Innovative-Technological and Structural-Organizational Transformations of Electric Power Systems: Changes in the Main Properties, and Research Lines

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***Abstract* — This paper discusses one of the most significant areas of systems research in energy that covers the study of the main properties of large-scale energy systems. An emphasis is on the electric power systems, which are currently undergoing organizational-structural and innovative-technological transformations. The evolution of classifications and structures of the main properties of energy systems is analyzed, and interpretation of these properties and the extent to which they manifest themselves in electric power systems in the period before the transformation processes and during the transformation period are given. Findings suggest that the properties had a rather capacious interpretation, which enabled the description of significantly different energy systems, including traditional vertically integrated and emerging new centrally distributed ones. For this reason, there was no need to introduce any new properties, although they can appear in the future. This study examines various transformation processes in the electric power industry and analyzes their influence on the levels of manifestation of properties. The transformation of energy systems and their features requires that the methodology and research tools be refined. Specific directions for such a refinement are proposed in this paper.**

***Index Terms*: Systems research, vertically integrated and centrally distributed power systems, classifications, properties, transformation, methodology.**

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I. Introduction

The research into the properties of large-scale energy systems (LESs), including electric power systems (EPSs), has a long and rich history. In [1], two main goals of studying the LES properties are formulated: 1) understanding the general LES control principles, provisions, and rules arising from individual properties or some combination of theirs; 2) considering the LES properties in mathematical modeling of energy systems to determine an appropriate type of models, specific algorithms and relationships. This paper addresses rather general properties inherent in various energy systems. There are two groups of properties [1]. The properties of one group are inherent in the systems regardless of people's will (for example, the property of incomplete information), the other group is necessary for the system to effectively perform its functions (for example, cost-effectiveness) and LES should be endowed with them in the process of creation. Both groups of properties are objective: the first is objectively inherent in LESs, the second is objectively necessary for LES.

Electric power systems are among the most significant LESs, which integrate other energy systems through their external fuel connections. The structural-organizational and innovative-technological transformations that are taking place in modern EPSs throughout the world considerably alter the systems themselves and affect their properties, and not always in a positive way, which requires research of such an impact, and the development and subsequent implementation of appropriate organizational, economic, and technical measures in EPSs and their control systems.

As will be seen below, the authors of [1–3] introduced a very comprehensive definition of properties, which expands their interpretation and allows using the same properties and their combinations to describe significantly different structures of energy systems, including, for example, traditional vertically integrated and new centrally distributed ones. Thus, it becomes possible to characterize the properties of current and future energy systems without

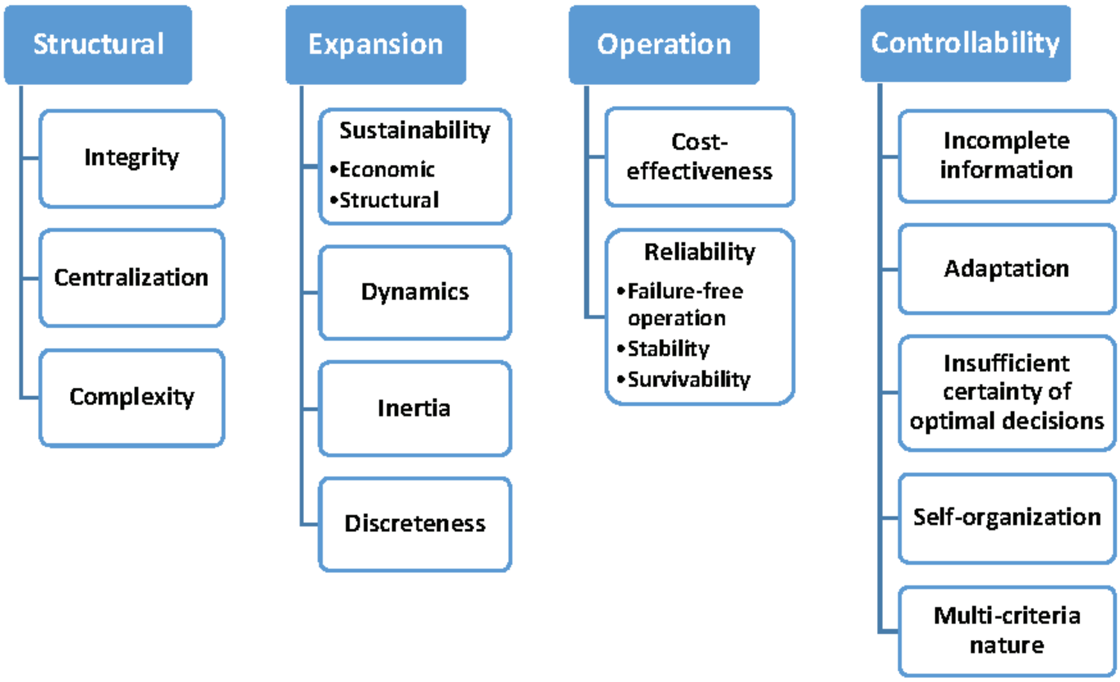


Fig.1. The classification of LES properties [2].

the obligatory updating of the composition of these properties, although it should not be excluded from the consideration.

This work does not claim to comprehensively cover the specified issues and, in this stage, does not aim to formulate an updated set of the energy system properties with their possible classification, adequate to the current conditions. We analyze the main LES properties given in the previously created classifications [1–3], their interpretation in terms of traditional EPSs, changes in these properties in the context of EPS transformation, and the establishment of centrally-distributed cyber-physical energy systems (CD CP EPSs). This paper also presents the lines for further research to provide the basis for creating such systems, given their transformed properties.

II. Evolution of the classification and composition of the main properties of large energy systems

A. The first classification of the main LES properties

The composition of the main properties of LES is a controversial issue, and different authors classify them differently. Academician L.A. Melentiev proposed grouping the properties by highlighting specific individual properties in each group. According to this approach, a two-, three-level hierarchy of properties was built. Originally, he proposed 4 groups of properties (Fig. 1) [2].

Structural properties reveal the essence of hierarchical systems in three closely interrelated properties: a) the integrity of individual systems/subsystems; b) centralization of control; c) the complexity of the hierarchical structure. LESs always have a hierarchical structure, i.e., include interconnected hierarchical systems united by vertical and horizontal links. There is an optimum combination of integrity and centralization. In a planned economy (for which the specified classification of properties was developed), the level of integrity of individual systems is lower, whereas the centralization of their hierarchical structure is higher.

The group of expansion properties characterizes the growth/expansion of any progressive system. Stability is understood as an ability of a system in motion to maintain its structure and properties. In terms of LES, we can consider the properties of *economic and structural stability*. Economic stability is understood as a system's feature under which its significant structural differences are characterized by considerably smaller changes in the costs of its expansion. Structural stability is the ability of a developing system to maintain its structure as a whole. The property of *dynamics* is interpreted as the influence of the current state on the future one and vice versa. *Inertia* is the property of a system to resist external and internal impacts aimed at changing its motion. The inertia of a system depends on the inertia of its components, the inertia of its controls, and the level of system stability. The high capital intensity of LESs, their links with mechanical engineering, metallurgy, transport, the construction industry, significant time spent on the construction of power facilities and related infrastructure cause their great inertia, which manifests itself in the impossibility of dramatically increasing production volumes in a short time, and changing the structure of capacities and fuel and energy balance as a whole [4]. In [1–4], the inertia feature was considered only in the economic sense, for this reason, only such an interpretation is given here. Further, inertia, as well as some other properties, will be considered from a technical *perspective. Discreteness* reflects the objective tendency towards the concentration of generating and transmission capacities in the power industry (the growth of the unit capacity of power units and power plants in general, the transition to higher voltage levels of power transmission lines with an increase in their transfer capability) and, is thus closely related to the inertia.

