Methodological principles of constructing the integrated energy supply systems and their technological architecture

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Abstract. Nowadays, the technological infrastructure of power, heat/cooling and gas supply systems is normally built and managed separately by system and objective. New challenges of the time foreground the issues of establishing self-organizing interconnected energy systems with several types of energy carriers to ensure quality of energy services, and their considerable expansion to meet the increasing and permanently transformed requirements of consumers (level of comfort, technological innovations in production and household, increase in diversity and power of energy loads, radical changes in their properties, etc.). These systems represent integrated energy systems characterized by a multi-dimensional structure of functional features and properties of expansion. They combine a great number of components, intelligence, efficiency, reliability, controllability, flexible application of technologies for energy conversion, transportation, storage, and active consumer.

1. Introduction
Modern energy sector represents an infrastructural complex including fuel, electricity, heat and cooling supply systems. Despite various kinds of services rendered by the systems, their common goal is to create comfortable living and working conditions for the population, and to effectively facilitate the development of the national economy. To perform their functions, each of the systems has their production, transportation and distribution structure connecting them with consumers. They often interact and compete in the existing market for energy services. This, in particular, refers to the electricity, heat, and gas supply systems. Despite their certain functional independence, these systems can interact with one another under normal and emergency conditions, and at the level of interchangeable primary energy resources and use of energy carriers. This is indicative of their natural integration which gets even stronger in the course of the formation of intelligent, information and telecommunication systems. In combination, all of them represent a new structure in the form of a metasystem. This metasystem combines certain independence of the systems that constitute it and their coordinated participation in solving the main goal related to the provision of social and economic activity. Coordination of the accomplishment of this goal is ensured by the information system that represents an infrastructural framework of the metasystem.

2. Situation in the energy sector
The current situation in the energy sector is characterized by a pronounced organizational and technological imbalance between expansion and operation. This is evidenced by severe emergencies with serious consequences that have occurred in the last years not only in Russia but also in the world.
The revealed problem lies in the fact that the technical systems were built according to one technological principle, whereas their control is performed by the organizational structures and mechanisms that do not correspond to it. A vivid example of the situation is Russia’s energy sector. Everything was constructed for centralized vertically-integrated control and territorial allocation of productive forces. However, when the energy sector restructuring started the ownership relations changed, the system of control in the energy sector underwent changes, whereas the ideology of control and the technical system remained as before. Moreover, the control principles of the systems and technologies for their operation are as previously aimed at the existence of the energy systems for the sake of the systems themselves. They were not oriented to the consumer then and are not oriented to the consumer now. They do not take into account consumers’ interests and do not establish equal relations. Privatization, liberalization, and organization of the wholesale and retail markets in the energy sector did not facilitate the democratization of relations in the energy market, and did not provide an appropriate level of development and control of the energy sector.

This resulted in numerous contradictions between suppliers and consumers of energy resources. The situation is aggravated by the fact that the tariffs rise, the quality does not improve, and to support major companies the Government of the Russian Federation increases the tariffs even more, for example through the mechanisms of capacity supply agreement, RAB regulation in the electric power industry, an alternative boiler plant model proposed in heat supply, through indexation, etc. This entire additional load often has to be borne by the population, budget and small business. Competition that takes place in individual systems does not provide appropriate technological, economic, investment and other expected benefits.

There is considerable competition between the types of energy supply and the types of systems, in particular between centralized and decentralized energy supply system, between large-scale and distributed energy generation facilities. In Russia 65 % of the territory is the zone of decentralized energy supply, where 15 million of people live. According to the data of the Ministry of Energy of the Russian Federation, that were obtained based on the data of Russian State Statistics Committee, the dynamics of growth of decentralized systems in Russia outpaces the dynamics of growth of centralized systems. Figure 1 presents the conditions for the competition between centralized and decentralized energy supply depending on the use of centralized electricity supply and natural gas as a fuel.

Figure 1. Conditions for technology competition.
3. Challenges of the new time

In the current situation, on the one hand, reliability, quality, accessibility to energy supply decline, on the other hand, the requirements for quality and reliability of energy supply increase, consumers’ activity rises, which manifests itself in the choice of a type of energy supply, a type of energy carrier, demand-side management, etc. To cope with this contradiction we need a new energy sector to be built using the other principles that correspond to the concept of a post-industrial society with a high quality of living conditions, intelligent automation of all spheres of activity and innovative economy based on the knowledge and highly developed human assets.

