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Research paper

The influence of technological changes in energy efficiency on the infrastructure deterioration in the energy sector

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ABSTRACT

The energy and its entire related infrastructure are the main drivers for a economic development and for ensuring a good level of employment. As part of a global study about international energy sector, we evaluate here the impact of technological changes on the state of the energy infrastructure. This study includes a detailed analysis of the global challenges facing the energy industry. We propose scenarios for the development of a modernized energy infrastructure with an assessment of the entire energy system. Our evaluation indicators are chosen in terms of the reliability of the energy infrastructure, of its quality, of the accidents that may happen and of the consequent environmental risks. This study is particularly adapted for forecasting the necessary measures (of technical nature, of governance kind) that have to be implemented to reduce the acceleration of the infrastructure deterioration rate. Our results reveal that the use of digital and information technologies has many positive impacts on the development and on the control of an efficient consumption of energy. In addition, our predictions, due to the further modernization of the energy sector, can contribute and help in the creation of preconditions that will be highly stimulating and profitable to the growth of investments in the energy infrastructure.

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1. Introduction

The energy and the whole infrastructure surrounding it are critical for the economic and social developments of the world. At the most basic level, people need access to clean, safe water for drinking and cooking, and power for lighting and heating their homes. The infrastructure has been positioned by the World Bank Group as an essential agent of change and transformation to address the challenges of achieving a sustainable economic development and the Sustainable Development Goals (SDGs) proposed by the United Nations. A recent analysis established that 72% of the SDG's targets require the modernization of infrastructures (either directly or indirectly) for their attainment (Lezak et al., 2019). Nowadays, to implement the government plans for decarbonization while maintaining a sustainable power supply, an energy transition is being implemented, requiring large investments in the modernization of the energy infrastructure (Szado and Fabok, 2020; Jones, 2015; Festel and Wurmseher, 2014).

The existing markets for transport and energy sales, as well as the energy infrastructure, have been previously developed during the era of the second industrial revolution until the middle of

the 20th century. In the era of the third industrial revolution, the energy sector is the most conservative constraint on national economy (Zhong, 2017; Guerado, 2017; Clark and Cooke, 2010). Under the dual tasks of economic growth and environmental protection, works of Wang et al. (2020a,b) and Soares et al. (2018) confirmed the importance of developing infrastructures, due to the fact that this affects the energy efficiency and as a straightforward consequence, the sustainable economic development in the world.

However, providing the capacity of the energy infrastructure to meet the unmanaged growing demand is ultimately unsustainable, both in environmental and economic terms (Knoeri et al., 2016). For developing countries, this issue is becoming more urgent than before, due to growth of population (O'Sullivan, 2020; Wilson, 2020; Bucci et al., 2019); due to the increase in urbanization (Mahmood et al., 2020; Wang et al., 2020a,b; Ahmed et al., 2020; Zhou et al., 2020; Xie et al., 2020; Adams et al., 2020; Shahbaz et al., 2017); due to the exponential increase in amounts of information that require an increased electricity consumption (Dogaru, 2020; Huynh et al., 2020; Bahga and Madiseti, 2016; Clark and Cooke, 2010). In line with the elements given above, the requirements for economy, energy security, environmental friendliness, energy efficiency and adaptability of the energy infrastructure will be tightened (Soares et al., 2018; Clarke and Wigan, 2018; Blum and Legey, 2012; Kessides and Wade, 2011).

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In many developed countries, the deterioration of the energy infrastructure also remains an urgent problem and it requires even more maintenance expenses. The asset renewal due to the deterioration of the habitat and anthropogenic alterations of the climate may change (Wang et al., 2020a,b; Shakou et al., 2019; Mikellidou et al., 2018; Wright and Batel, 2017; Matthews et al., 2015). Also, the depreciation of fixed assets increases, due to the underfinancing of renovation programs and to the lack of a systematic approach to the replenishment of the material and technical base from the responsible government agencies (Wang et al., 2020a,b).

Every year, the problem of the aging of the equipment is increasing in volume (IRENA, 2019). The problem of the deterioration of the energy infrastructure is receiving an increased attention from the governments, the public and the media. This is due to the fact that the main factor that determines the development of economic indicators of enterprises for all industries, including the energy ones, is the capacity of reconstruction and technical re-equipment of enterprises that are simultaneously modernized (Ginters et al., 2013; European Commission, 2020).

In addition, in modern infrastructure, there is a lack of integration of end users, together with the diversity of their needs and behaviors. Access to adequate, reliable and affordable energy remains a major challenge. In many cases, the demand grows much faster than the increase in energy supply, due to the time required to create a new infrastructure, due to the lack of enough funding and sometimes, socio-political reasons (Roelich et al., 2015).

Our study identifies five main regions, the quality of the energy infrastructure of which was assessed: The European Union, The United States, Asia, Russia and Africa. The quality factor of the energy infrastructure in the world was determined, according to the Global Infrastructure Hub (2020). It takes values ranging from 1 to 7. The quality of infrastructure of the energy sector is estimated as follows: 0–2 critical; 2–4 unsatisfactory; 4–6 normal; 6–7 favorable. Results are shown in Fig. 1.

Based on the analysis of results regarding the condition of the world energy infrastructure, we can note that this problem is of a global scale. Moreover, even despite a high quality of infrastructure in a number of EU countries, the problem of a premature aging of the infrastructure still remains unsolved. Recent societal and technological changes require an infrastructure that supports and enables new technologies (Linzenich et al., 2020).

Besides, the absence or an inefficient use of digital and information technologies leads to a lack of enterprise flexibility. It drastically reduces the ability to respond more effectively to market requirements changes (Dehgani and Jafari Navimipour, 2019; Balogun et al., 2020). The introduction of modern digital and technological solutions can improve decision-making processes and the efficient management of energy in real time and thus, it can improve relevant indicators of a performance.

The largest number of problems are observed in countries with a transitional economy. According to the International Monetary Fund (IMF, 2018), the Russian Federation belongs to this type. In this case, the reasons of worn-out infrastructures of the developing and developed countries are combined together. The fall-down in oil prices, as well as the 2014 sanctions and subsequent geopolitical tensions raised a substantial uncertainty and dampened domestic and foreign private investments. All these factors are the causes of the highest degree of depreciations of the infrastructure in the energy sector (Tcvetkov et al., 2020; Nevskaya et al., 2019; Zhukovskiy and Malov, 2018; Lavrik et al., 2018; Pashkevich and Petrova, 2017; Bazhin et al., 2017).

There are in addition many specific additional problems related to the geography of the country and temperature fluctuations, which in some regions can reach up to 60 °C between

summer and winter (Belsky et al., 2016). Although these problems pose significant risks for the Russian society, the economy and the public administration system, they simultaneously represent an important factor for the emergence of new and challenging opportunities and prospects for the modern scientific and technological developments of regions and countries (Litvinenko, 2020; Dvoynikov et al., 2020; Tcvetkov et al., 2020).

The degree of the depreciation of the equipments in the energy industry is the worst of all the industry branches in Russia. Since the Russian Federation possesses one of the most vulnerable energy infrastructure, the analysis of the state of equipment in the energy industry of this country was made with more details, in order to prove the need to search for new approaches to modernizing its energy industry. The current rate of introduction of new capacity is insufficient to ensure the growth of electricity needs, and the reliable stable power supply at this level of inefficient equipment output, and for full-filling the demand, and the need of consumption of costumers. Every year, the state of fixed assets becomes worse than it was the years before. The electricity consumption has been actively growing since 1995 (Fig. 4). However, the use of an outdated technology does not allow for high intensity and real efficiency in the production of electricity and in terms of its transmission to consumers (see Fig. 2) (Global Infrastructure Hub, 2020; EIA, 2020).