The operation properties include cost-effectiveness and reliability. *Cost-effectiveness* is the property of a system to carry out its functions with minimum costs under given restrictions, including environmental ones. Reliability is the property of the system and its components to perform the specified functions while maintaining the preset indices. Reliability includes such properties as *failure-free operation*, i.e., continuous operability during a given time, *stability*, i.e., the ability to restore the initial state of equilibrium during systematic short-term disturbances, and survivability, i.e., the ability to restore equilibrium during large disturbances.

The group of controllability properties characterizes the specific objective properties of LESs as objects of control and study. These include the property of *incompleteness/ambiguity of information* about the system. According to this characteristic, along with part of the information that can be considered as deterministic, a significant part of the information is probabilistic and, hence, indefinite. The property of *adaptat*ion is associated with the new components appearing in the system for its development under changing external conditions and with the time required for restructuring the system. The property of *insufficient certainty of optimal decisions* about the LES operation and expansion characterizes the impossibility of finding unambiguous optimal decisions on the control of the system. This property is in close interaction with the hierarchical structure of LES, the properties of *stability, inertia*, and others. The property of *self-organization* is the LES's ability to choose and implement the decision to preserve the nature of interaction with the "outside world" under changing conditions. The *multi-criteria nature* is understood as the property of LES to function optimally and develop under the influence of criteria and constraints that differ at different hierarchical levels. The main criterion is usually the economic one, and the rest of the criteria (environmental, social, and political) are either used as additional or set as constraints.

B. The second classification of main properties of LES

In his later monograph, L.A. Melentiev already proposed three groups of basic properties (Fig. 2) [4]. This classification of properties was simplified compared to the previous version. The properties of expansion and operation were integrated into one group of the properties of motion. Some properties disappeared, to be more precise, they were expressed through other properties, and, in general, the range of properties significantly shrank. Nevertheless, the two-, three-level hierarchy in the classification of properties was preserved.

As for the group of structural properties, in the new classification, they are combined into one property of *the hierarchical structure centralization*. At the same time, the "negative" relationship between the integrity and centralization of systems remains in the sense that the higher the integrity, the lower the level of centralization, and vice versa. Additionally, the duality of the property of the hierarchical structure centralization is specified, i.e., there is centralization in terms of material energy links among sources, transmission and distribution systems, and energy consumers, as well as centralization of bodies within the control system. The integrated group of *motion* properties includes the properties of *dynamics, flexibility, and cost-effectiveness*, with flexibility including the features of *inertia, adaptation, and reliability*. Interpretation of the property of *dynamics* remains the same as in the previous classification. This feature, however, is considered in conjunction with structural and economic *stability*, although the second classification does not contain this property separately (while the first version of the classification highlighted the property of stability). The *flexibility* property was not mentioned in the previous version of the classification at all, but it is closely related to the *adaptation* property, which was included in the first version of the classification. This relation was studied in detail in [5]. The second classification views adaptation as a property that concretizes flexibility. Flexibility is understood as the ability of a system to change its structure at the required speed to ensure normal expansion and operation under possible disturbances. Apart from adaptation, the properties concretizing flexibility include inertia and reliability. These properties were also present in the previous classification. However, inertia belonged to the group of expansion properties, and reliability - to the group of operation properties. In the new classification, however, with the groups of expansion and operation properties integrated into one group of motion, these properties acquired a broader interpretation, covering both the operation and the expansion of LES. The property of cost-effectiveness was previously in the operation group and in the expansion group as economic stability. It now applies equally to the LES operation and expansion. The group of controllability properties was significantly reduced and now includes only the insufficient certainty of optimal decisions and multi-criteria nature.

The new classification of properties does not contain the property of information incompleteness, although it is indirectly present in other properties, such as flexibility and adaptation, insufficient certainty of optimal decisions.

C. The main properties of LES

Later, in [1], it was noted that given the complexity and diversity of the actual relationships between properties as well as the existing ambiguity in the signs by which the

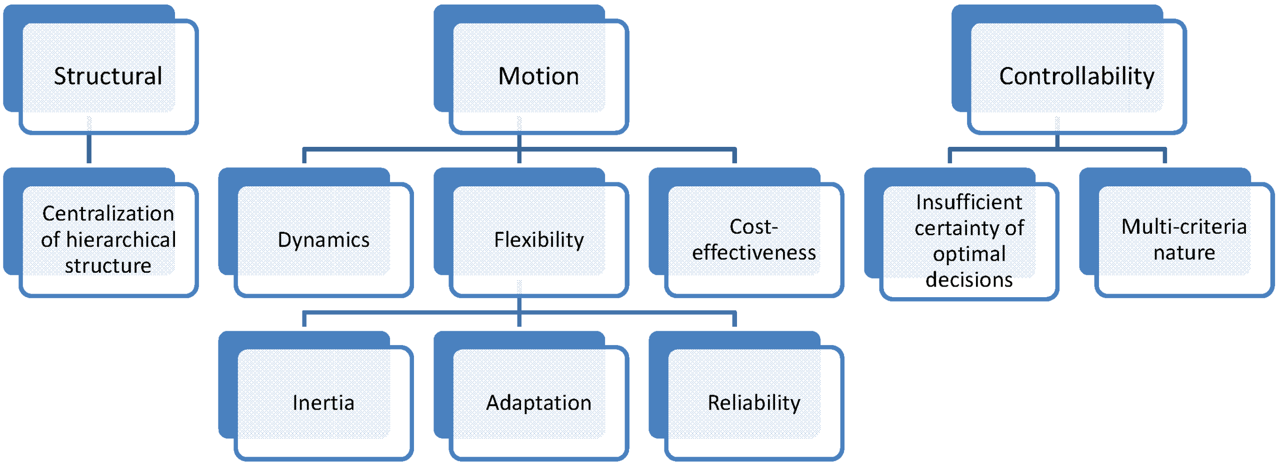


Fig.2. Classification of LES properties [4].

LES properties can be classified, in this stage of research, it is advisable not to group the properties but only establish their composition, i.e., indicate the main properties that are inherent in or needed by LESs. Table 1 shows the main (generalized) central properties characteristic of various LESs. According to [1], the given set of basic properties can be considered "open" and include new properties in the future. The range and the definitions of individual properties should not be regarded as final and generally accepted.

Almost all of the properties presented in Table 1 were indicated in the above classifications of properties by academician L.A. Melentiev. In the terminology of his classifications, the first two properties of *integrity and autonomy* are structural. In this case, however, they have a slightly different interpretation. Whereas earlier, the property of integrity characterized the LES subsystem, i.e., its "separation" from this system, now it characterizes the entire LES. The property of autonomy refers to the LES subsystems and characterizes the presence of their objectives. Together, these two properties describe the structure of LES, its complexity, and its hierarchical structure.

From these two properties considered together, it follows that there should be a rational combination of centralization and decentralization of control, and also coordination of its objectives at all levels of LES hierarchical structure. Thus, even then, it was assumed that LES could be not only a system with strong vertical centralized links but also a system with horizontal links and a "centrally distributed" structure. The property of the *hierarchy of decisions* is formally new, but earlier, it was part of the structural properties and characterized the hierarchy of the control system for the LES operation and *expansion.*

Information incompleteness and cost-effectiveness were previously included in one way or another with similar interpretations.

