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Innovation Management Models in the Energy Sector

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Abstract. Economic development, technological innovation, and policy change are especially prominent factors shaping energy transitions. The current stage of the energy transition is distinguished by a qualitatively new level of policy influence on all components of the energy complex. This policy affects the motivation and behavior of all stakeholders in the processes of generation, distribution, and use of energy. In terms of their importance, behavioral aspects have reached the same level as technology and energy economics. In the article, we analyze these features of the energy complex and offer modified and refined models for the innovative development of the energy complex as a socio-technical system. The proposed approach, in which the energy complex is considered a socio-technical system, can be taken into account when describing the sectoral innovation system in the energy industry. Considering the ongoing trends in digitalization and the advancement of cyber-physical systems, the general principles outlined by the authors for homogeneous production systems can be applied effectively in the management of projects related to the development of energy complex subsystems.

Keywords: Energy complex; Innovation models; Socio-technical approach

1. Introduction

The global energy system has entered a phase of a new energy transition, which is characterized by the widespread use of renewable energy sources (RES) and the displacement of fossil fuels (Zaytsev *et al.,* 2021; Sovacool, 2016). From the point of view of innovation management, previous energy transitions (to coal, oil, gas, and nuclear energy) fit well into the classical models of the innovation process "science/technology push" and "demand pull". Both the new energy generation technologies and the efficiency of new energy sources were drivers of the previous transitions. The current stage is characterized by the lack of economic attractiveness of RES compared to fossil fuels or nuclear energy. Despite the steady trend of reducing the cost of renewable energy generators and increasing their efficiency, energy production using RES is still more expensive than traditional energy production (Broom, 2020). The driving force behind the new energy transition has been the sustainable development goals and climate change mitigation.

The current energy transition is studied as a process that contains technical, economic, and political components (Cherp *et al.,* 2018). In this process, policy plays a

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Leading role by formulating strategic goals and realizing corresponding strategies for the development of the energy sector (Meadowcroft, 2011). These goals can be 'carbon-neutral' or 'sustainable', but in any case, they move the focus of research and investment projects from fossil fuels and nuclear energy to RES.

Our paper aims to promote an integrated approach to analyzing the energy sector as a complex system where processes of production, transition, and use of energy are interconnected, and the energy transition model described in the paper captures the dynamics of this system. From a systemic perspective, renewable energy sources (RES) and "traditional" energy should not be viewed as opposites but rather as complementary technologies, each occupying its own niche. Even in contemporary economic conditions, where the production cost of traditional energy is relatively low, renewable energy can still be cost-effective. It is relevant to apply a holistic approach to the analysis and design of complex energy facilities as a system, which contains technical, organizational, and social subsystems considered in interaction.

2. Methods

A holistic approach to the study predetermined the need for the convergence of three different approaches to the problem under consideration: models of innovation that form the basis of innovation systems in the energy sector, models of a homogeneous production environment describing the technical nature of the energy system, and a socio-technical approach, describing the energy sector from a management point of view.

2.1. Models of innovation

In the development of the classic innovation process models in the late 90s of the last century, Henry Etzkowitz and Loet Leydesdorff proposed the 'Triple Helix' model of the innovation ecosystem in the form of intertwined and closely interacted authorities, scientific organizations, and industrial enterprises (Etzkowitz and Leydesdorff, 2000). Subsequently, Elias Carayannis and David Campbell expanded the composition of the key "helixes" of the innovation system and included the "fourth helix," which is based on stakeholders who explicitly and implicitly use information systems and social media communication tools for decision-making and have own preference systems based on culture and knowledge system (Carayannis and Campbell, 2009). It is necessary to analyze how these models are adequate to modern trends in the development of the energy complex.

2.2. Homogeneous production environments

Production systems built on the principles of parallel execution of operations, structure variability, and structural homogeneity are called homogeneous production environments (HPE) (Konovalova, Nurulin, and Redko, 2020). This approach is actively used in the innovative development of structural solutions for production systems of material objects (Konovalova, 2021; Malindzak *et al.*, 2017). Such systems have practically unlimited possibilities for changing their performance by changing the number and functionality of elementary production modules (EPM).

2.3. Socio-technical approach

The socio-technical approach, serving as a doctrine for the organization of activities and encompassing a set of methods and techniques used in the analysis and synthesis of systems with distinctive properties, has been evolving since the middle of the last century.