The depreciation of equipment in the energy sector has almost approached 70% in 2019 (Global Infrastructure Hub, 2020). In the specific case of the oil and gas industry, one reaches 57% of the infrastructure deterioration: it requires more advanced methods of preventing accidents, a much more timely fixing of the depreciation operations (repair, replacement, modernization) (Zhukovskiy et al., 2019).

In the power supply systems, one reaches 60% of deterioration of the infrastructure.

- High-voltage lines and cable lines 0.38–20 kV are 65% deteriorated (Smolovik and Khalilov, 2017).
- High-voltage and cable lines 35–110 kV are 60% deteriorated (Ministry of energy of Russia, 2020).
- More than half of 0.38–110 kV transmission lines were designed and built more than 40 years ago (Zhukovskiy et al., 2019).
- Among the groups of main equipment and transmission lines, the 220 kV transformers are in better technical condition than the 110 kV transmission lines.

Thus, it follows that the level of physical wear and tear of the main equipment of power plants in general corresponds to the type of technical condition “unsatisfactory”, which requires an enhanced monitoring of the technical condition and overhaul. This situation reduces the reliability and the safety of operation of many electrical networks, many buildings, many structures, many equipment, many devices, many control systems and many communications. It increases the risk of dramatic emergencies in the power grid complex. In addition, one of the main indicators of distribution networks is the loss of electricity. Analysis of the loss structure showed that the total loss of electricity in networks at 0.38–110 kV varies from 10 to 15%. The real evaluated losses in Russia are 130 billion kWh (13.6% of supply to the grid). According to the Energy Strategy until 2035, electricity losses should be at a level of no more than 8% of supply to the grid, which indicates the need for technical and organizational measures aimed at reducing losses (Ministry of energy of Russia, 2020).

The assessment of wear of heat and water supply systems:

- 75% of heat-only boiler stations have been operating for over 40 years with a service life of 30 years (Tcvetkov et al., 2020).

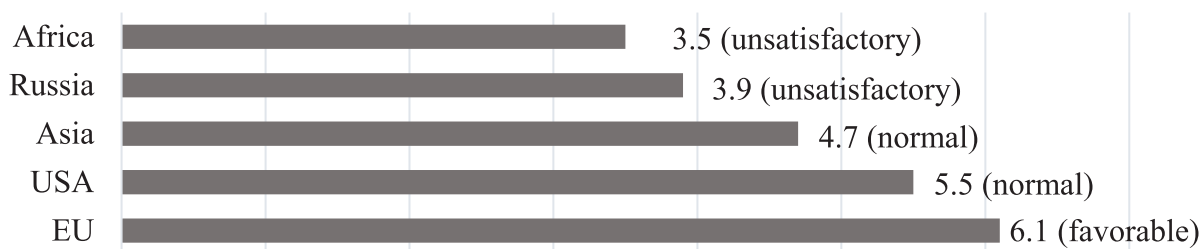


Fig. 1. The quality of the energy infrastructure in the world (1–7 points).

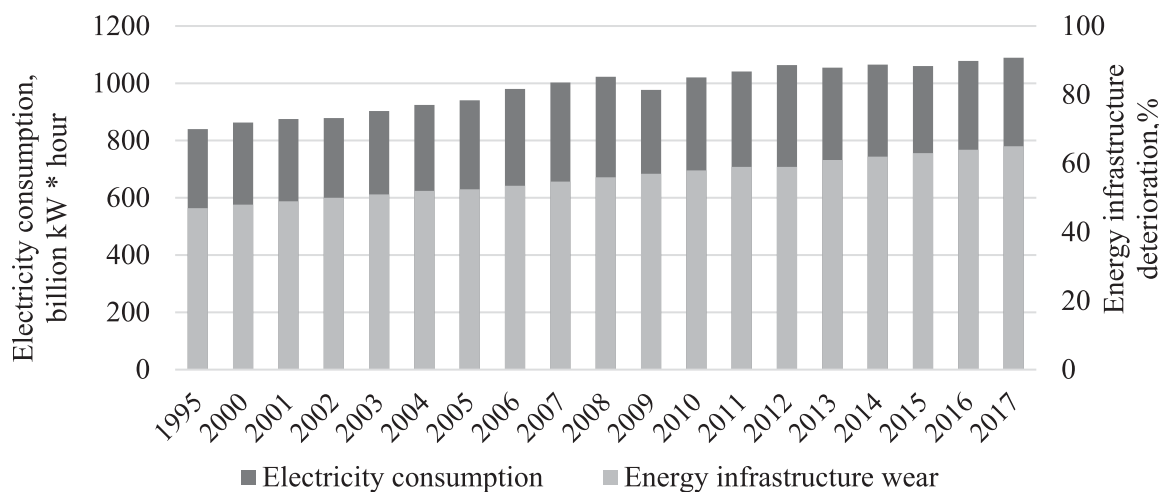


Fig. 2. The growth of energy consumption and deterioration of energy infrastructure in the Russian Federation (Global Infrastructure Hub, 2020; EIA, 2020).

- The water supply network is 60% of the deterioration (Ministry of energy of Russia, 2020).
- 35% of the equipment of hydroelectric power plants and 20% of the equipment of thermal power plants have already entered their end-of-life time periods (Ministry of energy of Russia, 2020).
- 28.8% of the heat pipes in the heat supply systems need to be replaced (Rosseti, 2020).

The low level of investment reduces the operating conditions of the equipment. This leads to an increase in the risk of accidents up to 80% by 2030. No less than 16 thousand accidents in electric networks of 110 kV and 5 thousand accidents at heat and water supply systems were registered in 2019 (Ministry of energy of Russia, 2020). It also substantially affects the socio-economic sphere, leads to an increase in tariffs, which should be limited to the planned indicator of inflation set by the Central Bank of Russia. However, today there is no systematic approach to solving the problem of these deteriorations of the infrastructure and for restoring the material and technical base, even despite the increase in tariffs, in funding from the state, as well as via the launching of developed investment programs. This is one of the most important problems for the energy complex of the Russian Federation.

Moreover, the investment in the infrastructure has been recognized by governments as a key driver of the economic prosperity. The lack of investment is one of the main reasons for the depreciation of the energy infrastructure (Paschke, 2017). Table 1 presents data on the state of the global energy infrastructure for 2018, the forecast data up to 2030, and the necessary investments as well. The investments that are allocated by the regions to solve this problem are insufficient, compared to the necessary ones, which causes the appearance of an investment gap. That is why the deterioration of the infrastructure becomes stronger every

year. For 2018, investments in the infrastructure are 1.7 trillion dollars, while the necessary investments locate in contrast near up to 2.1 trillion dollars.

The United States is one of the world leaders in financing the research in the field of energy and innovative technologies (World Energy Investment, 2019). However, investments in the development and modernization of the infrastructure are still insufficient and depreciation continues to increase. Russia has the largest investment gap of 41% compared with other regions. It is expected that, by 2030, investments will increase by only 15%. However, to cover the costs of infrastructure reconstruction, investments should increase by more than 1.7 times and should reach an amount to at least 58.8 billion dollars annually.