Formation of a new paradigm in the energy sector is facilitated by a great number of internal and external factors, including:

- Development of an accessible market for technologies and equipment, technical and design solutions.
- Formation of high level information support, telecommunication technologies.
- Price differentiation of produced energy (both of one type and various types) and possibility of choosing an energy carrier type to meet various needs.
- Infrastructural commonality that manifests itself first of all in the information and telecommunication support of the energy systems, despite their separate existence.
- Commonality of service area and market, delivery of analogous services, use of the same primary energy resources.
- Common main goal that consists in providing the social sphere and economic activity with reliable, quality, safe, environmentally friendly and accessible energy services, and integrates different targets.

Instability in the operation of markets for gas, electricity and heat, and demand side response cause a considerable uncertainty in the operating conditions of the electric power, gas and heat supply systems.

There is an increase in the commissioning of distributed electricity and heat generation based on renewable energy sources. According to the data of Bloomberg New Energy Finance, for example, electric capacity put into service in the world in 2016 made up:

- 116 GW – of conventional energy units;
- 138 GW – of renewable energy sources.

One of the reasons for an increasing share of distributed electricity and heat generation based on renewable energy sources is a decline in the cost of renewable energy sources. For example, the cost of solar panels has decreased by 4 times over the past 5 years [1]. The cost of electricity production by solar power plants is 8 cents/KWh (a two-fold decrease), by wind farms – 5 cents/kWh [1]. According to the forecast of the Ministry of Energy of the Russian Federation until 2030 [2] Russia will put into service about 30 GW of electric capacity based on renewable energy sources. According to the estimates of ESI SB RAS a potential of nonconventional renewable energy sources is above 250 GW [3, 4].

The rise in distributed electricity and heat generation, first of all, on the basis of renewable energy sources, including that belonging to consumers, leads to a dramatic change in the properties of the energy systems and strengthens their interrelations.

The growing number of applied technologies (heating, cooling, ventilation, electricity, security systems, water supply, rolling shutters, electric shutters and window gear systems, modern audio and video equipment, systems for information delivery, fire alarm systems and many others), strengthening interrelations between certain systems, increasing volumes of exchanged information, complication in the control of the systems lead to considerable risks of abnormal situations. Therefore, to overcome these problems the advanced countries started the process of integration and intelligent automation of energy systems.

Interconnection of separate systems of different levels into a single technological complex can ensure the implementation of new functional capabilities, the application of more advanced operation technologies, and the creation of integrated centrally-distributed systems with coordinated control of their operating conditions and active participation of consumers in the process of energy supply.
4. Integration trends in the energy sector

Active globalization in the energy sector requires a revision of the principles used to construct the energy systems, including those at the level of consumers, and to control their operation on the basis of the integration of these systems. The necessity of such a structural-technological transformation is obvious and is conditioned by the processes that occur in the energy sector already now. Those of them to be emphasized are:

- Conventional and modern technologies functionally integrate the systems for electricity and heat/cooling supply to the cities, industrial hubs, and local territories, in particular: cogeneration plants, i.e. combined electricity and heat/cooling production; alternative devices for the use of different energy types, applied by active consumers managing their demand for energy.
- Integration in terms of production and consumption makes it necessary to jointly consider the electrical, heat and gas networks, their interrelated operating conditions, especially emergency ones, and control these conditions.
- The concepts of Smart Grid and Smart Metering, developed in the world are also relevant for Russia’s electricity and heat/cooling supply systems in the cities, industrial centers, and local territories, since they require upgrading, reconstruction and development on the basis of innovative technologies.
- The relevance of the application of distributed energy generation, the formation of an ideology of virtual power plants for the integrated electricity and heat/cooling supply systems is increasing.

The plan of creating and controlling the integrated systems in Russia has only started to emerge, whereas in the other countries it has already been under implementation. The countries: Germany, Denmark, the Netherlands, Finland, France, Sweden [5–12] in Europe and China [13] in Asia have determined the experimental areas (some cities) where pilot projects on the intelligent integrated energy systems are implemented [5, 6, 14]. The major large-scale project is the pilot project “Integrated efficient large-scale municipal systems” aimed at establishing the intelligent electricity, heat and cooling supply systems. The project is implemented in five largest European cities: Gothenburg, Geneva, Cologne, London and Rotterdam [6, 15, 16]. Several tens of European cities have joined this project in the last years [17]. Russia is just in the stage of discussing the issues related to the construction of smart systems, and providing the consumer with quality energy supply (comfort), while the advanced consumers put forward new requirements to be met with the help of the intelligent integrated systems.

The processes of integrating the systems into a metasystem lead to an increase in the level of its integrity and organization, which raises the number and intensity of interrelations and interactions between certain components [18].