The recognized founders of research on this issue are Eric Trist and Fred Emery, who proposed the term "socio-technical system" in the 1960s and developed a socio-technical approach to the analysis and synthesis of organizational systems. This approach was further developed within the framework of the socio-technical model proposed by Harold Leavitt, which includes four interacting and coordinated dimensions - people, task, structure, and technology - as important components of the organizational system of work (Verbong and Geels, 2010).

A significant contribution to the development of the socio-technical approach was made by Christopher Freeman (Freeman, 1995), Frank Geels (Geels and Schot, 2007), and other developers of innovation theory, who substantiated the socio-technical nature of innovation systems and proposed a set of conceptual models of the innovation process. Research on innovation systems, in particular, has influenced the understanding of the dynamics of socio-technical change, including the links between knowledge and technology, institutions, actors, and networks.

3. Results and Discussion

The energy system has traditionally been the focus of research for innovation managers. A number of studies have focused on supply-side issues, discussing a wide range of issues ranging from the comparative characteristics of different generation equipment to existing institutional barriers to expanding the use of renewable energy sources (Watson, 2008; Foxon *et al.,* 2005). In the context of the transition to RES, energy distribution infrastructure is becoming a key factor for the introduction of renewable energy technologies, improving energy efficiency and managing the balance of supply and demand of energy (Bolton and Foxon, 2015,). With the development of RES, the number of energy generation points in the energy system increases sharply, and the energy system itself acquires pronounced features of a homogeneous distributed system. An obstacle to this can be ineffective or absent legislative norms regulating procedures for connecting new suppliers to electric grids (Nurulin, Skvortsova, and Vinogradova, 2020).

At the same time, in combination with innovative technologies of "traditional" micro-generation, RES can provide effective solutions for energy supply to remote regions where energy distribution infrastructure is underdeveloped or absent altogether. Taking into account the well-known dependence of some RES technologies on climatic characteristics (Krasniqi, Dimitrieska, and Lajqi, 2022; Brazovskaia and Gutman, 2021), the problem of energy storage comes to the fore. This problem has innovation-technical components (using different technologies for storage), economic components (additional costs for storage), and social components (stakeholders' behavior). The same components play a key role in the tasks of energy efficiency and energy saving in different subject areas (Himeur *et al.,* 2021; Lapillonne, Sudries, and Payan, 2021; Tzeiranaki *et al.,* 2019). These studies are generally limited to covering only technical and economic factors, while the political, social, and behavioral aspects of the proposed changes and possible social impacts are left to the discretion of the end user.

The above indicates the need for further development of an integrated interdisciplinary approach that takes into account the mutual influence of technical, organizational, economic, social, and behavioral components of the energy complex. In relation to the energy sector, traditional models of innovation require some clarifications related to the peculiarities of the structure of the system, the increasing role of authorities, and taking into account the socio-technical nature of the energy system.

3.1. Energy complex as a homogeneous production environment

The equipment required for the production, supply, and use of energy has the following properties.

Parallelism (multiplicity) of operations. This way of performing operations involves the parallel operation of both individual subsystems and the execution of parallel operations (multiplicity of operations) in each subsystem.

In the limit, the multiplicity of operations ensures the execution of any operation at any point in the production space, which makes it possible to achieve the necessary flexibility and versatility of the system with high performance.

The variability of the system structure implies the possibility of changing the composition of elements and the relationships between them, as well as the restructuring of the internal structure of elements. The structure variability property provides the possibility of implementing a large number of different functional structures based on the same set of elements and relationships between them.

Constructive homogeneity. Effective functioning and a high level of unification in complex systems are achieved due to the structural homogeneity of the elements and the connections between them. This allows us to represent the system as a set of elements of the same type with the same connections between neighboring elements. The production of the system is simplified to the repetitive replication of the same structural element, known as an elementary production module. This approach enables extensive parallel work to be conducted simultaneously on numerous elements and their connections during manufacturing, commissioning, and operation.

Failures of individual modules do not violate the functional completeness of the system but only temporarily reduce its performance. This property of the HPE makes it possible to ensure the non-redundancy of layout solutions that best meet the changing conditions of the production system.

The main advantage of the GPS is its high survivability. The absence of centralized general-purpose subsystems, the functional completeness of modules, and their management by local control systems ensure the operation of the HPE in the event of equipment or software failures.

The second important advantage of HPE is its easy adaptability to required production volume with practically unlimited productivity. The required volume of the HPE, i.e., the number of modules, can be achieved without a lengthy system redesign process using the HPE scalability property.