In addition, the economic crisis amid the coronavirus pandemic in 2020 affects the entire life cycle of facilities through the energy sector. Production chains are cut off, effective demand falls, investments are postponed, and the potential damage to the hydrocarbon energy industry from an economic standpoint is colossal.

In this regard, a unified investment strategy is needed. A number of policies and Government interventions are currently being developed to reduce or safely manage the investments. These include the use of regulatory measures as well as public finance mechanisms and public-private partnerships (Jones, 2015). However, this is not enough to overcome the deterioration. Measures for the reduction of the deterioration of the infrastructure should be carried out by introducing advanced technical solutions that fulfill economic and environmental requirements. Besides them, a modern technical level of energy distribution has to be conceived and achieved in accordance with the requirements of consumers.

New business models are needed that are more likely to meet the environmental and social goals of transformation of the infrastructure and open the door to new entrants. When risks and opportunities are quantified, they are well received

Table 1
Required investments in infrastructure and infrastructure deterioration until 2030.

Region	Deterioration of energy infrastructure (%)				Required investments (billion dollars)			Investment gap, billion dollars (%)
	2018	2025	2030	2030 ^a	2018	2025	2030	2030
EU	25	28	30	27	256.7	268.8	326.7	19.7 (6%)
USA	56.6	59	64	44	314.1	359.5	394.2	124.6 (31%)
Asia	48	54	55	30	1231.8	1462.8	1616.7	154 (9%)
Russia	66.6	75.7	84	49.5	45.4	51.7	57	23.1 (41%)
Africa	65	70	73	53	137	170.1	194.8	53.9 (27%)
All regions	52.2	57.3	61.2	42	2096.7	2368.1	2589.4	375.2 (15%)

^aPercentage of depreciation of the infrastructure that should to be achieved by 2030.

by stakeholders, including investors. So, *strategy and timing are both important, in addition to quantification*. In this regard, it is mandatory to determine what global challenges will affect the deterioration of the infrastructure over the next ten years, and it is also necessary to develop a methodology for predicting the state of infrastructure assets until 2030, both being realized taking into account the impact of technological changes in the energy sector.

Nowadays, the fourth industrial revolution based on the information and digital technologies, is often called the Digital Revolution (Dogaru, 2020; Zhong, 2017; Guerado, 2017). Digitalization is a key enabler for the sustainable development of cities having socio-economic dynamics, with the potential to simultaneously foster climate-friendly urban environments and societies (Balogun et al., 2020). The technological development in the field of digital and information technologies creates fundamentally new opportunities for increasing the efficiency of analysis, and for forecasting in various activity, and for helping to decision-making, based on the processing of extremely large arrays and data streams (Dehgani and Jafari Navimipour, 2019).

Accordingly, at the scale of the next 20 years, the energy sector of various regions and countries must cope with the issues of ensuring the energy security. It must become a guarantor of the sustainable development as the basis for meeting the needs for future generations through the introduction and the development of digital technologies in the energy sector (Annual statistics of world energy, 2018).

Despite the critical role that the infrastructure plays in the ability of a global society to face climate challenges, scientists are just beginning to explore the role of digitalization in improving the quality of the energy infrastructure to ensure a safe and reliable energy supply. The book “The Third Industrial Revolution (Clark and Cooke, 2010) suggested that the countries, states, regions, and communities of all kinds must embrace the reality of smart grids, emerging storage technologies, and renewable energy generation.

We analyzed big amounts of qualified literature, which confirm the relevance of the studying of energy infrastructure for last 10 years (Fig. 3). Most of a complementary scientific literature focuses on the calibration of the role of politics and of the government in the modernization of the infrastructure. In addition, it also analyzes the sustainable consumption and production.

Previous studies confirm the lack of information regarding new technologies that can be specifically applied to the energy infrastructure. However, the need for technological changes for the infrastructure is confirmed by many authors (Bayramov et al., 2018; Clark and Lund, 2008). In the work of Soares et al. (2018), a wide literature review was carried out on improving the energy efficiency and the environmental efficiency of systems, on developing new technologies, on increasing the use of renewable energy sources. Their paper confirmed that it is important to jointly improve information and communication technologies that both contribute to a better monitoring and to enhance control capabilities. The papers of Wu et al. (2021), of Teng et al.

(2021) and of Ali et al. (2020) present broad overarching rationales that digitalization and decentralization are the key enablers to achieve a sustainable infrastructure.

In this regard, a new approach to research is required to gain a more systematic understanding of the role of energy, of all its related infrastructure and of their impacts on the sustainable economic development of the countries of the world.

The research presented in this article focuses on the technologies that are mandatory for the sustainable development the energy infrastructure. We forecast the state of the energy infrastructure until 2030. Results determine which technologies have the greatest impact on the energy infrastructure. We also describe in detail how digitalization will affect the properties of the energy infrastructure in conditions of specific scenarios and how it will enable the achievement of SDGs. Based on our findings, we propose development programs for the sustainable development of the infrastructure.

Our paper has a specific emphasis towards the needs of the end user in the spirit of the work previously done by Roelich et al. (2015). However, in this paper it is worthwhile having in mind that offering the ad-hoc answer to all the needs of the present time requires finding a reliable, sustainable balance between the needs of all stakeholders.

Our review and analysis has five objectives:

- (a) the identification of global trends and the determination of their degree of influence on the deterioration of the energy infrastructure and equipment;
- (b) proposing the development of a methodology adapted to accurately evaluate the impact of technological changes on the rate of infrastructure renewal in the power industry;
- (c) the forecasting of the infrastructure condition, taking into account the impact of global challenges and the development of technology;
- (d) the identification of the key technologies that are needed to reduce the negative effect of aging on the equipment;
- (e) the identification of key technologies, the development of which will cause accelerated attraction of investments in the energy industry.

Results of our study will allow:

- (1) to help and enable decision-makers in energy policy to evaluate a wide range of infrastructure solutions and innovative technologies;
- (2) to estimate the impact of technologies on the properties of the energy system as a whole and on its sustainability;
- (3) to provide steps in the development of methods for assessing and for choosing the directions of investments in the energy sector. This sector is a complex infrastructure system that includes public and private actors along with a high degree of infrastructural changes and market uncertainty.

The complexity and the interdependence (both technically and socio-economically) of infrastructure systems require that any intervention or influence must carefully take into account both the historical co-evolution of the systems and their dependence on scenarios of development that could limit the potential for infrastructure aging. According to the co-evolutionary theory, it is

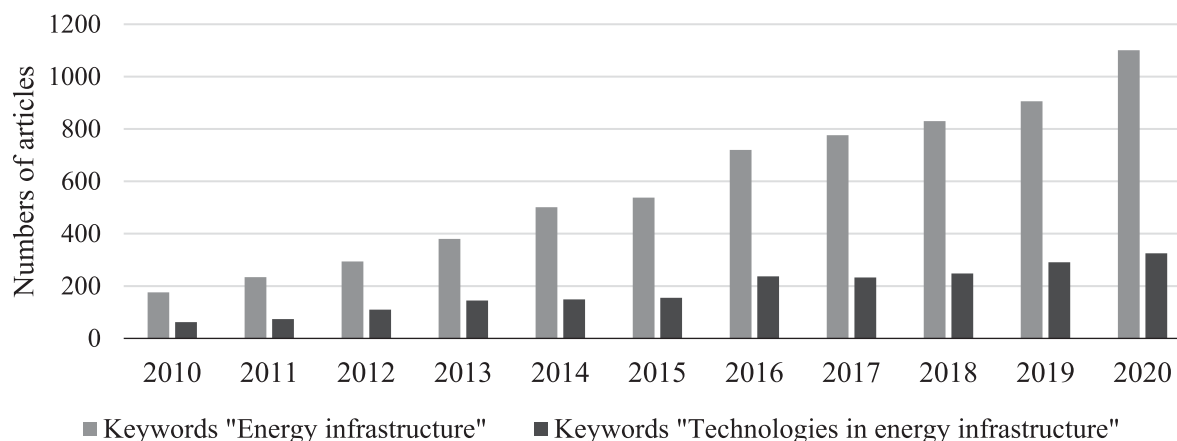


Fig. 3. The relevance of the research about energy infrastructure (Science Direct, 2020).

not possible to simply alter the technological basis of the society, from dirty to green, or unsustainable to sustainable, without severely altering the fundamental social, economic and institutional relations, that regulate our everyday lives (Knoeri et al., 2016).