The majority of recent studies in the area of the integrated energy system establishment and operation have been devoted to the creation of virtual power plants (VPP), energy hubs, multi-energy systems and intelligent energy systems.

In the publications, the VPP concept is treated as an instrument capable of providing an effective system integration on the basis of distributed generation with the use of energy storage plants. Furthermore, the consumers in such systems can control their load as a function of energy system operating conditions (energy supplier). In [19, 20] the optimization problem of VPP operating conditions is solved by using the linear programming methods on the example of individual systems. Besides, in [21, 22] the authors describe the VPP control system without some technical constraints in the system. A more complete model is presented in [23, 24]. It is devoted to the optimization problem of VPP operation with the day-ahead prediction of electric and thermal loads. The modeled VPP structure comprises sets of small-scale energy sources, consumers with self-generation, energy storage plants and cogeneration plants, with natural gas being a traditional fuel in these systems. The maximum financial gains for energy sellers are taken in the work as an objective function. The problem is solved by the methods of mixed integer linear programming.
In [23–25] the authors consider the main problems of integration of renewable energy sources into traditional energy systems with the prospect of transition to multi-energy systems (electric energy jointly with chemical production). The authors analyzed dynamic characteristics of a hybrid energy system to determine a range of power fluctuations of renewable sources as well as perspective variants of hybrid energy systems to estimate possible decrease of investment costs in construction of such systems.

The concept of energy hubs is developed in [26, 27]. These studies present mathematical models intended to determine optimal capacities for production and consumption of energy resources. Different forms of energy carriers, types of energy converters are considered and the complexity of the problem of energy hub control over time is underlined there.

In [28] the authors model an energy system with an energy storage unit as a multi-agent system (energy hubs). The research considers consumers connected to the centralized energy supply system with heat pumps. The model determines an individual or centralized consumer mode of operation as a function of the electricity tariffs.

Many foreign studies discuss and develop the problem of creating intelligent EPS – Smart Grids, whose review is presented in [29]. Recently this ideology has been applied to gas and heat supply systems.

Integration of energy systems is most developed at the level of cogeneration plants. It is a connecting link between the electricity, heat and gas supply systems. The advent of new technologies and economic mechanisms of their alternative utilization by consumers encouraged integration extension to this sphere, and introduction of the energy hub concept became generalization of these opportunities [30].

Such integration of energy supply systems at the levels of production and consumption of energy carriers caused the necessity to jointly consider electric, heat and gas distribution networks for solving the common problems of flow distribution optimization in such integrated energy supply systems [26, 27, 31–34], optimization of daily operating conditions at their dispatching control [35–37], analysis of energy supply reliability, when the integrated systems are used [38–40], etc.

Intensification of studies within the Smart Grid concept gives rise to certain studies on the analysis of integrated energy supply systems in terms of active participation of consumers in management of own energy supply, utilization of energy storage units, up-to-date information and telecommunication technologies, etc. [30, 41–46]. The authors also present specific applications of this concept to different integrated energy supply systems: electricity and heat; electricity, water and gas; electricity and gas; electricity, heat and cooling; and so forth.

5. Methodological principles of constructing the intelligent integrated energy systems

The key principles of constructing the intelligent integrated energy system are aimed at creating self-organizing interrelated energy systems with several types of energy carriers to provide high quality of energy services, and their considerable expansion according to the increased and permanently transformed requirements of consumers (level of comfort, technological innovations in the production and domestic spheres, enhancement of diversity and power of energy loads, drastic changes in their properties, etc.). Implementation of the principles supposes organization of a coordinated process of expansion and operation of the systems, and solving technological, organization, financial and legal tasks. This will concern only technical and technological aspects of the integration problem of the energy systems. The other aspects are also important but they should be considered separately.

The above discussed systems (for electricity, heat/cooling, and gas supply) are integrated at the levels of production (generation sources), transportation (electrical, heat, gas and other networks) and consumption. The integration of functionally different systems (process, telecommunication, information, cybernetic (intelligent) and others (Figure 2)) into the single metasystem makes a synergetic effect of providing reliability, security, cost-effectiveness, and environmental friendliness of the energy supply.
The intelligent integrated systems should be established according to the following important principles:

- Transition from several monosystems to a single metasystem when solving the tasks of control of their expansion and operation.
- Synergism reflecting a complex interaction between individual systems, which is characterized by the fact that their joint impact on the result considerably exceeds the benefit of each system and surpasses the result of their simple summation.
- Emergence, which implies that the metasystem takes on new properties, which were not characteristic of its components, for example synergy, multiplicability.
- Mutual redundancy, i.e. participation in supplying loads by various types of systems which do not exist under their separate operation.
- Transition from a vertically-subordinate control to a multiagent control (from vertical to horizontal) when each system and its components have an agent acting on their request, which receives an external input, determines its reaction to this input and responds. Decisions are made and implemented by independent centers.
- Integration of control of the operating conditions of the intelligent integrated energy system owing to the network (distributed) coordination of monitoring and control facilities.
- New automation devices based on artificial intelligence, as well as modern information and telecommunication technologies.
- Available common strategy for the implementation of current and prospective decisions.
- High degree of self-organization when without a purposeful external impact (aimed at creating or changing the system structure) the spatial, time, information or functional structure of the system is formed.
- Distribution of responsibility for security of vital activity among all components of the metasystem.

6. Concept of intelligent integrated energy systems

Intelligent integrated energy systems have a multi-dimensional structure of functional characteristics and expansion properties. They combine a great number of components, intelligence, efficiency, reliability, controllability, flexible use of technologies for energy conversion, transportation storage, and active consumer [29]. Conceptually, the integration is carried out in three aspects:

- A system aspect which represents the integration of systems by their type (electricity, heat/cooling and gas supply systems);
- A scale aspect which reflects the size of the systems with their differentiation into super-, mini- and microsystems;
A functional aspect which determines the functions of the system (its purpose), including energy (technological); communication, control and decision making.

In terms of the system aspect, the intelligent integrated energy system is represented by the key infrastructural energy systems that can be highly integrated with respect to the functional tasks, mutual redundancy, technological interrelations at various hierarchical levels, etc.

In terms of the scale aspect, we distinguish the following interrelated systems:

- **super-systems**, i.e. traditional centralized energy supply systems that consist of large-scale electricity and heat sources, gas fields, underground gas storages, electrical, gas supply and heat supply networks;
- **mini-systems**, i.e. decentralized (distributed) systems including mini electricity and heat sources (including those nonconventional and renewable), which are connected to the distribution electrical, thermal and gas networks, and these networks themselves;
- **micro-systems**, i.e. individual systems with nonconventional and renewable electricity and heat sources as well as house electrical, heat and gas networks.

Functional aspects of the intelligent integrated energy system include the following constituent functions:

- the energy functions that represent production, transportation, distribution and consumption of electricity, heat/cooling, gas at all levels and scales;
- the functions of communication and control that represent measurement, processing, transfer, exchange and visualization of information, control of operating conditions and expansion of the metasystem;
- the decision-making functions, i.e. the metasystem intelligence which includes models and methods for planning the expansion of the integrated energy systems as well as settings for their control.

All the functional properties of the intelligent integrated energy system have strong interrelations with one another in terms of input and output state variables, structure of forecasts both at the level of operation and at the level of expansion. They form an absolutely new technological architecture which defines the organization of the metasystem implementing the design solutions of its components, their interactions with one another and with the external environment, as well as the principles of evolutionary development of such a multi-component structure.

### 7. Technological architecture of integrated systems

Integration into a single information-technological platform of all functional technologies is conditioned by the necessity to transition to new principles for the construction of both individual systems and their integrated structures. The design of the integrated energy supply systems changes greatly as it switches from a traditional hierarchical concept to a preferable horizontal network construction. This principle should be implemented both in the metasystem (at the physical level) and in the system of its control (at the logical and information levels). The intelligent integrated energy system is formed on the basis of a new architecture of the metasystem (Figure 3), which provides it with new properties and new capabilities.

![Architecture of the intelligent integrated energy system](image)

**Figure 3.** A technological structure of the intelligent integrated energy system.
The formed rigid technological structure “generation – networks – consumer” transforms into its more flexible form, in which each node of the network is an active component (both a consumer and a supplier). Such an intelligent integrated energy system becomes a self-tuning system, and depending on the external and internal inputs it can automatically reconfigure itself, which will enable it to fit in the changed conditions. The configuration of the system (connection or disconnection of certain components, a change in the connections between them or a pattern of their subordination) is changed by switching the technological communications and generating control actions to the control devices with their subsequent functional performance. By exchanging messages with one another the consumer nodes determine themselves through their agents the state of the network, generate coordinated decisions on its reconfiguration and implement these decisions.

These changes can be provided by creating a mesh architecture of the intelligent integrated energy system, which forms a distributed (mesh) network whose nodes independently generate and determine the way of energy supply. Each of the nodes in such a system is connected to one or several nodes of the network. Presence of redundant ties in the distributed network guarantees energy supply along a set of dynamically built alternative ways, which enables the system to operate even in the conditions when most of its nodes fail. This ensures resilience and adaptation of the system to any external and internal disturbances. Consumers here are protected not only from single failures of components but from simultaneous failures of several components in the system.

