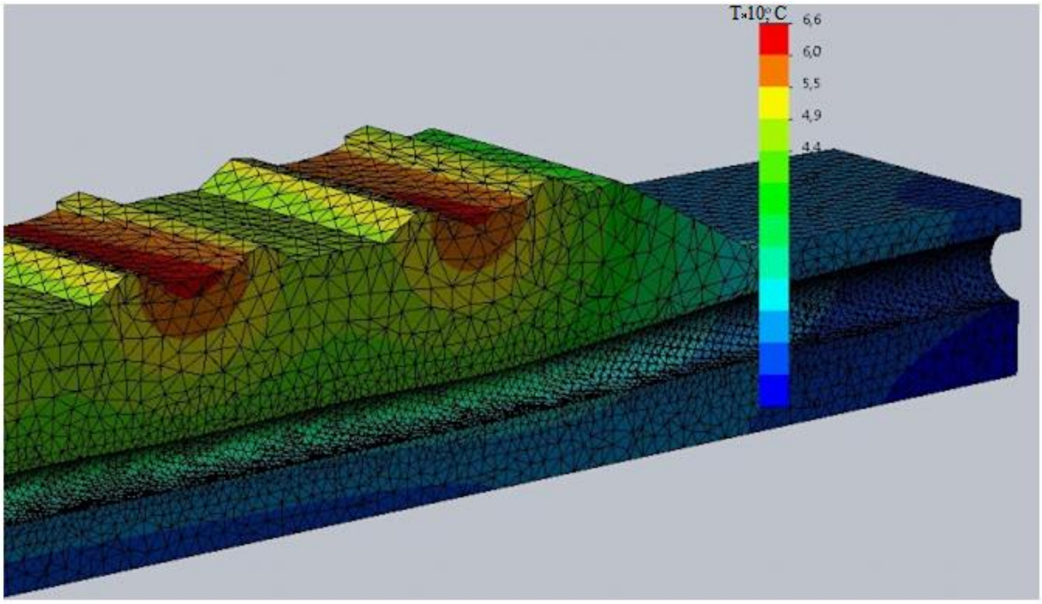

Figure 15. Simulation results of individual layers of a photovoltaic panel used in a microgrid, where T is the surface temperature, °C.

The process of natural fuel combustion in a diesel generator is shown in Figure 16: It is established that the temperature and the length of the flame change when regulated by neural network algorithms. When organizing the joint operation of a diesel generator in a micro-network with hybrid energy objects of type 2, 4 and 5, the temperature circuit changes. The combustion temperature and other characteristics of the biogas of object 2 differ significantly. This makes certain changes in improving the 3-E efficiency of combustion processes with prolonged use of diesel generator set equipment as part of the micro-grid.