The *reliability, dynamics, multi-criteria nature, inertia, and adaptability* properties indicated in Table 1 were considered earlier. Their interpretations have changed in some cases.

Reliability was previously considered part of a group of motion properties and covered both the aspect of operation and the aspect of expansion. In our case, this feature is considered in terms of operation alone (as in the second classification by L.A. Melentiev). Reliability includes several single properties, including *failure-free operation, maintainability, survivability, and others*. The interpretation of *the multi-criteria nature*, on the contrary, has been expanded. Multi-criteria nature means not only the presence of several criteria for justifying decisions (economic, environmental, etc.) on the LES expansion and operation but also the presence of their goals for LES subsystems at different levels of the hierarchy. This expands the interpretation of LESs and allows them to be considered not only as centralized vertically integrated systems but also as systems with horizontal links, which has already been noted.

The property of inertia was previously interpreted as the ability to withstand external and internal impacts, whereas Table 1 interprets it as a response to disturbances (including control) with a delay. The manifestation of this feature in the aspect of the expansion, as mentioned earlier, is due to the high capital intensity and long periods of construction of power facilities, and, in addition, the presence of close external ties of the energy sector with other, also inertial, sectors of the country's economy (power plant engineering, geological exploration, etc.). In terms of operation, inertia can be associated with equipment maneuverability, which rises with decreasing inertia. The property of *adaptability* is presented in the "cybernetic" interpretation, which was also used in previous classifications of properties. This interpretation, however, is supplemented by the consideration of adaptation as the ability of LES to adapt its motion to new short-term external and internal disturbances. In this interpretation, *adaptability* is closely related to the property of *flexibility* (which is not presented

Table 1. Main properties of LES [1].

Properties	Definition
The integrity of the system	Unity and the presence of common expansion and operation goals, a central control body
Subsystem autonomy	The relative independence of subsystems the presence of their control bodies, and their expansion and operation goals
Hierarchy of decisions	The objective presence of a set of interrelated decisions to be made in a definite sequence and with the necessary lead time to manage LES expansion and operation, as well as the need to resolve a set of issues to justify these decisions
Incomplete information	The impossibility of obtaining the initial data necessary to unambiguously determine the past, current, or future state of the system
Cost-effectiveness	Performance of its functions with minimum costs of direct and materialized labor
Reliability	Performance of specified functions in a predefined volume under certain operating conditions
Dynamics	Mutual influence of the system's states at different moments (intervals) of time (the present state on the future one, and vice versa)
Multi-criteria nature	The presence of several criteria (goals) for assessing the effectiveness of the system operation and expansion, as well as the discrepancy between the goals (criteria) of subsystem control at different levels of the hierarchy
Inertia	The ability of the system to respond to external and internal (control) actions with a delay
Adaptability	The use of new information to adjust behavior and structure to optimal ones

Table 2. Characteristics of the main properties of EPS during the period of their centralized control.

Property	Characteristic
System integrity	High
Subsystem autonomy	Low
Hierarchy of decisions	Branched decision hierarchy
Incomplete information	Available
Cost-effectiveness	High
Reliability	High
Dynamics	Is present
Multi-criteria nature	Low level of manifestation
Inertia	High level of manifestation in economic and technical terms
Adaptability	Low level of manifestation from the economic perspective, high – from the technical viewpoint.

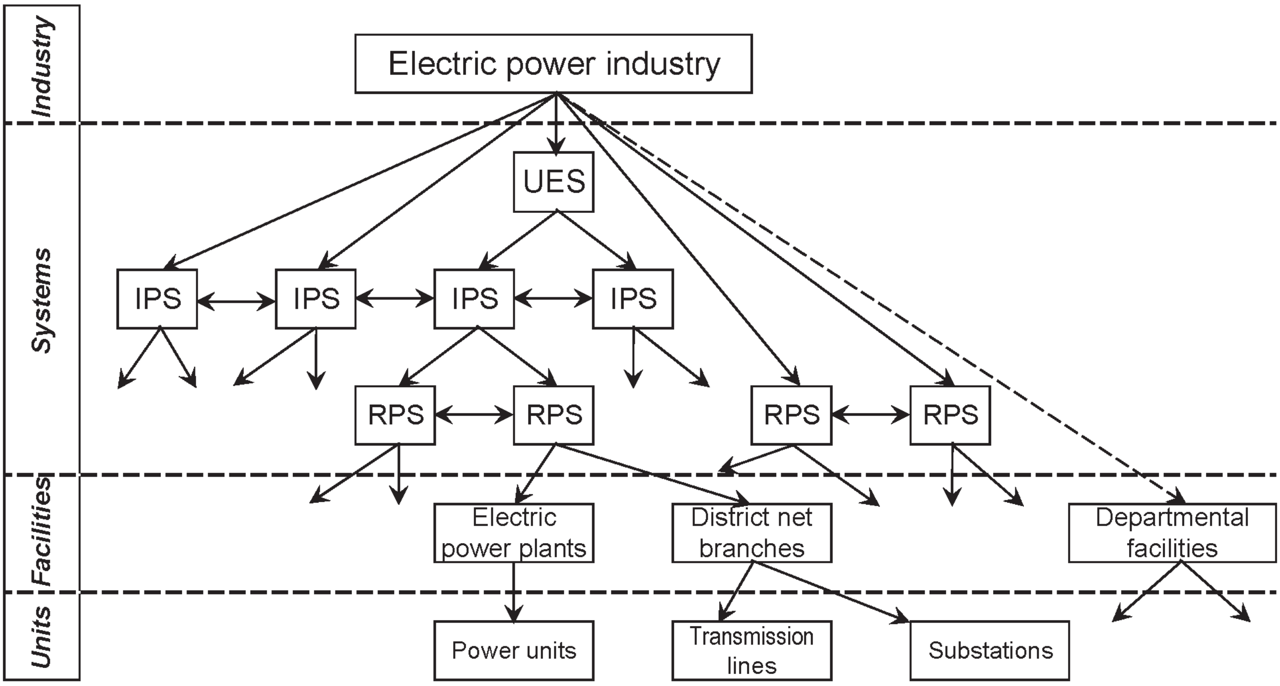


Fig. 3. Territorial and technological hierarchy in the electric power industry of the USSR [7].

explicitly in the specified set of properties). The property of *adaptation* was taken into account when managing the LES expansion and operation. The operational dispatch control of the EPS involved the real-time adjustment of operating conditions and the use of appropriate control and automatic tools. Design and expansion planning of the systems entailed a systematic refinement of plans based on the prevailing conditions.

D. Integrated property of LES reliability

In [6], the of LES authors analyze the property of reliability of power systems, which was previously considered as a main property in the classification by L.A. Melentiev [2]. According to [6], with the development of the electricity industry, more attention must be paid to reliability. This is because the "cost" of accidents is becoming increasingly higher due to the growing unit capacity of generating units and transfer capability of power transmission lines, and accidents can develop in the changing and more complicated operating conditions of energy systems. This property is complex and includes such single features as failure-free operation, maintainability, durability, preservation, stabilability, operational controllability, survivability, and safety [6]. In this case, the range of single properties is wider than that considered earlier and includes, in particular, such new single characteristics as stabilability, i.e., the ability to continuously maintain stability for some time; operation controllability, i.e., the ability to maintain normal operating conditions through control; safety as a property of an object to avoid situations dangerous to people and the environment.

III. The main properties of EPS in a pre-transformation period of centralized control

The characteristics of the main properties of EPS in the set of properties considered in the previous section in the period before the large-scale organizational-technological transformations are summarized in Table 2.