The next advantage of the HPE is associated with a significant simplification of requirements for the manufacture of modules and their connection into a single structure. The terms of the HPE manufacturing, delivery, and implementation as well as the necessary volume of spare parts, are significantly reduced, and troubleshooting and training of maintenance personnel are facilitated.

The HPE performance increases significantly in case the information and material links exist constantly and do not require additional means and time for formation and reconfiguration.

To concentrate EPM modules on a common task, it is necessary to set the structure of the local EPM, organize the exchange of information and material objects, and manage this combination of modules. Such an approach to the creation of production systems provides ample opportunities for the development of the system and for the achievement of required parameters.

In the energy complex, the HPE principles can be most effectively implemented in the power transmission subsystem within the framework of the smart grid concept. The transition to RES has led to a multiple increase in the number of energy generators integrated into a single energy system and opens up new prospects for using the HEP principles in the development of the energy sector.

3.2. Hierarchic innovation model

The well-known innovation models reflect the various stages of energy development quite well. The nuclear power industry can be a vivid example of the "science/technology push" model: nuclear power plants appeared as a result of the transfer of military nuclear technologies to the power industry. Natural gas liquefaction and transportation technologies began to develop as a response of the scientific and technological sector to market demands for the transportation of natural gas over long distances without the use of pipelines (the "market pull" innovation model).

Until the beginning of our century, innovations in the energy complex were described quite well by the above models. But then politics came to the fore. To achieve their geopolitical goals, states use both economic mechanisms (subsidies, tax breaks, tariff regulation) and non-economic measures to control energy markets (industry standards for fuel and vehicles, forced closure of coal mines and nuclear power plants etc.). The ideas of climate change mitigation and decarbonization are being actively exploited, and a system of CO_2 emissions trading is being introduced. All these measures are caused not so much by scientific and technological solutions or market demand as by political decisions. As a result, the current stage of the innovation process in the energy complex can be characterized as a "policy push and pull" hierarchical model (Figure 1).

3.3. Socio-technical approach

A number of authors use the concept of a socio-technical regime to analyze the energy complex (Verbong and Geels, 2010; Stegmaier, Visser, and Kuhlmann, 2021). According to this concept, the socio-technical regime consists of three dimensions: a) material and technical elements, such as resources, network infrastructure, generating plants, etc.; b) networks of actors and social groups, such as utilities, ministries, large industrial customers and households; c) formal, normative, and cognitive rules that govern actors, such as rules, belief systems, guidelines, search heuristics, behavioral norms (Verbong and Geels, 2010).

When analyzing the energy complex, Cherp *et al.* identified three different types of systems:

(1) techno-economic systems defined by energy flows associated with energy extraction, conversion, and use processes involved in energy production and consumption as coordinated by energy markets;

(2) socio-technical systems delineated by knowledge, practices, and networks associated with energy technologies; and

(3) system of political actions influencing energy-related policy (Cherp *et al.*, 2018).

In doing so, the life cycle of the energy complex product (energy) is considered as the main systemic feature only for the techno-economic system and is not explicitly taken into account in other subsystems. Furthermore, politics has become detached from the economy; however, today, it is politics that shapes the economy and establishes corresponding norms and rules for the behavior of energy market participants.

While generally supporting the proposed composition of the main elements of the energy complex, we nevertheless consider it more appropriate to use the term "energy system" when analyzing these elements and the complex as a whole. In addition, we propose to redistribute the content for the selected dimensions. Levels a) and b) should consist of categories that can be formally described using quantitative estimates, and level c) should combine categories that can only be described qualitatively with relatively weak formalization. Level b) will integrate a network of actors and social groups, as well as norms and rules governing their activities, and level c) will contain cognitive components (information and knowledge), belief systems, guidelines, and norms of behavior. The essential elements of level b) should be economic relations that determine the rules for interaction between subjects of the energy market.