Thus, this article describes an approach to modernizing the energy infrastructure through the development of digital and information technologies. The goal of this approach is to ensure controlled and long-term sustainable energy consumptions, taking into account the needs of the consumers. Section 2 describes the approaches and methods used in the present research and it assesses the contribution of digital and informational technologies to the improvement of the quality of the infrastructure. The subsequent discussion of the results in Section 3 provides the basis for the conclusions addressed in Section 4.

2. Methodology

The methodological approach in this research is based on several scenarios for forecasting. Scenario planning or analysis is a consolidated and structured process of generating future possibilities which have social-economic and environmental implications.

Forecasting by using scenarios is one of the most effective tools for predicting trends and options for the development of certain socio-economic phenomena. Scenarios are not intended to be predictions of likely future events or outcomes and investors thus should not rely on them when making an investment decision. Scenarios are based on plausible assumptions and quantifications. They are designed to force the management to consider, even events that may only be remotely possible (Hew et al., 2020).

In this paper, the scenario planning began with an analysis of the external environment of electric power enterprises and was followed by the identification of the main factors affecting the enterprises and the industry.

The analysis of the external environment of the industry results in the compilation of a list of macroenvironmental factors that, in the considered time period, have the greatest impact on the activities of the organization. The next step is the **development of scenarios**. This stage includes:

- the selection of influencing factors;
- the forecasting of the various potential outcomes of scenarios;
- a combination of significant factors leading to the formation of scenarios.

To select the pertinent factors, it is recommended to rely on the results of the analysis of the external environment in order to identify the most significant factors that will form the consolidated basis of the scenarios. We chose the brainstorming method in order to optimize the identification of the most significant factors, with the utilization of cause–effect diagrams (Mercer, 1995; Al-Samarraie and Hurmuzan, 2018). The result of this should be the one selection of several of the most significant and independent factors. The stage of forecasting various outcomes of scenarios is based on the analysis of the identified factors and on the compilation of several of their outcome options. The purpose of the combination of the most significant factors is to establish the interdependence between the predicted outcomes of the factors under consideration, as well as to write scenarios. Next, it is required to combine the resulting mini-scripts into several large scripts. At the same time, as the opinions of researchers differed regarding the question of the required number of scenarios, we proposed to develop two main scenarios, including all favorable outcomes of key factors in one scenario (positive), and negative outcomes in another one (pessimistic scenario).

This having being done, it becomes then mandatory to assess the plausibility of the scenarios and, if necessary, to eliminate options for outcomes that are not possible. We will also have to assess the resulting scenarios from the point of view of the main stakeholders and of employees of the companies.

This paper proposes to use the Delphi survey (Chen et al., 2020; Jones, 2015). This method is widely used in planning scenarios in the energy sector. It involves the generalization of all individual expert assessments regarding one situation. The Delphi process was split into three phases and five steps. The different steps of our research method through the Delphi process are presented in Fig. 4.

On the basis of the results of the first survey, we developed weights to calibrate quantitatively the relationship between the characteristics of the infrastructure and global challenges and technologies. The second round of the survey allowed discussion of the results. We received comments during the analysis results and continued the study using additional opinions.

Thus, the forecasting of the mutual influence of global challenges and key technologies on the deterioration of the infrastructure of the energy sector is based on the survey over a large set of professional workers and teachers of specialized universities familiar with this topics, and selected worldwide.

An expert group is composed of 82 experts in our research. Based on the results of this survey, we identified key technologies to improve the efficiency of the energy sector.

The volume of work devoted to this study is considerable and each step has been very carefully done, from the evaluation of

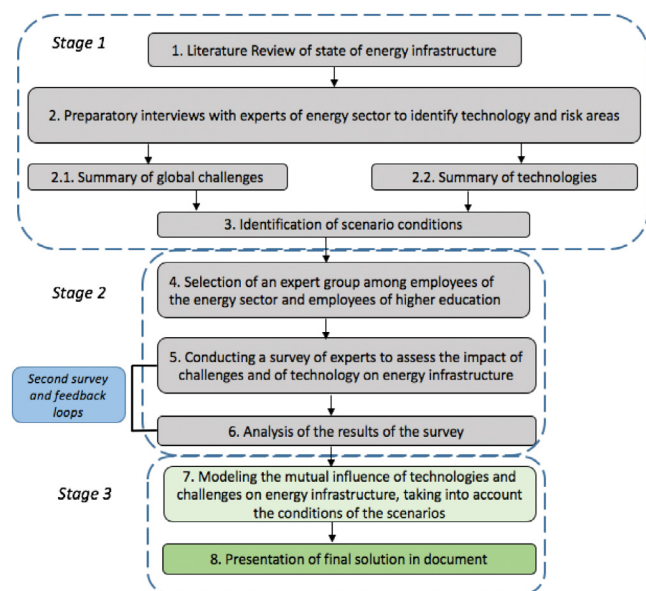


Fig. 4. Steps of our research method through the Delphi process.

today's situation in the energy infrastructure, to the method of investigation we chose, to the conception of a questionnaire, to the selection of the evaluators of this questionnaire, to the data analysis, up to the formulation of the solution we discovered.

2.1. The description of scenarios

Each scenario presents a different set of strategic objectives and core capabilities that achieve the most thorough exploration of the process of decision making (Postma and Liebl, 2005; Schoemaker, 1995).

The scenarios combine vast amounts of data on an eclectic variety of issues such as global economic growth, political factors and environmental issues, and they illustrate the relationship between the main driving forces in interesting or provocative ways (Coates, 2000). It is proposed to solve the problem of determining the degree of influence of global challenges on the infrastructure conditions in the energy sector by forecasting on the basis of an extensive utilization of the scenario approach. At the initial stage of the Delphi method, a small group of 10 experts was assembled. This group of experts was mandated for choosing, from a wide matrix of all scenarios for the development of the energy sector, only two extreme scenarios for the development of the state of the energy infrastructure by the method of brainstorming. These scenarios were formed as the best-case or worst-case scenarios. As a result of the study, two scenarios were formed that determine the possible state of the economic situation. The assessment of the plausibility of the scenarios was made on the basis of an expert survey of the second group of experts in the framework of the Delphi method.