Based on what was stated in the previous section, EPS in the USSR can be characterized as an LES with a high level of system integrity, combined with a low level of autonomy of its subsystems. The territorial and technological hierarchy of the UES of the USSR is shown in Fig. 3 [7].

The high level of system integrity is due to the unity of the operation and expansion goals of the electric power industry and electric power systems of different hierarchical levels, which are aimed at ensuring uninterrupted supply of consumers with electric and thermal energy, and due to the unified (state) ownership of the fixed assets of the electric power industry.

The hierarchy of decisions on the EPS expansion and operation was highly developed and consistently conditioned, and detailed the general decisions made at the upper level into more specific ones at the lower levels of the system's hierarchy. *Uncertainty of information* inevitably existed and affected the general methodology of LES control and, specifically, EPS. The Unified Energy System of the USSR was also distinguished by rather high levels of *cost-effectiveness and reliability*. *Multi-criteria nature* manifested itself in the sense of the possible presence of non-economic criteria (environmental and social) along with economic, as the main one. As for the extended interpretation of multi-criteria nature, i.e., the presence

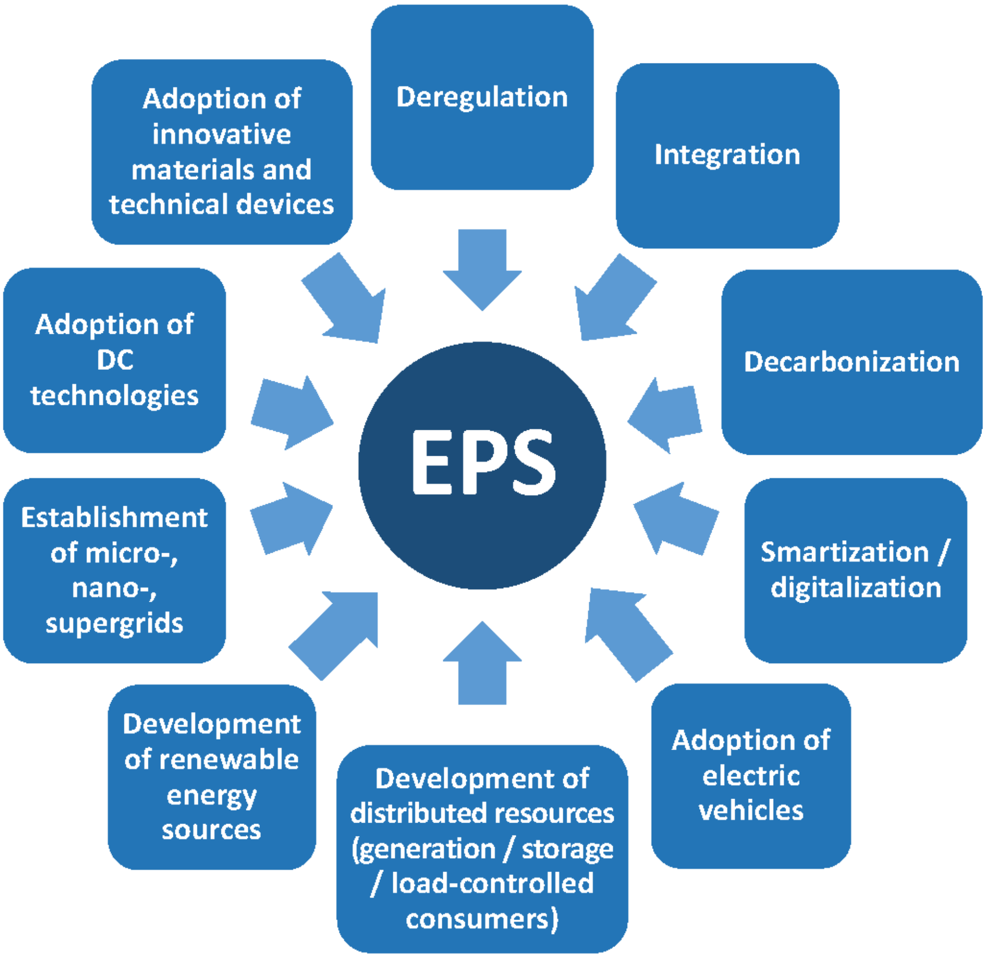


Fig. 4. Trends affecting EPSs and contributing to their transformation.

of the goals for the LES subsystems at different levels of the hierarchy, this property did not manifest itself highly. Subsystems' goals were usually to achieve the overall goal of the entire system. Due to the high concentration of unit production capacities in the energy sector, their high capital intensity, and long construction time, the *system's inertia* was quite high. For these reasons, *the adaptability* of the system (in the economic sense), on the contrary, was rather low. The system *flexibility* associated with adaptability was also low and, although it was not included in the main properties of LES, some authors considered it a significant characteristic of the system. According to [5], adaptation is managed using flexible structures.

Technically, the *inertia* caused by the inertia of the rotating masses of rotors of large synchronous and asynchronous electrical machines was high. However, it is the high inertia in this sense, together with the action of the load-based voltage and frequency regulating effects; the action of the control systems, protection, and emergency control systems; which provided good EPS adaptability to sudden changes in the operating condition and disturbances [8]. In this regard, the flexibility of traditional EPSs (in the technical sense) can be characterized as very high.

Consumers, despite some load regulation programs, incentive tariffs, and others, mainly acted as passive "actors," i.e., as participants having little influence on the processes of production, distribution, and control in the EPS. Therefore, they are not shown in the diagram in Fig. 3.

IV. The main properties of EPS in a pre-transformation period of centralized control

A. Organizational-structural and innovative-technological transformations of EPS

As noted by the former President (2010) of the Institute of Electrical and Electronics Engineers, Power & Energy Society (IEEE PES) V. Raeder, and the IEEE PES President F. Lambert (2020–2021), the electric power industry is transforming, and "everything is changing and changing at the same time" [9].

Different processes/tendencies are taking place in the electric power industry and electric power systems. Some authors identify several most significant processes in current conditions, such as, for example, digitalization, decarbonization, decentralization (3D) [10]. Particular attention is paid to the "energy transition," which implies a transition from the predominant use of gas to the widespread involvement of renewable energy sources in

Table 3. Structure of electrical loads

Superlarge	Large/medium	Small
Megacities, large-scale industrial centers	Large /medium-sized settlements, individual enterprises	Separate small municipal and industrial consumers, including distributed ones
	Total electrical load	
Units/tens of GW	Tens/hundreds MW	From several kW to several MW
	Energy density	
Up to 1000-2000 W/m^2	50-100 W/m^2	15-20 W/m^2

the energy balance [11]. Apart from the above factors, however, there are many processes and trends that also affect electric power systems and radically change their appearance. These processes/trends are shown in Fig. 4.

These processes/trends are extremely diverse, include organizational-structural transformations and innovative-technological modernization of electric power systems, and differ in duration. The electric power integration, which means the formation of interstate power interconnections with the establishment of interstate electrical connections, has more than a century of history [12]. At the same time, this process continues moving to a new level of formation of transcontinental energy interconnections, and the creation of a Global pool in the distant future. It is worth noting that integration also means the interconnection of energy systems with different energy carriers and the creation of the so-called multi-energy systems, including power, heat, cooling, gas, and other technologically connected

subsystems, which allows converting one type of energy into another [13]. This process is still in the initial stage of development.