An integral part of such a system is its “intelligence” which rests on the agent-oriented paradigm where each consumer getting information about all the other participants of the energy supply process through its intelligent agents assesses its role in this process and forms its behavior. This excludes the necessity for permanent control and management, and facilitates a rapid response to a change in the situation. Since the coordinating center cannot know all the aspects of the technological process that takes place at consumer’s (first of all a complex production process), the intelligent automation of the energy systems should start with consumers. Only consumer having all the necessary technological knowledge can optimize their process of energy consumption. In the other countries, the process of intelligent automation started with consumers, which was related to the emergence of renewable energy sources with stochastic operating conditions.

The technology of the intelligent metasystem operation also becomes new since the one-direction motion of energy flows from source to consumer within the system turns into a multi-directional (symmetric), distributed among a set of nodes with varying flows from the system (from source to consumer) and to the system (from consumer - energy generator). The infrastructure of the intelligent integrated energy system should provide supply, transportation and consumption of different energy flows (energy carriers).

Due to a complex structure, possible conflicts and competition in the intelligent integrated energy system, the classical hierarchical scheme of design and control of individual systems cannot accomplish the common goals. The new system structure should combine certain independence of a set of decision-making centers and their coordination to ensure stable energy supply to consumers. It should be built according to the principle of subsidiarity and self-regulation according to which the control action is formed within the system under control but not from outside. This principle can be fulfilled by a multi-agent approach that supposes the organization of interaction among the agents, which results in the internal control actions. In this case the systems have their own control, goals, tasks, and operate independently by coordinating themselves with the other systems to accomplish the common goals. A natural addition to this can be a network-centric control which is in many ways similar to a subsidiary one and suggests that the centralized bodies transfer most of their powers and rights to independently make decisions to peripheral centers that have highly adaptive properties.

It is necessary to organize a network model of relations, which is based on the principle of complementarity when the actions done by one participant to solve some problems simultaneously foster solving certain problems of other participants. The network organization is a system of a higher order with respect to the current hierarchical structure of the Russian energy sector. It implies weakening of
vertical ties, debureaucratization and development of horizontal ties. Network organizational processes are highly adaptive, diverse, and can be embedded into any control systems.

The systems are coordinated by a single center through logically constructed horizontal ties based on the principles, similar to those presented in [47]. Horizontal control dominates the vertical one with only those powers delegated to the upper level which cannot be fulfilled at the horizontal level.

The multi-dimensional structure of the intelligent integrated energy system, high level of integration and self-organization, intelligence, comprehensive use of technologies for energy conversion, transportation and storage, and active consumer considerably expand the functional capabilities of the formed metasystem and provide it with new properties. The most significant properties of the intelligent integrated energy system to be highlighted are aimed at quality and timely satisfaction of consumer requirements:

- Flexibility, i.e. adaption to any external disturbances and, which is extremely important, to the current requirements of consumers.
- Intelligence, i.e. capability of the system to timely and adequately respond to the requirements of consumers.
- Integration, i.e. fitting into the municipal infrastructure.
- Efficiency, i.e. correspondence to the requirements of the energy efficiency.
- Competitiveness, i.e. correspondence to the economic efficiency and access of consumers to energy resources.
- Reliability, i.e. meeting a growing demand for energy, resistance to emergency situations.
- Mutual complementarity when solving the common task.
- Unity of principles of organization, operation and independence when performing their functions.

8. Results and Discussion

The process of transition to the intelligent integrated energy system represents a quite complex multi-aspect problem including technological, organizational and other transformations of the systems as well as changes in their methodological support. At the same time, whereas in terms of technologies many things are prepared, the methodological developments are at the level of problem statements. The presented conceptual principles of the intelligent integrated energy systems make it possible to consider the problem from different angles and formulate the goals of the studies more comprehensively.

In general, the tasks that require scientific and practical research can be presented as follows:

- Develop technological principles of constructing the integrated energy supply systems in combination with intelligent tools and systems to control them.
- Form technical solutions on flow sheets of energy sources and transportation complexes of energy supply systems.
- Develop methodological and technological frameworks for the creation of intelligent systems to control energy supply to the cities and industrial centers.
- Devise methods for monitoring the state of equipment and its operation in energy supply systems.
- Originate models and methods for an analysis and calculation of electricity, heat/cooling and gas supply systems.
- Develop the next generation methods and software to calculate and optimize the integrated energy supply systems and their components.
- Develop universal information-computational technologies for computer modeling, calculation and optimization of intelligent integrated energy systems.
- Prepare practical recommendations and proposals on the creation of intelligent integrated systems for electricity, heat and cooling supply to consumers.
This is just a short general list of tasks to be solved in the process of integration and intelligent automation of energy supply systems. Further, the tasks can be differentiated according to different levels of the considered systems.