The negative scenario. The rates of economic growth in the world will continue to slow down; the dynamics of world industrial production will be deteriorating. World trade in monetary terms and in physical volumes will be declining. The growth of internal crisis phenomena in real economy will be based on the high volatility of prices of energy resources with a general trend being inclined towards a decrease in their value. The growing unemployment of citizens will lead to massive non-payments for energy and an outflow of investments from the energy infrastructure, which will contribute to the accelerated aging of infrastructure assets, will worsen the environmental situation

and will contribute to an increase in the risks of man-made accidents. There will be a decline in investment demand and uneven investment in the fuel and energy complex, which will lead to an increase in the energy intensity of the Gross Domestic Product (GDP). Attraction of international investment projects will become unlikely, because potential investors will be mostly concerned about the lack of transparent regulation and certainty in the prospects for the development of the fuel and energy industry.

The positive scenario. The globalization of the world and the launch of large-scale supranational infrastructure and energy projects will lead to a worldwide increase in trade, both in monetary and physical volumes. The storm associated with the crisis and quarantine measures will be gradually fading away. The temporarily destroyed global supply chains of energy, materials and goods, in an effort to reduce costs, will be restored in a supranational circuit and they will become more efficient, due to the elimination of political influences. Investment activity will lead to a significant renewal of fixed assets in the energy industry and network infrastructure. Due to moderately high prices for hydrocarbons, the demand for new technologies and equipment, including the renewable energy, will increase. Large-scale introduction of Industry 4.0 and the Internet of Things (IoT) will significantly reduce the cost and personalize most types of products and services, and they will enhance the role of energy-saving technologies and environmentally friendly energy sources. The growth in the global standard of living will become more sustainable. On the basis of digital technologies, organizational and structural optimization will be carried out in the life cycles of all energy hydrocarbons and final forms of energy. International planning and financing, as well as the regulatory framework, will create the prerequisites for integration into the coordinated development of energy infrastructure for sustainable development.

These two kinds of scenario conditions are transformed into sets of coefficients and they are used in the forecasting model for global infrastructure indicators.

2.2. Modeling the impact of global challenges on the deterioration of the infrastructure of the energy industry

For the first time ever, a scenario modeling of the impact of the global challenges on the deterioration of the energy infrastructure across the technological and socio-economic spheres is performed. The analyzed problems are presented in Table 2.

Thus, the underfunding of modernization programs, environmental and climatic changes, in line with the increase in the density of energy consumption associated with the urbanization of the population, with the digitalization and with the smartification, as well as scientific and technological progress, all of them being more energy demanding do contribute and do add more weight to the already existing problem of infrastructure deterioration. By 2030, the impact of such challenges as "Growth of population", "Urbanization" and "Growth of Energy Consumption" will only increase, which will affect the aging of infrastructure assets that require large investments to maintain environmental safety and "activate" scientific and technological progress.

To formalize and to establish the numerical values of the influence of global challenges (G1–G6), it is proposed to use a model scenario of influence. The global challenge was presented to a group of experts. At this stage, an expert survey was conducted on the impact of global challenges on the state of the energy infrastructure. We distinguish three main factors:

- K_1 is the speed of deterioration of the infrastructure. K_1 takes values ranging from -1 to 1 ;

Table 2
Global challenges affecting energy infrastructure.

Challenge	Main feature of the challenge	Impact on the technological sphere	Impact on the socio-economic sphere
G ₁ . Growth of population	The growth of population is projected to 9.1 billion people by 2040 (UN, 2020), requiring additional energy supply for almost 2 billion people (EIA, 2020).	The growing need to improve the quality of life, which will lead to the creation of new technological solutions and adaptation of the elderly to the digital age.	A stimulating economic growth while creating problems with food, water and energy resources.
G ₂ . Urbanization	The concentration of the population within large administrative territorial entities requires an increase in the density of energy consumption and in values of electricity consumption per person.	The need to create separate power grid structures with their own energy sources and capable of taking on the task of meeting consumer demand at a maximum peak load when the central grid cannot provide it.	The increase in specific energy consumption (kW h/m ²); the further growth in the construction of buildings and structures, which will spur such an energy-intensive industry as the production of building materials. The requirements for the complexity of the energy infrastructure, the quality and customization of food, goods and services are growing every year.
G ₃ . Scientific and technical progress	The development of digital and information technologies (end-to-end technologies covering all industries) aimed at improving the energy efficiency of production within Industry 4.0.	The development of personalized flexible infrastructure, however, increased load on energy infrastructure and increased electricity consumption.	The birth of plenty of new markets, services, business strategies and a qualitative transformation of energy markets. Creation of new professions in the field of modernization of energy generation systems, recuperation systems, energy storage, smart grids.
G ₄ . Growth of energy consumption	The demand for energy is provided by the process of incessant human development and scientific discoveries and technological progress.	An energy efficient use of resources is needed, which in turn creates preconditions for the development of smart energy systems. An increase in requirements for the quality of electricity.	Growth of electricity tariffs and degradation of the country's environmental situation. In this regard, there is a need to modernize infrastructure and to develop energy efficient thinking.
G ₅ . Climate change	The environmental situation affects the growth and aging of the population, increased consumption, deterioration of the energy industry infrastructure. An increase in the share of renewable energy sources, the introduction of energy-efficient equipment, the formation of prosumers.	Digital and information technologies will allow attracting investments for the implementation of environmental projects, the introduction of clean technologies and the reduction of emissions of harmful substances into the atmosphere.	Encouraging the population to sort, recycle, and reuse household waste. A rational use of non-energy resources.
G ₆ . Economic downturn	The economic and financial downturns are forcing significant budget cuts, which is the main reason for lack of repair and reconstruction in infrastructure facilities. Increased costs for maintenance, technical upkeep, repair of outdated result, to unprofitable technologies.	The introduction of technological changes at the production facilities of the energy sector is slowing down: the risks of shutting down many production processes are increasing, where the costs of the capital and the operating expenditures become incommensurate with oil prices; construction work is suspended due to restrictions on the entry of foreign specialists.	The economic crisis affects the entire life cycle of facilities in the area of hydrocarbon energy: production chains are cut off, effective demand falls, and investments in new technologies are postponed.

- K_2 is the force of the influence or of an obedience between challenges. K_2 takes values ranging from -1 to 1 ;
- K_3 is the force of influence of the global challenge for the energy infrastructure. K_3 takes values ranging from 0 to 1 .

Each of these indicators is estimated in conventional units. The assessment largely varied, depending on the infrastructure development scenario and on the availability of evidence of an impact on the infrastructure as a whole. In the course of the survey, it was analyzed how the challenge will manifest itself in negative and positive scenarios. *In an attempt to make the expert's assessment as independent as possible, none of the selected experts participated as scriptwriters.*

The application of the Method of Interaction Matrices allows, on the basis of the interaction matrix, to reveal the degree of mutual influence of the factors of the considered set and to predict their behavior in the future (Ceryan and Usturbelli, 2015).

The simulation resulting of the negative scenario are presented in Fig. 5. The feature of global challenges is the degree of influence (K_2). It represents the force of influence (that takes values ranging from 0 to 1) or obedience (that takes values ranging from 0 to -1) between challenges on the horizontal axis. The other feature of global challenges is the speed of deterioration of infrastructure (K_1). It represents the acceleration/deceleration of the deterioration of the infrastructure under the influence of a particular challenge in a particular scenario on the vertical

axis. *The force of this influence is reflected by the diameter of the spheres.* The name of the challenge is indicated on the graph. These scenario conditions, in the form of weight coefficients, are used in the forecasting model.

The results of modeling a positive scenario are presented in Fig. 6.