As for deregulation, which implies the restructuring, privatization, and liberalization of the electric power industry with the transition from regulated vertically integrated structures to market ones, this process began in the 1980s and is currently continuing in the form of re-reform (adjustment of the originally formed structures that did not ensure the efficient operation of the market). Russia started an active phase of reforming the electric power industry at the beginning of the 2000s. Electricity and capacity markets were created, but this process has not finished yet. At the same time, there are significantly different views on the reform implications, including their negative assessment [14]. The deregulation process has radically changed the structural organization and some basic properties of the electric power industry, which will be discussed below.

The decarbonization process is global in nature [15], and the development of renewable energy sources (both distributed and centralized) is a measure to reduce carbon emissions and overcome global warming.

The development trend of distributed energy resources, including energy generation, energy storage, and load-controlled consumers, has become extremely large-scale. It is even opposed to the development of "centralized" energy sources and energy systems, and the question is raised how far this process will go and whether "centralized" energy systems will remain at all [16]. This issue is discussed further.

The development of distributed energy resources is closely related to the establishment of microsystems (mini-, nano-systems) [17] and the adoption of electric vehicles. Lower-level systems (micro-, nano-, mini-) become crucial active EPS components exchanging energy with each other through horizontal connections and supplying its surplus to a "centralized" system. Since many modern electrical loads operate on direct current, it becomes expedient for the power systems of the lower hierarchy level to operate on direct current or to create hybrid AC/DC systems [8].

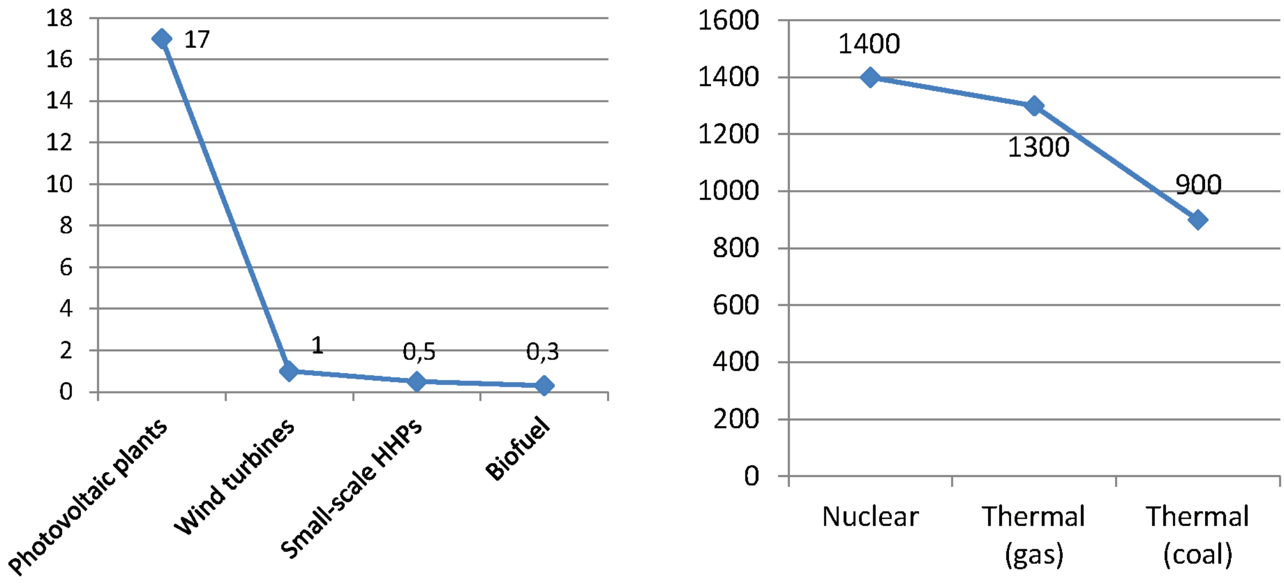
The process of introducing direct current into modern EPSs is not limited only to micro- (nano-, mini-) systems. DC lines are widely used to transport large amounts of electricity over long distances; DC links are employed for asynchronous connections of power systems, including those having different frequencies of alternating current.

Innovative materials and devices, smartization and digitalization tools, when used in energy systems and their control systems, turn modern EPSs into complex cyber-physical systems [18], which also changes their basic properties.

B. "Centralized" EPS and distributed generation

The question is often raised about how far the processes of distributed sources expansion and electrical load control can go, as they reduce the role of large "centralized" power plants in EPS and lead to their "decentralization." As a result, the level of the integrity of EPSs will continue to decrease, while the level of autonomy of their subsystems will increase. There are some factors, however, which impede the complete "decentralization" of EPSs and maintain their structure as a combined centralized-distributed one. These are the structure and density of electrical loads, the energy density of generating sources, economies of scale, and terms of project financing.

According to the structure, electrical loads are



a) b)

Fig. 5. The energy density of generating sources, W/m²: a) unconventional (renewable) energy sources [16]; b) conventional energy sources (calculated based on the data from [19]).

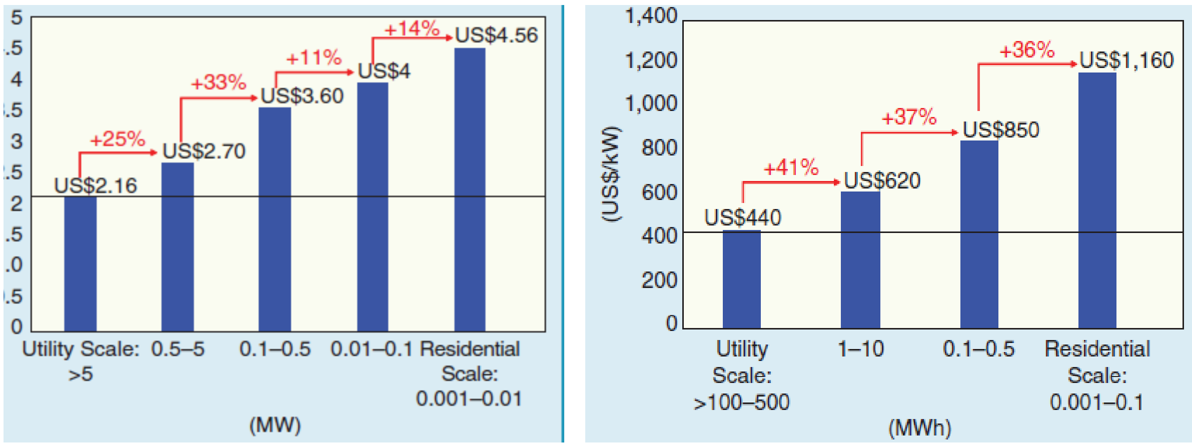


Fig. 6. Economies of scale in electricity generation and storage [21]: a) photovoltaic converters; b) lithium-ion storage systems.

divided into super-large, large, medium, and small (see Table 3). The first ones, which include large-scale urban agglomerations and industrial centers, are gigawatt loads, the second and third (individual urban settlements and industrial enterprises) are megawatt loads, and, finally, small ones (individual municipal and industrial consumers) are loads of kilowatt class. According to [16], the electrical load of the first of the listed groups of consumers cannot be covered only by distributed, primarily renewable, generation, it requires large centralized energy sources.

This point is confirmed by the data presented in Fig. 5. Comparison of the energy density of renewable energy sources with the energy density of consumers of the first group (Table 3 and Fig. 5a) shows that distributed sources of renewable energy sources alone cannot cover the demand of the specified group of consumers.