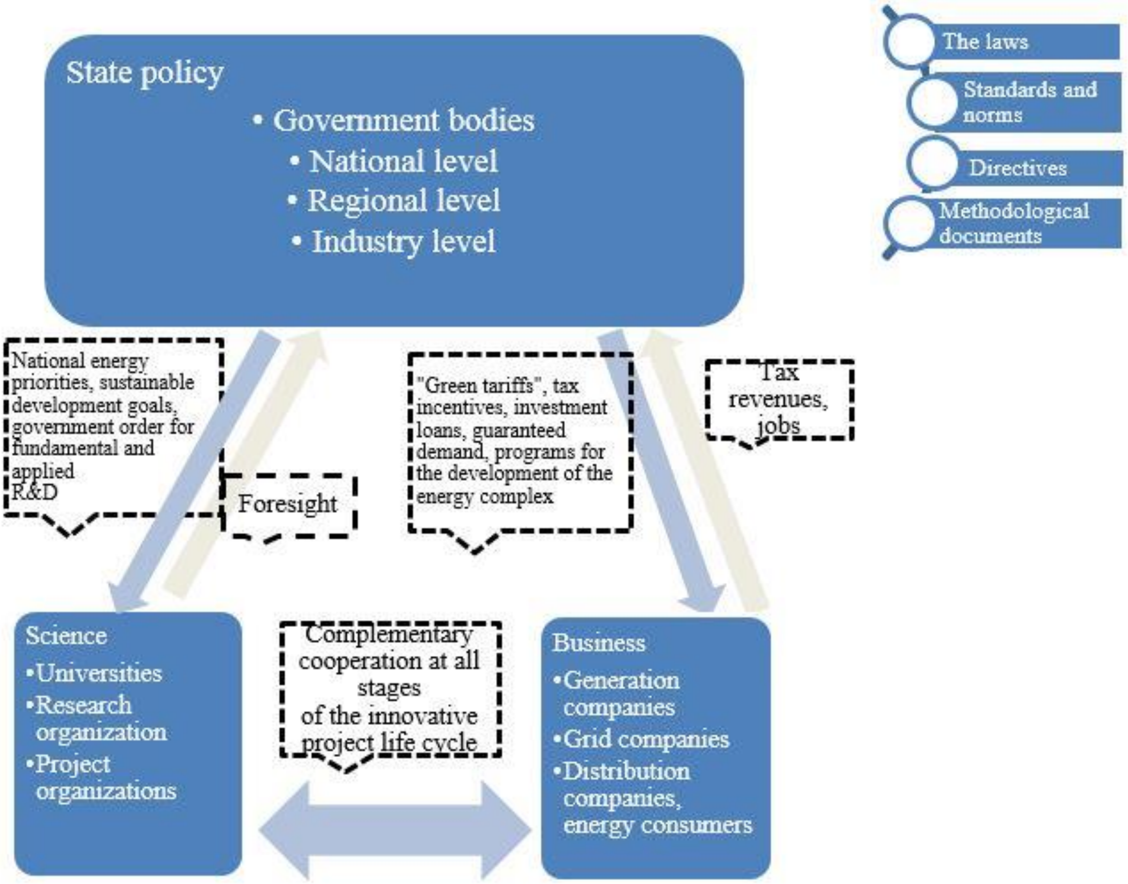

Figure 1 Hierarchical triple helix model of innovation in the energy sector

Summing up the discussion, we propose the following structure and composition of the energy complex as a socio-technical system (Figure 2).

3.4. Energy complex from the perspective of proposed models: case from the Russian Federation

Russia is rightfully considered one of the leading producers of energy resources. Its innovation system ensures the development of the energy complex according to the model presented in Figure 2.

State policy at the national level. In 2011, by Decree of the President of the Russian Federation on July 7, 2011, N 899, a list of federal-level critical technologies was approved, including:

- Technologies of new and renewable energy sources, including hydrogen energy.
- Technologies of energy-efficient production and conversion of energy on organic fuel.
- Technologies for creating energy-saving systems for the transportation, distribution, and use of energy.

As follows from this list, these technologies reflect the processes of production, supply, and use of energy. Their development is supported within the framework of existing federal programs that provide funding for fundamental and applied R&D in the energy sector. These R&D are aimed at increasing the share of low-carbon energy generation, implementing the concept of smart grids in the energy sector, and developing microgeneration and RES.

In subsequent years, a number of regulatory documents were adopted at the federal level, clarifying and detailing the identified priorities. Energy efficiency and energy saving have been identified as priority areas for the development of science, engineering, and technology at the federal level. The implementation of relevant technologies is supported by relevant standards, norms, and methodological documents.