Based on the data of positional maps, each of the scenarios can be represented in the form of a generalized coefficient of influence K , which is derived from the following formula:

$$K = ((K_1 + K_2) \cdot K_3) / 2, \tag{1}$$

Based on the results of the analysis and calculations using formula (1), the final generalized influence coefficient is obtained for both scenarios, which determines the final degree of significance for three indicators of each challenge for the energy infrastructure. The result of our analysis is given in Table 3.

According to the data we obtained, it was estimated that in the case of a negative scenario, the generalized influence coefficients of the global challenges impact on the infrastructure condition will be $K_N \approx 0.5$, while in the context of a positive scenario, this coefficient will be minimal and will be $K_P \approx 0.1$. This unambiguously indicates the possibility of implementing a program to develop a sustainable energy infrastructure with a minimum number of risks if all the conditions described in the positive scenario are met.

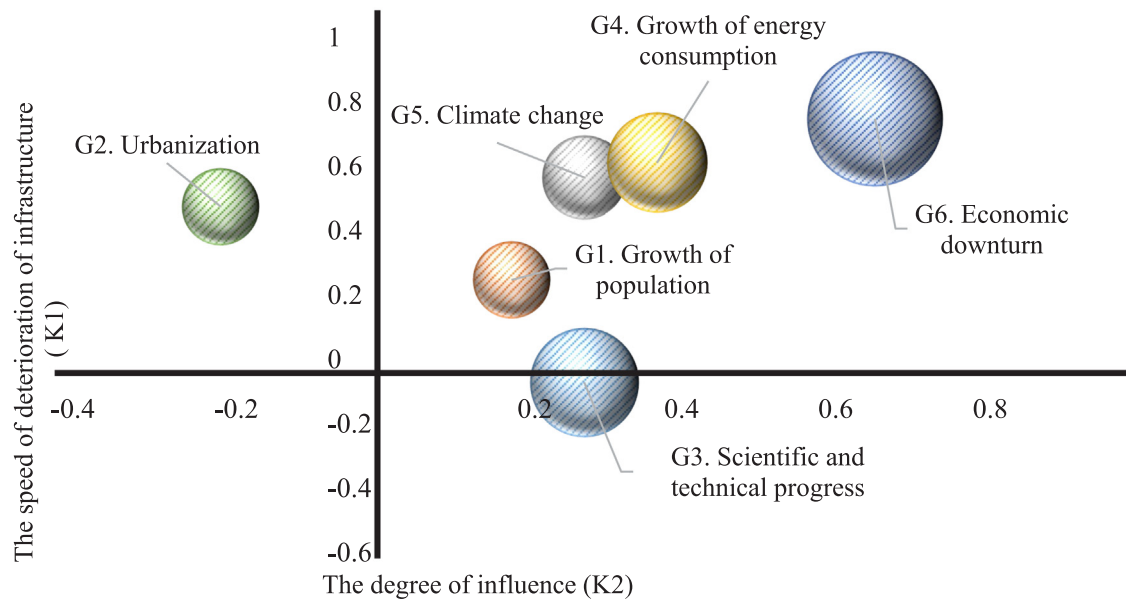


Fig. 5. Results of modeling the impact of challenges on the energy infrastructure (negative forecast). The diameter of the spheres is proportional to the force of influence of the global challenge for the energy infrastructure.

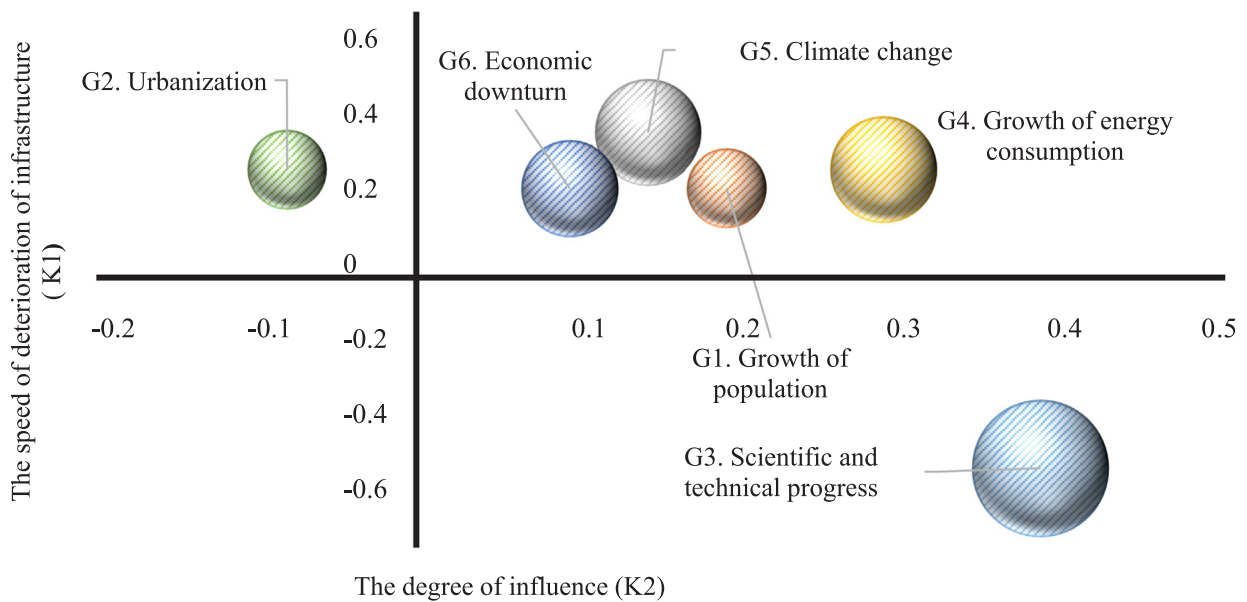


Fig. 6. Results of modeling the impact of challenges on the energy infrastructure (positive forecast). The diameter of the spheres is proportional to the force of influence of the global challenge for the energy infrastructure.

Table 3

Generalized influence coefficients of impact of the global challenges on the infrastructure for two conditions of scenario, where K_N is coefficient of influence in negative scenario; K_P is coefficient of influence in positive scenario.

	K_N (Negative scenario)	K_P (Positive scenario)
Growth of population	0.0808	0.0175
Urbanization	0.0120	0.0060
Scientific and technical progress	0.0140	-0.0300
Growth of energy consumption	0.0808	0.0450
Climate change	0.0480	0.0405
Economic downtime	0.2170	0.0187

The scenario conditions were compared with the results of the expert group. For the purposes of a robust testing of the validation, the expert judgment is considered as the best reflect of the reality. The expert survey is based on a more detailed evidence of the provision of the impact of global challenges on infrastructures rather than on a quick estimate based on statistics. However, the assessment of experts must be supported by reasonable justifications. Scores with high dissensus were considered to be unsuitable for validation. For assessments where there was moderate and high dissensus, the reasons for the dissensus were sought in the rationale provided in order to examine whether or not the variation has implications for or against the method.

For the next stage of the study, it is necessary to assess the impact of global challenges on the infrastructure conditions, in

Table 4

The weights coefficients W_{ij} (i is the number of challenges and j is the number of characteristics) for the relationship between the infrastructure characteristics and the global challenges.