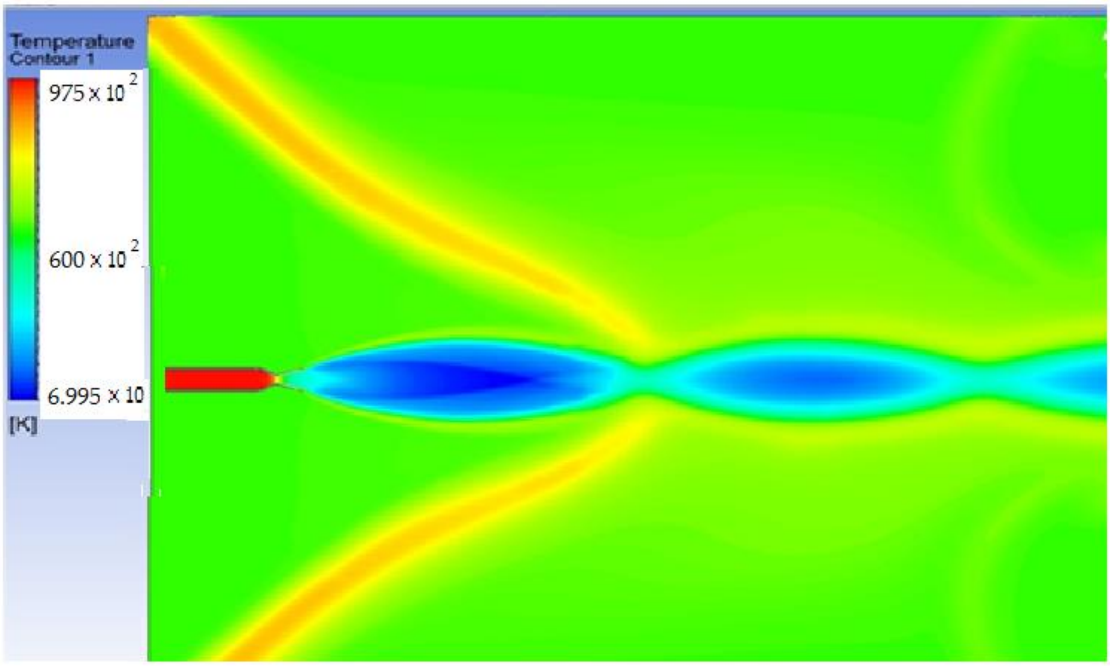

Figure 16. Results of modeling of fuel combustion in a diesel generator as an object of a micro-grid, where T is the temperature in the initial area of the flame, K.

3.2. Results of Experimental Studies

Experimental studies were conducted for an advanced scheme of digital control and dispatching of energy and logistics flows in the transaction network of a hybrid energy facility in the energy technology complex being formed (Figure 1). The testing system is composed of a loading system and an actuating system: Simulink control [35,36], Real-time control [37,38], Sinnal processing [39].

An experimental study of the amount of transmitted energy in hybrid complexes was carried out on a model of photovoltaic cells and a model of a burner running on diesel fuel (Figures 17–20). A model of a photovoltaic panel is shown, which was tested for the efficiency of energy transformation processes as a backup power source for microenvironment objects.

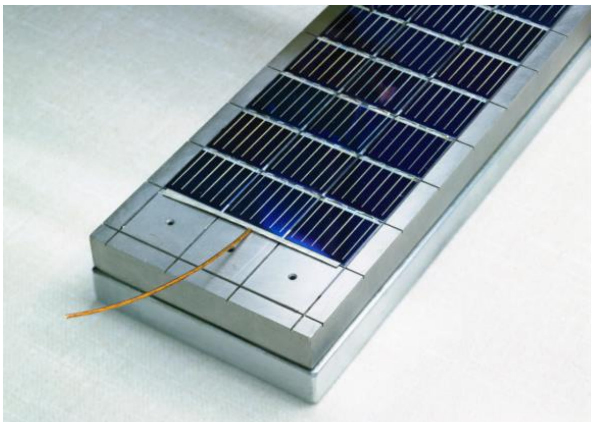

Figure 17. Model of photovoltaic cells used in microgrid objects.

Figure 18. Application of solar collectors in the oil and gas field in subarctic conditions.

Figure 19. Combustion of diesel fuel.

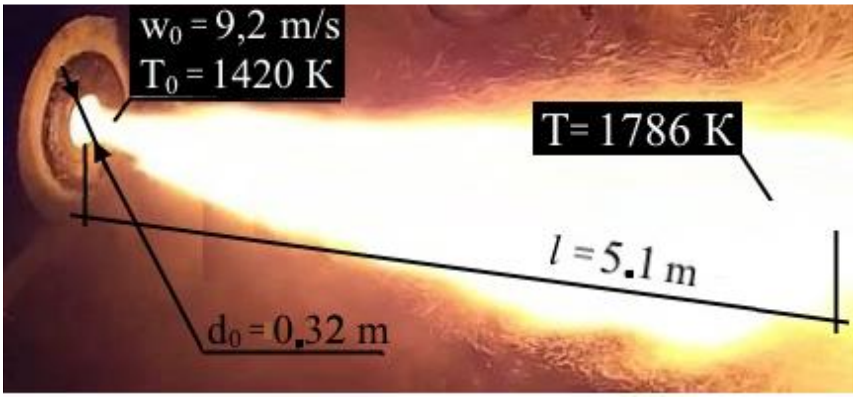

Figure 20. Fuel combustion in a steam generator and the results of the study.

There is an opportunity to use modern expensive technologies economically, especially since there are all the reasons for strategic, economic and regulatory nature. It is important to understand that oil and gas fields in subarctic and arctic climate areas should adopt renewable energy trends.

In the foreseeable future, it is necessary to adequately restructure the energy balance so that renewable energy sources in the far north occupy at least 20%, which is necessary in hard-to-reach and remote regions.

The average annual energy input of direct solar radiation in the arctic varies from 2 to 4 kW/h per square meter daily, and this is a very good indicator. For comparison, in the southern regions of Germany, it reaches 3.4 kW/h per square meter daily. In Siberia, on clear summer days, the supply of solar energy can reach indicators of 6–8 kW/h per square meter daily.