The level of system. At the level of systems for their certain types there are methodological and computational tools for calculation and optimization. These tools enable us to obtain separate solutions and then integrate them within a single intelligent integrated energy system. However, first of all, they are oriented to super-systems and, to some extent, to mini-systems. Secondly, they require involvement of artificial intelligence that provides learning, formation and implementation of control actions. Thirdly, they should take into consideration a multi-directional motion of energy carrier, which is conditioned by distributed generation involved in the energy supply. The level of micro-systems is virtually a new object for research.

The use of intelligent technologies and tools can radically change the properties of energy systems and initiate new problems that will need to be solved.

The level of scale. The problems related to the physical interrelations between energy systems of different levels are sufficiently studied. They are characterized by ordinary conditions and situations, and correspond to a traditional paradigm of designing energy systems. The use of intelligent technologies and devices at all levels of energy systems and the principal change in their properties will require the development of a new methodology, performance of additional studies on adjustment of requirements to interface, and creation of corresponding software and hardware for computational, control and measurement systems.

Modeling of multi-level energy systems of various scales with advanced computers provided can be performed in their initial form. However, the use of aggregated models of adjacent levels is more effective when considering the models of the studied level. This implements a hierarchical approach and corresponds to the physical understanding of the multilevel systems.

The level of functions. In the research into the technological functions of the intelligent integrated energy system it is essential to solve the problems of communication and control. They implement the intelligent information and computer technologies, high-speed and accurate tools for measurements, processing, transfer and visualization of information, as well as the intelligent technologies and methods for control. The information support of respective tasks is provided by appropriate allocation of measurement devices with required redundancy. It is important to know how to place them properly in order to be able to estimate the system state and monitor its operating conditions.

The efficiency of control is achieved not only by the intelligent information technologies and computer models. Of great importance here are modern highly effective physical devices at which the intelligent information technologies and models are implemented. On the whole, these two aspects of control systems are inseparable and should be considered jointly. The development of a methodology and methods for such an integrated control of operating conditions of jointly operating energy systems is the most important objective of the research in the framework of the considered problem.

To develop the necessary decisions it is necessary to solve the tasks related to the adaptation of the existing models and methods to the intelligent integrated energy systems and preparation of new models and methods. These models and methods should take into account all specific features related to the uncertainty of information, a great amount of criteria and differences in the interests of stakeholders.

Solving the above enumerated tasks is accompanied by the problems of modeling the intelligent integrated energy systems as new objects of research with respective new properties and features. They manifest themselves first of all in the following aspects:

- Alignment of a common goal with a great amount of targets by system.
- Intersystem distribution and a great amount of decision-making centers.
- Development and implementation of an optimal strategy for the entire system and for individual systems.
- Settlement of intersystem conflicts.
- Alignment of interests of consumers and suppliers
- Coordination of a set of control centers.
• Coordination of hierarchical levels in each system and horizontal ties between individual systems.

Construction of a new methodology for decision making to plan the expansion and control of the operation of the intelligent integrated energy systems, formation of a corresponding system of models and methods are essential objectives of further studies.

9. Conclusion
Russia’s energy sector is at the stage of a shift to a new paradigm of development. New challenges of the time pose new problems which cannot be solved on the basis of the structural-technological framework existing in the sector. It is necessary to transition to new structures in the form of intelligent integrated energy systems. These structures suggest the integration of self-organizing systems for electricity, heat, cooling and gas supply which are built according to the multi-agent principle on an intelligent basis. Ideology, creation and control of such systems are important tasks that require intensive studies.

According to the experts, potential enhancement in the energy efficiency for electricity supply systems is estimated at about 10%, and for the heat supply systems – at about 15%. This can be achieved by reducing fuel consumption and transmission losses through the application of modern energy efficient equipment and technologies. Based on theoretical calculations [48, 49], the total benefit to be gained from the transition to the intelligent integrated energy systems can reach 20%. On the whole, the coordinated process of energy supply system expansion and operation as well as consideration of different types of energy systems as a single integrated energy supply system will increase their security, reliability, economic viability and environmental friendliness.