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
G_1	0.786	0.674	0.732	0.532	0.620	0.534	0.611	0.134
G_2	0.765	0.575	0.467	0.437	0.482	0.362	0.932	0.132
G_3	0.880	0.945	0.834	0.760	0.832	0.782	0.901	0.822
G_4	0.879	0.838	0.956	0.656	0.741	0.821	0.930	0.181
G_5	0.456	0.759	0.478	0.357	0.389	0.745	0.145	0.942
G_6	0.698	0.889	0.930	0.781	0.791	0.621	0.543	0.281

order to further predict the state of its energy part, taking into account the mutual influence of global challenges and technology development.

In this part of the study, indicators characteristics of the energy infrastructure use eight coefficients $P_{j=1...8}$ that are established, from the results of the study and are based on the results of an expert survey. Their weights coefficients W_{ij} were evaluated for the connection with six global challenges $G_{i=1...6}$. For this study, we focused on 6 key challenges, 31 technologies divided into 6 blocks, and 8 characteristics that describe infrastructure conditions as a whole.

Features of infrastructure conditions are reference indicators by which a general conclusion can be drawn about structural problems and vulnerabilities of the entire energy infrastructure:

- P_1 – the reliability (includes reliability, recoverability, survivability, safety, controllability, preservation, stability);
- P_2 – the cost of ownership (for the entire period of operation);
- P_3 – the availability (the state of the infrastructure, in which subjects with access rights can implement their work without hindrance);
- P_4 – the observability (the ability of the system to provide necessary information about its current conditions);
- P_5 – the accident rate (total number of emergency situations for the entire period of operation);
- P_6 – the maintenance time (equipment commissioning, operation, maintenance and repair, equipment removal, disposal);
- P_7 – the throughput (the maximum possible power that can be transmitted, taking into account the operating conditions and parameters of the infrastructure reliability);
- P_8 – the environmental safety (properties of the energy infrastructure that allow to not pose a threat to human life and health, as well as to the environment, during operation and in the event of a malfunction).

The research results are presented in [Table 4](#).

The coefficients take values ranking from 0 to 1 with a step of 0.001. We distinguish three different situations taking into account the ranges: $W_{ij} \leq 0.3$ for the weak influence; $0.3 < W_{ij} \leq 0.6$ corresponding to conditions of a medium effect; $0.6 < W_{ij} \leq 1$ in the context of a strong influence. It should be noted that we averaged these values for all experts, excluding observations with incomplete information on the key characteristics of infrastructure conditions. Thus, the first goal of the study was fulfilled: the analysis of global challenges affecting the infrastructure was conducted and the degree of their impact on key characteristics was determined based on the scenario modeling. The next stage of the study is the development of a methodology for assessing the impact of the ecological changes on the rate of infrastructure renewal in the electric power industry.

2.3. Assessment of the impact of technological changes on the rate of renewal of infrastructure in the electric power industry

According to [Di Silvestre et al. \(2018\)](#) the paradigm of the fourth industrial revolution in the fuel and energy complex involves the introduction of modern high-tech solutions at all stages of the cycle of the product life.

Today, almost all companies in the fuel and energy complex use information and communication technologies (ICT) in their activities. But, unfortunately, the ICT of many countries, including the Russian Federation, consists only of personal computers, local networks, warehouse automation and accounting systems, websites, outdated technological applications or proprietary functional products. Share of innovative goods, works and services in the overall volume of exports of goods, works and services in 2018 amounted to only 7.1%.

Ineffective use of information technologies at enterprises of the fuel and energy complex leads to such problems as:

- (1) the impossibility of remote control;
- (2) the lack or the low level of automation;
- (3) a low observability;
- (4) a non-standardized management;
- (5) stricter requirements for energy infrastructure;
- (6) the absence of a single information platform in the structure of vertically integrated oil and gas enterprises and energy companies.

The lack of information and technical support leads to an increase in requirements of the consumer for the quality of the supplied products and for the reliability of their transportation. However, the main factor hindering a qualitative increase in electricity consumption and full electrification is the deterioration of the energy infrastructure. The use of fundamentally new approaches, materials and technologies allows achieving a higher level of sustainability and reliability of the infrastructure. Large-scale implementation of Industry 4.0 and IoT can provide environmental safety, can provide resilience to severe weather and seismic impacts, can improve customer service, can update the mechanism of spare capacity reallocation, can change social and economic trends and it can also improve the planning of natural resource exploitation planning.

Thus, it is expected that digital technologies will make a great contribution to the quality of the infrastructure, but the question of which particular set of specific technologies will be needed, still remains unresolved. Some of the digital technologies were previously used but they were restricted to the production process only. It is now obvious that their extension to the entire value chain is needed, what can be called end-to-end technologies. Of course, these digital technologies themselves consume energy, but the effect of their implementation can drastically reduce emissions and significantly improve the quality of services. Based on the results of our study using of international and domestic sources of information, we identify 31 main technologies which will allow the transition to the digital smart energy (they are hereafter labeled A_1 – A_{31}). All the analyzed technologies acting within the same field direction were gathered into 6 specific groups (labeled $T_{m=1...6}$), according to their functional properties.

In this regard, it is necessary to take into account the contribution of the key technologies A_1 – A_{31} to certain properties of the energy infrastructure. Their own influences appear in the infrastructure conditions specific to the energy sector. The full set of data is given in [Table 5](#).

During the study, for eight characteristics $P_{j=1...8}$, based on the results of the study and on the expertise survey described in paragraph 3.2, the weights coefficients Z_{mj} are established for the connection with technological blocks $T_{m=1...6}$. They make it possible to identify the degree of the influence of each technological change on the infrastructure conditions as a whole group and

Table 5
The key technological blocks $T_{m=1...8}T$ and technologies A1–31.

Group name	Technology name
T ₁ Renewable energy	A ₁ . Network generation; A ₂ . Small distributed generation of renewable energy sources; A ₃ . Network storage technologies; A ₄ . Local storage technologies; A ₅ . Technologies for converting secondary resources into electricity; A ₆ . Hydrogen energy;
T ₂ Information technology	A ₇ . Foreseeable maintenance and repair; A ₈ . Intellectual diagnostics of electrical equipment; A ₉ . Big Data and Machine Learning; A ₁₀ . Internet of things (IoT); A ₁₁ . Distributed register; A ₁₂ . Information security.
T ₃ Digital technologies	A ₁₃ . Intelligent sensors; A ₁₄ . Intelligent accounting; A ₁₅ . Active-adaptive electrical grid A ₁₆ . Intelligent automation and control systems; A ₁₇ . Unmanned aerial systems; A ₁₈ . Microgrid and aggregation of demand; A ₁₉ . Digital substation.
T ₄ Materials science and equipment	A ₂₀ . New construction materials; A ₂₁ . High-temperature superconductivity; A ₂₂ . Cables and wires; A ₂₃ . Power electronics; A ₂₄ . Switching equipment.
T ₅ Energy saving	A ₂₅ . Energy-efficient production; A ₂₆ . Energy-efficient equipment; A ₂₇ . Energy management.
T ₆ Non-renewable energy	A ₂₈ . Clean system for producing charcoal; A ₂₉ . Increase in oil recovery; A ₃₀ . Technologies for developing of difficult recoverable reserves; A ₃₁ . Gas utilization, including liquefaction.

Table 6
The weight coefficients Z_{mj} of the relationship between the infrastructure characteristics and technological blocks.