The joint operation of new technologies for combining hybrid energy resources was reliably controlled and controlled by Big Data and Data Science tools. They were used to collect and process data based on neural network algorithms. In the process of obtaining data from the model of photovoltaic cells, it was found that the predicted quality of the control parameters was achieved. As physical experiments have shown, the model under study can be used as part of a hybrid complex in order to increase its reliability (Table 6).

Table 6. Comparison of the authors' experimental data on the efficiency at the flame ignition site.

Parameter	Standard Value	Standard Value with New Methodology
Efficiency, %	10	10.5

Figure 19 shows an experimental setup for studying the flame temperature and the length of the torch of a diesel generator set.

The authors conducted a number of experiments on power plants. Measured the temperature of the flame, the rate of expiration of reagents, the concentration of combustion products, as well as a number of other equally important parameters of the combustion process.

These experimental results were compared with the analytical calculation and with the data of predictive regulation through the use of neural network algorithms. As mentioned earlier, in the previous section, all experimental data underwent the procedure of finding the range of uncertainty and validation of the applied methodology.

The following is an example of experimental studies. With a torch length of l = 5.1 m, the flame temperature T = 1786 K. At the same time, the fuel burned had a calorific value of 26,780 kJ/kg, Figure 20.

We present experimental data on the operation of Barnaul boiler plant (BKZ) boilers. For the boiler, the data are given at the rated load of the boiler D = 53 kg of steam per second, in addition, when burning coal with a calorific value of 24,560 kJ/kg. Parameters measured in the experiment: velocity w_0 = 8 m/s, T_0 = 1371 K, d_0 = 0.9 m, T = 1721 K, l = 5.33 m. For a boiler with a nominal boiler load of D = 44 kg of steam per second, in addition, when burning coal with a calorific value of 22,450 kJ/kg, the parameters measured in the experiment are: velocity w_0 = 9.2 m/s, T_0 = 1389 K, d_0 = 0.86 m, T= 1685 K, l = 4.75 m.

The experimental data obtained show the dependence of temperature and speed on the type of fuel and operating mode.

We present analytical calculated data, which were compared with experimental data. Forecast data: velocity w_0 = 7.85 m/s, T_0 = 1363 K, T= 1709 K, l = 5.16 m. For installation at rated load when burning fuel with a calorific value of 22,450 kJ/kg forecast parameters: velocity w_0 = 9.1 m/s, T_0 = 1377 K, T = 1672 K, l = 4.63 m. Thus, the data obtained by the predictive method is the closest to the experimental data.

As experiments have shown, the most suitable equipment from the point of view of reliability of the hybrid complex is the equipment that uses spray-type burners. The results are shown in Table 7.

Table 7. Comparison of the authors' experimental data on the temperature at the flame ignition site.

Parameter	Experimental Data	Calculation with Correlation Coefficient
Temperature, K	817	818.4

Calculations based on the above formulas should be supplemented by modeling energy transactions in terms of inter-machine and physical interaction of objects—users of the Internet of energy show. At the same time, the volumes of mutual energy transfer in the ETC network are determined under contracts concluded between objects 3–5. Calculations, for example, of heat energy flows between the objects of the above-mentioned microgrid are carried out as follows.

Thus, it is established that the criterion 3-E of the efficiency of the processes of combining resources in the ETC by methods of energy transactions becomes achievable in the proposed platform for the interaction of traditional and renewable energy microgrid objects.

3.3. Results of Comparison of Experimental Data and Simulation Data Using the New Method

The authors emphasize that the obtained modeling results in ANSYS are very akin to the theoretical and experimental data. The differences are insignificant since the error in the experimental measurements was leveled by the use of modern tools certified by the European Union. For example, this is evident by the temperature values. During standard modeling without the use of sampled data, the temperature value ranged from 38.7–38.9 °C. At the same time, when using the authors' developments, the value of the average temperature was 38.6 °C. This value is the closest to the experimentally obtained values of 38.8 °C. Thus, the maximum differences are obtained between the experimental data and computer modeling data without the use of the authors' developments, while the maximum coincidence is shown between the average values according to the modeling results taking into account the sampled signals and the experiment. The error in calculating the results of scientific research is summarized in Figure 21.