As for such distributed generation resources as microturbines, gas reciprocating plants, and other mini-TPPs [20, and others], which have an energy density comparable to consumers of the first group, their placement in the electrical load centers, which are already considerably affected by transport, residential, industrial and other essential infrastructures, can be constrained by socio-ecological factors (emissions of harmful substances, thermal pollution, noise, unacceptable appearance, and others) and limited possibilities of organizing fuel supply (under the conditions of many existing connections, including pipeline and information-communication ones).

In connection with the above, power supply to consumers of the first group requires the use of large "centralized" power plants located outside these load centers and the electricity transport through powerful

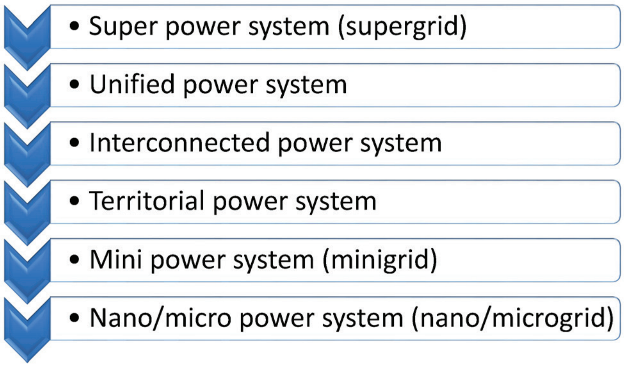


Fig. 7. Territorial and technological hierarchy of EPSs under transformation.

power lines. It is worth noting that the energy density of such sources corresponds to the energy density of consumers of the first group (see Fig. 5b).

According to modern research, the electricity generation sector enjoys economies of scale, including those for solar and storage plants with a modular principle of capacity expansion, i.e., large plants of this kind, operating in an EPS, are more cost-effective than small ones operating at the consumer. Therefore, depending on the specific conditions (a developed power grid infrastructure, economic indicators, and others), large centralized sources and distributed generation plants (including those based on renewable energy sources) also expand. According to the estimates [21] (Fig. 6), switching from small distributed generation sources and storage facilities to large "centralized" plants reduces specific capital investments by more than 2 times.

Another factor in favor of keeping "centralized" energy systems in some form is that "centralized" generation projects implemented by large energy companies are usually funded by banks on more favorable terms than small distributed generation projects [22], which reduces the economic efficiency of distributed generation plants. The state's support to distributed generation projects under concessional lending programs, however, will increase their economic attractiveness.

Thus, still, there are conditions under which it is expedient to develop large centralized energy sources and systems, as well as their interconnections, which continue to play a crucial role in the energy supply of consumers. Although the active development of distributed generation is also ongoing

C. Transformation of EPS properties

In the context of the transformation of EPSs, their hierarchy becomes more complicated. Instead of the traditional two-level territorial-technological hierarchy of energy systems (Unified system - Territorial system) for small countries and EPS, or three-level hierarchy (Unified system – Interconnected system - Territorial system) for large countries (Russia, China, the USA) and EPSs, there emerges a six-level hierarchy, which at the upper level covers interstate power interconnections and at the lower level additionally includes mini- and micro-systems (Fig. 7). As a result, the property of the *hierarchy*

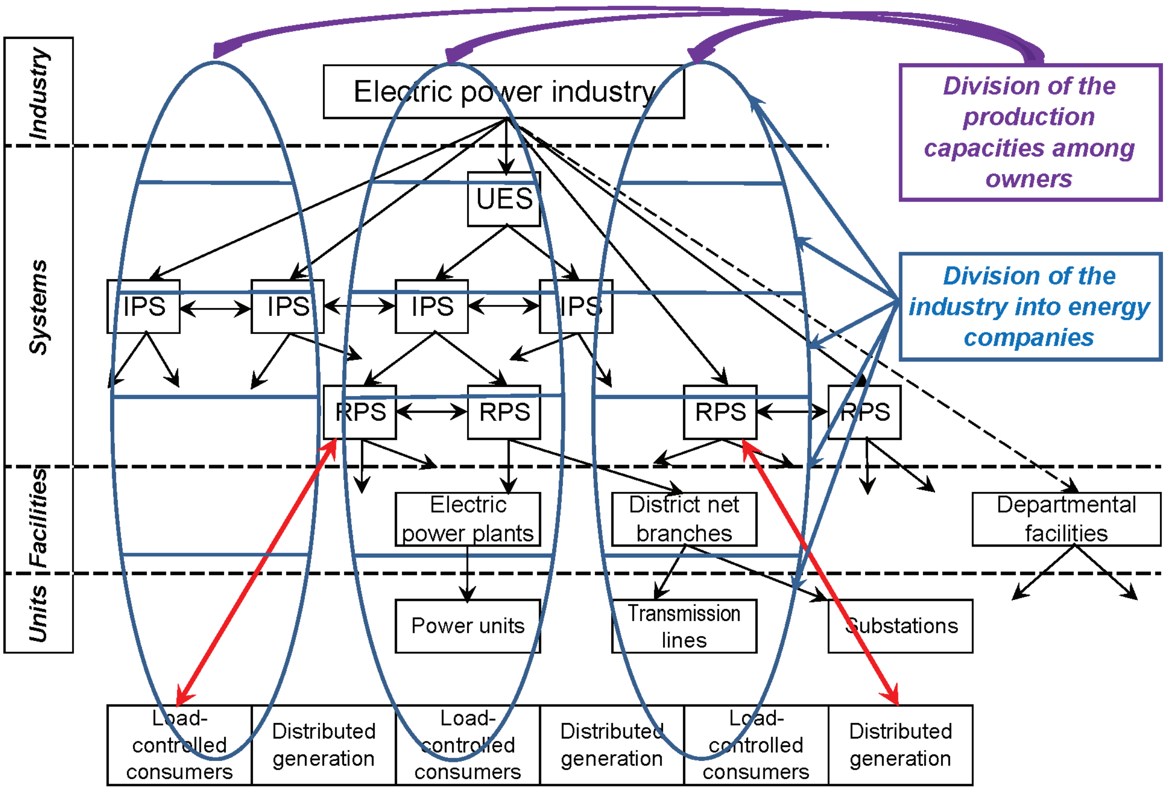


Fig. 8. Organizational-structural transformation of the electric power industry.