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References
[1] IRENA 2015 Renewable Power Generation Costs in 2014, https://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf (Accessed 15 August 2018)
[2] Minenergo of Russia 2009 Energy strategy of Russia until 2030, https://minenergo.gov.ru/node/1026. (Accessed 15 August 2018) [in Russian]
[3] Stennikov V A 2016 Distributed energy generation: mission, situation, opportunities Energiya: ekonomika, tekhnika, ekologiya 1 2–10 [in Russian]
[4] Stennikov V A 2016 Distributed energy generation: mission, situation, opportunities Energiya: ekonomika, tekhnika, ekologiya 2 2–8 [in Russian]
[5] International Energy Agency 2014 Linking Heat and Electricity Systems. Co-generation and District Heating and Cooling Solutions for a Clean Energy Future, http://www.iea.org/publications/freepublications/publication/LinkingHeatandElectricitySystems.pdf (Accessed 15 August 2018)
[6] Schmidt R-R, Fevrier N and DUMAS P 2013 Key to Innovation Integrated Solution. Smart Thermal Grids, https://eu-smartcities.eu/sites/all/files/Smart%20Thermal%20Grids%20-%20Smart%20Cities%20Stakeholder%20Platform.pdf (Accessed 15 August 2018)
[7] Stadtwerke Crailsheim 2014 Projekt Solaranlage, http://www.stw-crailsheim.de/stadtwerke-crailsheim/top-themen/projekt-solaranlage.html (Accessed 15 August 2018)
[8] DBDH 2017 Danish Board of District Heating, http://dbdh.dk (Accessed 15 August 2018)
[9] Danish Energy Agency 2017 Energistyrelsen, http://www.ens.dk/ (Accessed 15 August 2018)
[10] TU Delft 2017 Delft University of Technology. TU Delft Energy Monitor, http://www.energymonitor.tudelft.nl/ (Accessed 15 August 2018)
[11] Roijen E, Op’t Veld P and Demollin-Schneiders E 2007 The Minewaterproject Heerlen - low exergy heating and cooling in practice, http://www.chri.nl/upload/art.%20minewaterproject.pdf (Accessed 15 August 2018)

[12] Verhoeven R, Willems E, Harcuët-Menou V, De Boever E, Hiddes L, Op’t Veld P and Demollin E 2014 Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling Energy Procedia 46 58–67

[13] Ran X, Zhou R, Yang Y and Lin L 2012 The multi-objective optimization dispatch of combined cold heat and power based on the principle of equal emission IEEE PES 1–5.

[14] Celsius Consortium 2016 Demonstrators, http://celsiuscity.eu/demonstrator/ (Accessed 15 August 2018)

[15] EIP-SCC 2017 Market Place of the European Innovation Partnership on Smart Cities and Communities, http://eu-smartcities.eu (Accessed 15 August 2018)

[16] Celsius Consortium 2013 CELSIUS (smart district heating and cooling solutions), https://eu-smartcities.eu/content/celsius-smart-district-heating-and-cooling-solutions (Accessed 15 August 2018)

[17] Celsius Consortium 2016 CELSIUS member cities, http://celsiuscity.eu/new-celsius-cities/ (Accessed 15 August 2018)

[18] Voropai N I and Stennikov V A 2012 Innovative directions in the expansion and control of operation of urban intelligent integrated energy systems Proc. III Int. Conf. “Electric power industry through the eyes of the youth” (Yekaterinburg: Ural Federal University named after the First President of Russia B. N. Yeltsin) pp 38–45 [in Russian]

[19] Zdrič M, Pandžić H and Kuzle I 2011 The mixed-integer linear optimization model of virtual power plant operation Proc. of 8th Int. Conf. on the European Energy Market (EEM) (Zagreb) pp 467–71

[20] Salmani M A, Tafreshi S M M and Salmani H 2009 Operational optimization for a virtual power plant Proc. of IEEE PES/IAS Conf. on Sustainable Alternative Energy (SAE) (Valencia) pp 1–6

[21] Caldon R, Partia A R and Turri R 2004 Optimisation algorithm for a virtual power plant operation Proc. of 39th Int. Universities Power Engineering Conf. (UPEC 2004) (Bristol) vol 2 pp 1058–62

[22] Giuntoli M and Poli D 2013 IEEE Transactions on Smart Grid 4 942–955

[23] Garcia H E, Mohanty A, Lin W C and Cherry R S 2013 Energy 52 1–16

[24] Garcia H E, Mohanty A, Lin W C and Cherry R S 2013 Energy 52 17–26

[25] Carvalho M, Serra L M and Lozano M A 2011 Energy 36 3779–90

[26] Arnold M and Andersson G 2008 Decomposed electricity and natural gas optimal power flow Proc. of 16th PSCC (Glasgow) pp 1–7