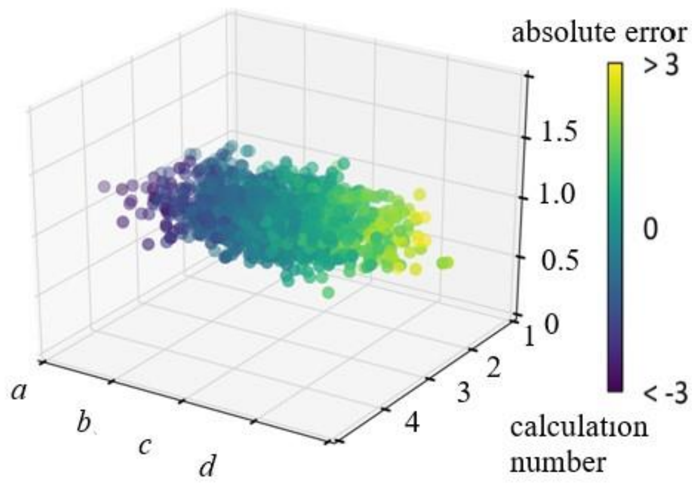

Figure 21. Calculation errors during mathematical modeling: *a*—ignoring the experimental data; *b*—taking into account the experimental data; *c*—taking into account the experimental data and the mathematical approaches; *d*—taking into account the experimental data but ignoring the mathematical approaches, where absolute error (dimensionless unit), calculation number (dimensionless unit).

We calculate the arithmetic mean of the flame temperature from all measurements at a given point [35,36]:

$$T = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{T_i}. \tag{15}$$

After calculations using Equation (15), we get the value T = 817 K.

For sources of random uncertainty, we calculate the uncertainty by type A [37,38]:

$$\mathrm{u_A}(T) = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{T_i} - \mathrm{T})}{\mathrm{n}(\mathrm{n}-1)}}. \tag{16}$$

Calculations using Equation (16) gave the result [39] $\mathrm{u_A}(T) = 0.8\%$.

For sources of systematic uncertainty (instrument error) calculating the uncertainty by type B [39]:

$$\mathrm{u_B}(\mathrm{T}) = \frac{\Delta \mathrm{T}}{\sqrt{3}}. \tag{17}$$

Calculations using Equation (17) showed the value of $\mathrm{u_B}(\mathrm{T}) = 1.58\%$.

Calculate the total standard uncertainty [39]:

$$\mathrm{u_C}(\mathrm{T}) = \sqrt{\mathrm{u_A}(\mathrm{T})^2 + \mathrm{u_B}(\mathrm{T})^2}. \tag{18}$$

Using Equation (18), we get the value $\mathrm{u_C}(\mathrm{T}) = \sqrt{0.64 + 2.4964} = 1.771\%$

For the confidence probability (coverage probability) *p* = 0.95 (recommended in the Uncertainty Calculation Guide), we set the coverage factor k = 2 and calculate the extended measurement uncertainty [39]:

$$\mathrm{u} = \mathrm{k}\mathrm{u_C}(\mathrm{T}). \tag{19}$$

The total value of the extended uncertainty is determined to be u = 2·1.771 = 3.542%. According to the regulatory document "Guidelines for measurements and their uncertainties in the countries of the Eurasian Economic Union", the maximum permissible value is 5% for experimental data. Therefore, the results obtained fall within the confidence interval and confirm the data of modeling and experiments.

3.4. Sensitivity Analysis and Validation of Research Results

Validation of the methodology was carried out in the software package Matlab (MathWorks Developer, Natick, MA, USA). Validation is shown on Figures 22 and 23, with Error = 201.5694 (Normal), Error = 39.3117 (Lognormal). The graphs are made in Matlab. The validation error for the effective power of the power complex was determined.