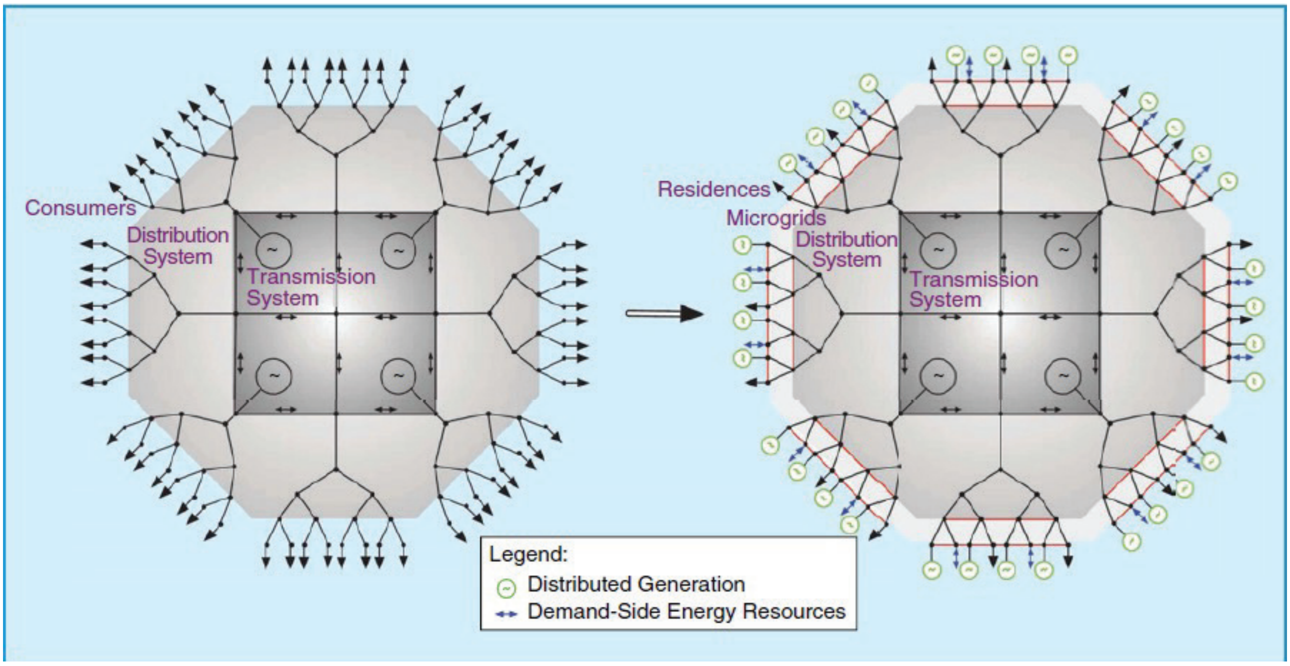


Fig. 9. Centralized-distributed cyber-physical electric power system [25].

of decisions significantly expands. Moreover, at the lower levels of micro-and mini-systems, the horizontal coordination of decisions is enhanced.

Privatization and restructuring resulted in the division of production assets in the Russian electric power industry between various owners, including foreign ones (energy companies from Germany, Italy, Finland). The state (the Russian Federation) also remained one of the owners, but to a different extent in different companies. New LES subsystems were created, i.e., energy companies owned by different owners, as well as electricity and capacity markets, within which these energy companies operate. Energy companies and their owners have their objective functions of efficiency that determine their behavior in the process of operation and expansion. In addition, new "actors" have appeared, i.e., load-controlled consumers, prosumers (producers-consumers), and distributed generating plants, which have become active participants in the electric power markets as a result of the electric power industry reform (Fig. 8). Thus, in terms of organizational and structural aspects, the level of the *autonomy* of subsystems (energy companies and consumers) has increased, and the level of *integrity* of the entire system, on the contrary, has decreased.

Since, as noted above, the reform results in the emergence of many new entities with their goals and interests, given the extended interpretation of the property of the *multi-criteria nature* [1], this leads to an increase in the level of this property. In addition, initially, when assessing the efficiency of the energy system's operation and expansion, the property of multi-criteria nature implied considering not only economic criteria but also non-economic, including environmental ones. Given the global trends in the development of renewable energy sources and the greening of energy production, Russia's ratification of the Paris Climate Agreement, and the country's transition to a low-carbon development path [15, 23, 24], the significance of considering environmental criteria when justifying and making decisions in the field of energy increases dramatically. Moreover, the importance of these criteria becomes commensurate with that of economic criteria. Thus, the level of the multi-criteria nature rises further.

Finally, with the growing number of entities in the electric power industry, one can expect an increase in the *uncertainty of information* about the future conditions for the EPS operation and expansion. With the emergence of load-controlled consumers and distributed generation, the uncertainty of prospective demand for electricity and capacity increases when justifying and making decisions on the expansion of large "centralized" energy sources and power transmission lines. Current demand will also be more uncertain since it will be formed under the influence of a larger number of uncertain factors, including, apart from the traditional demand of electricity consumers, also the consumption/generation of many prosumers, stochastic generation of renewable energy sources, both centralized and distributed ones. On the other hand, the uncertainty is likely to be minimal for distributed plants/prosumers themselves, since they will work according to their schedule, supplying surplus to the network, or, conversely, receiving energy from the network, if necessary, thus "shifting" their uncertainty to the "centralized" system.

In the context of transformation, the development of distributed generation within the "centralized" EPS (see above) leads to the establishment of a centralized-distributed electric power system, and this system becomes a cyber-physical one, which, based on the digitalization, integrates technological, control and market systems, as well as all stakeholders involved, i.e., business, consumers, and prosumers [18]. As noted in [25], the centrally-distributed cyber-physical (CD CP) EPS (Fig. 9) represents a compelling vision of future electric power systems that are formed through the convergence of trends, forces, and policies. CD CP EPSs include thousands of local distribution areas/networks managed (controlled) by Distribution System Operators (DSOs) connected to large/"centralized" EPS for electricity trading in/exchanging with the wholesale market and providing ancillary services. The final state of the CD CP EPS has not yet been studied in detail, the motion towards it from the current state occurs at various rates in different countries and regions of the world, and the transition can be chaotic.

The transformation of energy systems and their change into CD CP EPS will undoubtedly affect their properties. As noted above, many entities operate within the CD CP EPS, including distributed small generating plants and prosumers. These power plants have low capital costs, short construction periods, and, accordingly, the possibility of a rapid increase in capacity, which reduces the *inertia* of the system (economically), enhances its adaptability to changing uncertain conditions (for example, changes in the electricity demand), and makes it more *flexible* in an economic sense.

These properties also have a technical interpretation. In contrast to traditional units of "centralized" power plants, the rotors of small generators of distributed plants have a reduced inertia constant and simplified control systems [26]. This and the active use of innovative technologies based on power electronics in electricity production, transport, distribution, storage, and consumption considerably reduce the load-based regulating frequency and voltage effects, and the inertial capabilities of the EPS, and, as a consequence, the levels of the system adaptability and flexibility go down (in a technical sense) either. Moreover, an increasing share of randomly fluctuating generation based on renewable energy resources leads to a further decrease in the EPS flexibility [27]. However, advanced highly-efficient control systems can provide a dramatic increase in the controllability and flexibility of EPS [8, 28].

Changes in the properties of EPSs due to their transformation manifest themselves in operation, expansion, and the market organization of these systems.

The property of reliability in the basic set of properties of LESs is associated with their operation [1]. In the context of EPS transformation, this property undergoes changes that affect its features, such as stability, survivability, and others [29, 30]. As the EPS transforms, "voltage" stability, "frequency" stability, and thermal stability, which previously were local, come to the fore, although the stability that prevailed in the traditional EPS was "angle" stability. Stability losses are closely intertwined and are complexly connected by cause-and-effect relationships with each other and phenomena (events) in the EPS. Any of the above-mentioned phenomena can spread in one form or another to other parts of the EPS and finally to the entire power system and evolve into a system accident [29]. On the other hand, the distributed generation plants on the low voltage side of consumers, on the contrary, have a positive effect on the level of reliability of power supply to consumers since if a high voltage supply substation fails, these plants at least allow reducing (or eliminating) the electricity shortage for consumers [26].

As stated above, structurally and organizationally, the EPS integrity decreases, while the autonomy, on the contrary, increases. It is important to scrutinize this issue from the "technical" viewpoint, to be more precise, from the perspective of operational dispatch control. The system of operational dispatch control of the EPS is improved to reflect the ongoing transformations, especially given the involvement of consumers and the spread of distributed generation. Load-controlled consumers and, to an even greater extent, prosumers increase the uncertainties in dispatching control of EPSs due to the independent control of their electric loads and small generating plants [31]. Therefore, in addition to network and system operators, it is advisable to create "aggregators of distributed energy resources" and "distribution operators" to ensure participation of consumers in the EPS control, which complicates the dispatch control system and increases the hierarchy of dispatch decisions. Thus, the strengthening of the autonomy and the weakening of the integrity of the transformed EPS extend to the dispatch control system, thereby increasing the role of lower levels of the control system hierarchy (load and prosumers) and strengthening the horizontal connections between these hierarchical levels, and also manifest themselves in the operation of the entire EPS.