[27] Geidl M and Andersson G 2007 IEEE Transactions on Power Systems 22 145–55

[28] Ahcin P and Sicic M 2010 Simulating demand response and energy storage in energy distribution systems Proc. of Int. Conf. on Power System Technology (Hangzhou) pp 1–7

[29] Voropai N I and Stennikov V A 2014 Intelligent integrated energy systems Izvestiya Rossiiskoi akademii nauk. Energetika 1 64–73 [in Russian]

[30] Mancarella P, Gan C K and Srbrac G 2011 Fractal models for electro-thermal network studies Proc. of 17th Power System Computation Conf. (Stockholm) pp 1–7

[31] Lund H and Münster E 2006 Energy Policy 34 1152–60

[32] Li Z, Huo Z and Yin H 2011 Optimization and Analysis of Operation Strategies for Combined Cooling, Heating and Power System Proc of 2011 Asia-Pacific Power and Energy Engineering Conf (Wuhan) pp 1–4

[33] Rees M T, Wu J, Awad B, Ekanayake J and Jenkins N 2011 A modular approach to integrated energy distribution system analysis Proc. of 17th Power System Computation Conf. (Stockholm) pp 1–7
[34] Almassalkhi M and Hiskens I 2011 Optimization framework for the analysis of large-scale networks of energy hubs Proc. of 17th Power System Computation Conf. (Stockholm) pp 1–7

[35] Vasebi A, Fesanghary M and Bathae M T 2007 Electrical Power and Energy Systems 29 713–19

[36] Chaudry M, Jenkins N and Strbac G 2008 Electric Power System Research 78 1265–79

[37] Chao-Ling C and Shi S L 2012 Improved particle swarm optimization for economic dispatch of combined heat and power systems Lecture Notes in Information Technology 13 133–9

[38] Koeppel G and Andersson G 2006 The influence of combined power, gas and thermal networks on the reliability of supply Proc. of 6th World Energy System Conf. (Torino) pp 646–51

[39] Haghiifam M R and Manbachi M 2011 Electrical Power and Energy Systems 33 385–393

[40] Chaudry M, Wu J and Jenkins N 2013 Energy Policy 62 473–83

[41] Le Blond S, Levis T and Sooriyabandara M 2011 Towards an integrated approach to building energy efficiency: Drivers and enablers Proc. of IEEE PES Innovative Smart Grid Technologies Europe (Manchester) pp 1–8

[42] Jiang Z, Li F, Qiao W, Sun H, Wan H, Wang J, Xi, Y, Xu Z and Zhang P 2009 A vision of Smart Transmission Grid Proc. of IEEE PES General Meeting (Calgary) pp 1–10

[43] Xue Y 2008 Some viewpoints and experiences on Wide Area Measurement Systems and Wide Area Control Systems Proc. of IEEE PES General Meeting (Pittsburgh) pp 1–6

[44] Piovano M, Carretero T, Jane R, Wankelmuth A, Lofti A, Lorentz C and Landwehr K 2012 Smart gas meters and middleware for energy efficiency embedded Proc. of XXV World Gas Conf. (Kuala Lumpur) pp 2066–88

[45] Gervigni G, Di Castelmovo M, Cagnobi S, Sica M and Franceseo V 2012 The policies for the Large-scale deployment of smart gas meters in some European countries and draw policy implications, in particular for Italy Proc. of XXV World Gas Conf. (Kuala Lumpur) pp 3202–11

[46] Yuasa K and Fujii Y 2012 Developing advanced metering (the ubiquitous metering system) Proc. of XXV World Gas Conf. (Kuala Lumpur) pp 1887–901

[47] Bushuev V V, Kamenev A S and Kobets B B 2012 Energy as an infrastructural “system of systems” Energeticheskaya politika 5 3–15 [in Russian]

[48] Voropai N, Stennikov V, Senderov S, Barakhtenko E, Voitov O and Ustinov A 2017 Modeling of Integrated Energy Supply Systems: Main Principles, Model, and Applications J. of Energy Engineering 143

[49] Voropai N, Stennikov V, Senderov S, Barakhtenko E, Voitov O, Kovernikova L, Oshchepkova T and Semenova L 2015 Integrated Infrastructure Energy Systems – Challenges for Russia Proc. of Joint 6th Conf. of Int. Institute for Critical Infrastructures and 6th Int. Conf. on Liberalization and Modernization of Power Systems (Saint Petersburg) pp 115–21