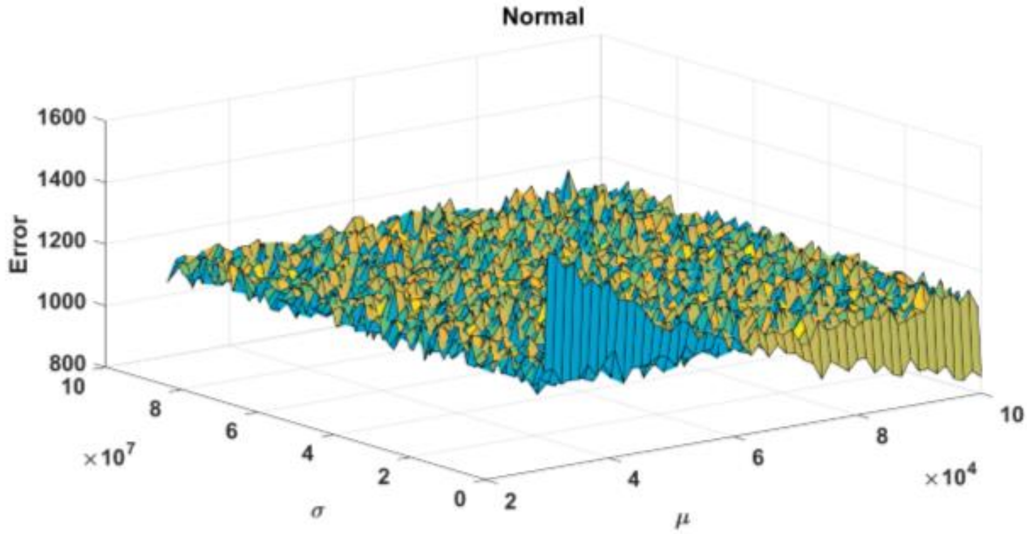

Figure 22. Validation error (Normal): Error—error value, σ—sample variance, μ—sample mathematical expectation.

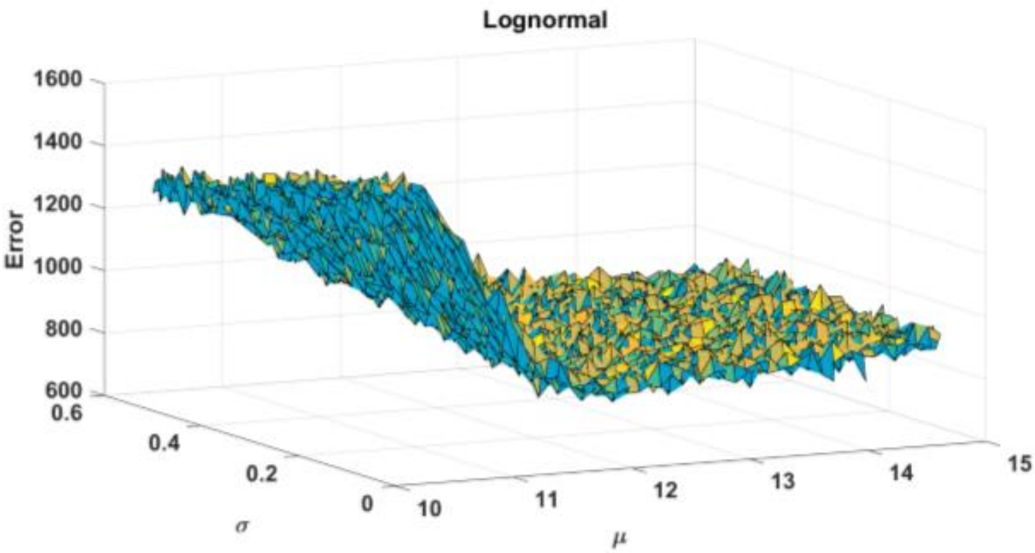

Figure 23. Validation error (Lognormal): Error—error value, σ—sample variance, μ—sample mathematical expectation.

These Figures 22 and 23 show the error value defined as normal in Figure 22 and lognormal in Figure 23. The values in these figures are dimensionless and represent: Error—error value, σ—sample variance, μ—sample mathematical expectation.

4. Discussion

The presented technical and economic analysis method can be considered as one of the steps towards digitalization of control systems for heat and power installations of a new model.

This study is aimed at a systematic study of the occurrence of non-optimal operating modes of power plants, as well as the development of algorithms and programs to improve the management system of the energy complex.

The top-level program with the introduction of artificial intelligence, built into the control system to optimize the operation of the power plant, is adaptive and trainable. The first time the program is turned on, it must test the sensor system of the power plant. After the power plant operation mode is stabilized, the self-learning system reads the sensor readings. An analysis of research is carried out, as well as promising developments in the field of thermodynamics and energy are identified.

Methodological approaches for the analysis based on new methods of approximation of piecewise linear functions are developed. In addition, it is proposed to use this method not only to optimize energy losses.

In addition to this information, all measurement divergences can also be calculated using a mathematical model that is developed taking into account the results of numerical modeling.

The project is aimed at combining the algorithm of the analysis method and the algorithm for controlling the power plant based on the analysis of the sensor data array.

This method is proposed for the first time, the authors have not identified any analogues in publications, patents and programs. The proposed method can be adapted for any control system of a power plant of any capacity. The proposed methods and approaches allow us to successfully solve the tasks and complete the project at a level that significantly exceeds the world level.