A decrease in the integrity of the system and an increase in the autonomy of its subsystems, as a result of restructuring and privatization of the industry; the formation of many independent energy companies, load-controlled consumers, and prosumers with their economic interests and objective functions of efficiency; and due to the growing hierarchy of decisions through the creation of additional hierarchy levels (micro-, mini-systems at the lower level and super-systems at the upper level) are also observed for the aspect of EPS expansion. These factors increase the uncertainty of the future EPS expansion conditions and complicate the process of this expansion. Therefore, it is necessary to create a management system for the electric power industry development, within which the many interests of the entities involved at all levels of the territorial and technological hierarchy of the EPS are coordinated, and provide further advancement of the methodology for planning the development of the electric power industry, power systems, and power companies in the context of their transformation.

Table 4. Transformation of EPS properties in a changing environment

Property	Transformation
System integrity	Declines in organizational, technical, and control terms
Subsystem autonomy	Grows in organizational, technical, and control terms
Hierarchy of decisions	Expands
Incomplete information	Expands
Cost-effectiveness	↙ ↗
Reliability	↙ ↗
Dynamics	Persists
Multi-criteria nature	Expands
Inertia	Declines economically and technically
Adaptability	Rises economically and declines technically

The expansion of microsystems and the involvement of consumers and prosumers cause the transformation of the electricity and capacity markets. They become structurally more complicated, with the number of their participants rising dramatically, which raises the uncertainty, increases the hierarchy of decisions, enhances the autonomy, and decreases the integrity of the structural organization of the electric power industry. The cost-effectiveness of the electric power industry in a market environment is assessed ambiguously. On the one hand, the competition is believed to force market participants to reduce their costs "in the fight" for the consumer; on the other hand, the real markets are imperfect, which allows companies to overcharge equilibrium prices and generate excess profits.

Table 4 summarizes the analysis of EPS properties brought about by their structural-organizational and innovative-technological transformations.

The *integrity* of the systems decreases in organizational, technical, and control terms. *Autonomy* of the subsystems in all these respects, however, on the contrary, increases. *The properties of the hierarchy of decisions* and the *incompleteness of information* expand. The change in the level of the system *cost-effectiveness* property is not obvious because, as noted, it is affected by two oppositely directed vectors: competition in the electricity markets, on the one hand, leads to a decrease in prices, on the other hand, in the imperfect markets, it can also lead to their growth. Change in the level of the reliability property is not apparent either. Dynamics of systems, as can be estimated, is preserved, and the property of *multi-criteria nature* expands due to the emerging multitude of new EPS entities with their interests and goals. The *inertia* of systems decreases both in the economic and technical sense. However, whereas in the economic sense, this has a positive result, in the technical sense (i.e., in the sense of reducing the ability to "extinguish" internal and external destabilizing factors in the system), it is rather negative. As a result, this decreases the level of another property, i.e., *adaptability* and the related *flexibility* of the system. The decrease in the inertia of systems causes adaptability to grow in the economic sense.

V General lines for further research

The change in the EPS properties, which, as noted, in the context of transformation does not always have a positive direction, will require various compensating measures and means. These are the improvement in control systems, the development of energy storage devices, intelligent FACTS devices, automatic reconfiguration of the electrical network [8], and others. First of all, however, it is necessary to conduct a whole host of scientific research in this area. These studies will follow the requirements for the methodology and modeling of EPS in a new environment and rely on the above analysis of the transformation of EPS properties.

Firstly, a decline in the level of the system integrity and, accordingly, an increase in the level of subsystem autonomy, as well as the expansion of multi-criteria nature, require the consideration of the organizational unbundling of the EPS with a cardinal widening of the set of decision-makers, and, accordingly, the need to use equilibrium, multi-agent and two-level modeling in problems of operation, expansion and structural organization of the electric power industry. Secondly, the expansion of the property of the hierarchy of decisions presupposes the studies to be conducted for the hierarchical levels of mini- (micro-) and super-systems, and the use of two-level modeling to study centralized – distributed EPSs integrating large "centralized" systems at the upper hierarchical level, and micro-and mini-systems, as well as individual consumers prosumers at the lower level. Thirdly, the growing incompleteness of information leads to the need to develop new approaches and models

Table 5. General directions of research due to changes in the EPS properties

Architecture and properties
Micro, mini, super systems
Two-level (centralized system – distributed resources) models of EPS operation, expansion, and structural organization
Expansion and operation of control systems with vertical horizontal coordination of centralized generation and distributed energy resources
Consideration of the high uncertainty of "clean" power consumption in real-time control and long-term development
Conceptual and methodological studies and modeling of multi-level markets, including many participants
Equilibrium models of operation and expansion in terms of structural organization of the EPS
Mathematical models of expansion and operation based on multi-criteria optimization
Electric power applications of the Internet of Things, blockchain, big data, artificial intelligence

to factor in the extended range of information uncertainty in the process of expansion and operation of EPSs and their control. Fourthly, as noted, changes in the properties of cost-effectiveness and reliability in the context of EPS transformation are ambiguous and, therefore, require research of market structures that affect the property of cost-effectiveness (as well as the reliability of microsystems), load-controlled consumers, prosumers, and the impact, along with the reliability of large "centralized" systems, on the reliability of power supply to consumers in general. Fifthly, the increasing significance of environmental factors, primarily due to the problem of global climate change coming to the fore, and the need to reduce carbon dioxide emissions today require the development of appropriate mathematical models, including those using multi-objective optimization. Sixthly, in a new context, the decline in the levels of EPS inertia, adaptability, and flexibility in the technical sense requires compensation for the negative consequences of this decline and appropriate research and development of highly-effective protection, automation, and control systems.

General directions of research, due to the transformation of the main properties of EPS in the new context, are presented in Table 5. In this case, they are not divided into specific problems, but such a division was made in the studies, which are currently underway at the Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences.

These studies include those focusing on the properties of flexibility, stability, survivability, and vulnerability of EPS [30, 32]; dealing with the creation of intelligent multi-agent hierarchical systems of operational dispatch control of cyber-physical centralized-distributed EPS [17], equilibrium modeling of the EPS expansion given their structural organization [33]; addressing mini- and super-systems/grids [17, 34], expansion management system [35] and a further improvement in the methodology for planning the development of the electric power industry in the context of EPS transformation [36]. The in-depth studies are also conducted to investigate the transformation of properties and examine new properties, which are expected to arise in the process of future EPS formation. Finally, it is necessary to develop applications to the considered subject domain of the Internet of things, blockchain, artificial intelligence, and digital twins and carry out a variety of other scientific studies.

VI. Conclusion

In the context of current and expected transformations, electric power systems are becoming even more complex in terms of structure, technology, and control, and their behavior and conditions of existence are getting less predictable. Control systems of such complex centralized-distributed cyber-physical systems are becoming increasingly "smartized," and acquire, albeit to a limited extent, the ability to make decisions. Thus, the emergence of new properties characterizing the expanded capabilities of future EPSs is real, which will require their conceptual interpretation from various perspectives, and comprehension.

Further scrutiny is necessary to create and improve scientific, methodological, and model tools, which will ensure efficient and reliable operation, expansion, and structural organization of centrally-distributed cyber-physical systems, given the transformation of their properties.

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