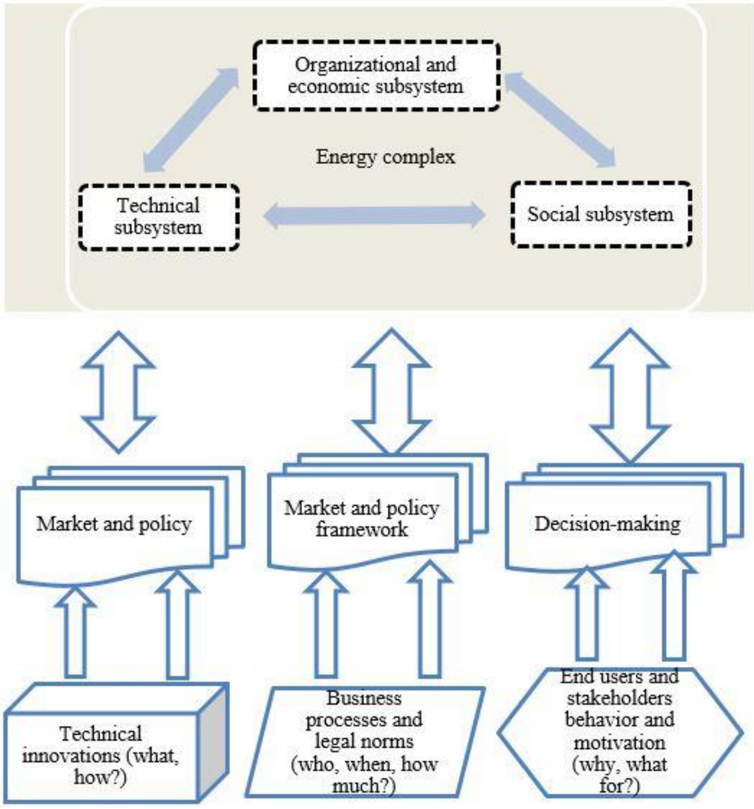

Figure 2 Energy complex as a socio-technical system

State policy at the industry level. This level of the energy complex in the Russian Federation is represented by the Ministry of Energy, which initiates the development of the regulatory framework for the energy industry and manages state programs for the development of the energy complex. The main emphasis in these programs is placed on subsystems of energy generation and supply, where federal generating and grid companies play a key role.

State policy at the regional level. All regions of the Russian Federation have their own state organizations which manage the energy complex in the region.

Science. Using foresight technology, scientific organizations provide long-term forecasts for the development of the energy sector, which forms the basis for strategic political decisions on the development of the energy complex (Makarov, Mitrova, and Kulagin, 2019).

Business. Market interaction between business organizations in the Russian energy sector is strongly influenced by politics, which is manifested through state regulation of tariffs for electricity and heat consumption, state subsidies for modernization of generating and grid technologies and equipment, as well as by guaranteed purchase of electricity generated by RES. Additionally, strict requirements are imposed on public organizations to reduce energy consumption.

The socio-technical approach in the energy complex development. The potential of the socio-technical approach is most prominently demonstrated in the energy use subsystem. Effectively addressing priorities in energy conservation necessitates the integration of technical solutions focused on minimizing energy resource losses during utilization, along with a deliberate shift in the motivation and behavior system of end users of these resources. This task is of particular importance in cases where end users do not have direct economic motivations for energy saving (schools, hospitals, universities, etc.). Realizing this, the Russian authorities are implementing a number of programs and activities at the federal and regional levels aimed at involving all stakeholders - from schoolchildren to municipal employees - in innovative projects for the development of energy-saving technologies in housing and communal services, as well as at shaping their energy-efficient behavior.

All of the above is largely true not only for the Russian energy complex but also reflects the general trends in the development of global energy. This conclusion is confirmed by the results of five projects of the European programs INTERREG (Interreg, 2023) and CBC ENI (CBC, 2023), which were implemented in 2018-2022. Comparative analysis and joint research of priorities, methods, and tools for the development of subsystems of the energy complex in Russia and European countries, which were carried out within the framework of these projects with the participation of the authors of this article, showed the invariance and perspectives of this approach.

4. Conclusions and further studies

By its nature, energetics is a complex multicomponent system. The proposed models for the innovative development of this system take into account the socio-technical nature of the processes of generation, distribution, and use of energy, as well as the leading role of the authorities in determining policies and strategies for the development of the energy sector within the current energy transition. When describing a sectoral innovation system in the energy sector, the relevant state structures should be considered not as its external environment but as participants with specific functions. Managers of innovation projects in the energy sectors should consider representatives of the relevant authorities as key stakeholders or even as project participants. Energy sector development projects should be guided by the general principles of socio-technical and homogeneous production systems. A restraining factor and limitation in this regard may be the high degree of technical (technological) diversity of energy generation equipment and systems. Further development of the principle of convergence of innovation management methods, a socio-technical approach, and a homogeneous production environment is expected in the direction of cyber-physical systems, where information and knowledge play a leading role at all stages of the development process.

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