5. Conclusions

New knowledge about the formation of mathematical analysis in order to optimize the operation of the power plant was obtained. Scientific significance consists in obtaining essential and important new knowledge for world science. The applied significance lies in the use of this knowledge to create a computer model of a power plant.

The authors proposed the formulation of the technology concept, the scientific justification of the concept, the search for technological approaches to the implementation of the concept, the identification of advantages over alternative approaches, the determination of the feasibility of further development of the technological concept and the assessment of the risks of its implementation. The obtained result is the ways and methods of applying the previously studied phenomena and the acquired knowledge to solve practical problems of maximum optimization of the power plant operation, the presentation of the results in the scientific and technical report on the research work, the results of the study of the computer model. The scientific significance lies in the creation of new knowledge important for the world science in the form of universal algorithms. The applied significance lies in the use of this knowledge to create software that implements the algorithm of the power plant.

Experimental proof-of-concept, modeling, and testing are provided. The result of the research is a test of the software performance on existing power plants, the scientific significance also lies in the universalization of the created solutions, which is important for the global energy industry and creates prerequisites for a significant economic effect. The applied significance lies in the replication of the created software on a global scale:

(1) It is proposed to realize the needs for cyclic processes of network interaction of objects during the transfer of capacities and complementary types of products registered in the structure of the Internet of Energy. The concept of combining organizational, economic and mathematical models for improving technical, technological and information methods of effective integration of renewable and traditional energy facilities is formulated.

(2) A digital platform for machine-to-machine automatic transaction processing has been formed to formalize the relationships of network users using the technical and organizational elements of the energy internet. This made it possible to organize the economic, organizational, informational and physical interaction of objects in it. The

tasks of increasing the energy and environmental-economic efficiency of electricity transmission through the network of the formed energy-technological complex are solved. This allowed the development of schemes for using photodetectors to generate energy in distributed energy. As a result, there was an increase in the reliability and durability of wireless monitoring of digital assets for the conclusion of contracts, control of electrical and thermodynamic parameters of equipment in its diagnostic sensors and use in electric actuators of the Industrial Internet of Things (IoT). These elements were implemented in the processes of machine-to-machine and physical interaction of complex objects.

(3) The following theoretical results are obtained:
- The authors' methodology of integration and balancing regulation of the three specified types of interactions between the objects of the formed complex and the integration of resources is adapted;
- New possibilities of combining organizational, economic, mathematical, technical, technological and information methods of energy transactions in the Internet of energy are justified;
- The results of the authors' approximation of piecewise linear (step) functions for modeling processes in control cycles are obtained.

(4) The use of big data and data science tools is aimed at achieving a number of practical results: the differentiation of the composition of capacities and sources in the complex of hybrid energy facilities is expanded; the possibilities of modeling their regulated interaction based on mathematical methods of concluding contracts for Internet users of energy are expanded; a model of integration-balancing regulation in the transactional energy platform of the Center for Coordinating the Interests of Complex Objects is developed.

(5) The results obtained as a result of the research are fully consistent with the goal, reflect new scientific methods and practical consequences of the work. "integration of generation systems" based on organic fuel and photovoltaic cells into a single energy technology complex. To confirm it, experimental studies were carried out using physical models. Comparison of experimental data and simulation data using the new method, sensitivity analysis and validation of research results showed the validity of the theoretical assumptions of the concept. In the preliminary mathematical modeling of dynamic processes in technological devices, new approximation methods reduce the calculation time and the calculation error.

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Nomenclature

$H_i(t)$	3-E efficiency (dimensionless unit);
t	The cycle time (s);
x	Variable (dimensionless unit);
δ	Variable function (dimensionless unit);
a, b, n	Variable values x (dimensionless unit);

$f(x)$	An arbitrary function of a variable x, (dimensionless unit);
P	The probability of failure-free operation (dimensionless unit);
r	The number of failures at the time of operation (use) of the installation;
N	The number of elements at the beginning of the use of wind energy;
$Y_i(t)$	Dependability (dimensionless unit);
$f(\omega)$	Standard function (dimensionless unit);
ω	The argument of standard function, for example dimensionless speed (dimensionless unit);
$f(t)$	Function of the level of economic losses (dimensionless unit);
$Z_i(t)$	Equipment failure probability (dimensionless unit);
T	The temperature, °C (K);
l	The torch length, m;
Error	Error value (dimensionless unit);
σ	Sample dispersion (dimensionless unit);
μ	Sample mathematical expectation (dimensionless unit).

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