	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈
T ₁	0.571	0.691	0.829	0.311	−0.286	0.112	0.362	0.759
T ₂	0.763	0.443	0.685	0.796	−0.467	−0.422	0.221	0.247
T ₃	0.790	0.522	0.356	0.782	−0.786	−0.121	0.142	0.178
T ₄	0.597	0.141	0.241	0.111	−0.690	−0.124	0.365	0.030
T ₅	0.124	0.423	0.624	0.211	−0.578	0.090	0.657	0.698
T ₆	0.791	0.652	0.561	0.141	0.121	0.154	0.221	−0.274

separately one by one. The results of this research are presented in Table 6.

During the modeling of the weight coefficients, the degree of the influence of technological blocks on the state of the infrastructure was determined. As a consequence, with the help of the division into technological groups, the model allows to track changes in features that will be influenced by the challenges under consideration. The reverse sequence allows to identify the necessary technological changes that can impact the features of the infrastructure conditions and that can determine the most problematic sectors that need to be considered with the most attention and the most care by the state.

Thus, in this section, the second task of our study – measuring the impact of technologies from blocks $T_{m=1...6}$ on the rate of infrastructure renewal in the electric power industry, according to the main characteristics $P_{j=1...8}$ is achieved. It is found that the greatest impact on the energy infrastructure condition is exerted by technological blocks as Information Technology, Digital Technologies (the highest ratio of reliability, observability, reduction of accidents and maintenance time).

The scenario modeling of the impacts of the global challenges on the deterioration of the energy infrastructure and the assessment of the impact of technological changes on the rate of renewal of real assets in the electric power industry will make it possible to act on the followings:

- tracing the mutual influence of challenges on the infrastructure condition and taking into account limits of scenarios and technologies;
- achieving the consolidated identification of the key technologies required to reduce the negative impact of the aging of the equipment and of technologies, the development of which will lead to an accelerated attraction of investments in the energy sector.

2.4. Mutual influence of challenges, taking into account scenario limits and technologies, on the condition of the infrastructure

The next stage of our study is to determine the mutual impact of challenges, taking into the limits account of scenario and technologies, on the characteristics of the energy infrastructure up to 2030. First of all, for this, it is necessary, as a prerequisite, to determine the coefficient of change in the global challenges $X_{i=1...6} = [G_i(2035) - G_i(2020)] / (G_i(2020) * 100\%$, in accordance with the forecasts of the leading agencies and companies of the energy sector.

It is related to the indicators of characteristic of the energy infrastructure through the weighting coefficients obtained during our study. The quantitative change in global challenges until 2030 has been determined in accordance with the leading energy agencies. The data from Table 7 was estimated globally and can be applied to any country in the study.

The weight coefficients W_{ij} from Table 4 for the relationship between the 8 characteristics of the infrastructure $P_{j=1...8}$ and the 6 global challenges $G_{i=1...6}$ are multiplied by the coefficient of change in the global challenges X_i by formula:

$$V_{ij} = W_{ij} \cdot X_i, \tag{2}$$

where the V_{ij} are the new weight coefficients for the relationship between the 8 characteristics of the infrastructure and the global challenges with considering the coefficient of change in the global challenges X_i ; W_{ij} is the weights coefficients for the relationship between the 8 infrastructure characteristics and the 6 global challenges from Table 4; X_i is the coefficient of change in the global challenges from Table 7; i is the number of global challenges and j is the number of characteristics.

The new value of eight characteristics of the infrastructure \bar{P}_j with considering all six challenges is calculated by the formula:

$$\bar{P}_j = C_j \frac{1}{6} \sum_{i=1}^{i=6} V_{ij}, \tag{3}$$

where $C_{j=1...8}$ is the current level of the value of characteristics of the infrastructure $P_{j=1...8}$ from Table 8; V_{ij} is weights coefficients for the relationship between the characteristics of infrastructure and the global challenges with considering the coefficient of change in the global challenges X_i from formula (2); i is the number of global challenges.

Taking into account the coefficient K_N in the negative scenario and the coefficient K_P in the positive scenario from formula (1) and Table 3, we determine the variation in the characteristics of the infrastructure for the negative and positive scenarios using the formulas:

$$\Delta \bar{P}_j \text{ negative} = (C_j - \bar{P}_j) \cdot K_N \tag{4}$$

$$\Delta \bar{P}_j \text{ positive} = (C_j - \bar{P}_j) \cdot K_P \tag{5}$$

Table 7
Changes in the studied global challenges 2020–2035.

No	Index	2020	2035	X, %
G ₁	Population, (billions)	7.79 (UN, 2020)	8.89 (UN, 2020)	14
G ₂	Population in Urban Areas, (%)	56.2 (UN, 2020)	62.5 (UN, 2020)	11.2
G ₃	Research and development costs, (%)	22.5(WB, 2018)	26.5 (WB, 2018)	18
G ₄	Energy consumption, (quadrillion Btu)	4.82 (EIA, 2020)	5.14 (EIA, 2020)	6.6
G ₅	CO2 emissions, (Gigatons CO2)	35.34 (BP 2020; EIA 2020)	37.46 (BP 2020; EIA 2020)	5
G ₆	Gross domestic product (GDP), (thousand billion US dollars)	103.04 (OECD, 2020)	156.2 (OECD, 2020)	51

Table 8
The current level C_{j=1...8} of the value of characteristics of the infrastructure.

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈
2020 (the current level)	0.31	0.91	0.4	0.21	0.71	0.90	0.55	0.10

Table 9
The required level L_{j=1...8} of the value of characteristics of the infrastructure.

	L ₁	L ₂	L ₃	L ₄	L ₅	L ₆	L ₇	L ₈
2020 (the required level)	0.80	0.30	0.65	0.95	0.51	0.41	0.85	0.85

Table 10
Characteristics of energy infrastructure, taking into account the impact of global challenges.

	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈
2030 (the negative scenario)	0.28	0.72	0.38	0.17	0.77	1.02	0.50	0.08
2030 (the positive scenario)	0.30	0.69	0.40	0.21	0.68	0.88	0.56	0.11

where $\Delta\bar{P}_j$ negative is the variation in the characteristics of the infrastructure for the negative scenario; K_N is coefficient of influence in negative scenario; $\Delta\bar{P}_j$ positive is the variation in the characteristics of the infrastructure for the positive scenario; K_P is coefficient of influence in positive scenario.

We obtain the final value of \bar{P}_j negative is the characteristics of the energy infrastructure in negative scenario and \bar{P}_j positive is the characteristics of the energy infrastructure in positive scenario using the formulas:

$$\bar{P}_j \text{ negative} = C_j - \Delta\bar{P}_j \text{ negative} \tag{6}$$

$$\bar{P}_j \text{ positive} = C_j + \Delta\bar{P}_j \text{ positive} \tag{7}$$

These formulas will be applied for infrastructure indicators P₁, P₃, P₄, P₆, P₇, P₈. Since the indicators have a negative effect (P₂, P₅), then when calculating their parameters, it is necessary to transform the formulas into the following form:

$$\bar{P}_j \text{ negative} = C_j + \Delta\bar{P}_j \text{ negative} \tag{8}$$

$$\bar{P}_j \text{ positive} = C_j - \Delta\bar{P}_j \text{ positive} \tag{9}$$

The results are presented in Table 10.

The results indicate the characteristics of the conditions under which the energy infrastructure will remain unsatisfactory without modernization by the introduction of advanced technologies. Unfortunately, the required level L_{j=1...8} of the P₁–P₈ characteristics cannot be achieved even in the long term up to 2030 under the condition of a positive scenario.

By using formulas (1)–(9), we can carry out a similar calculation in order to account for technological changes. The global challenges G_{i=1...6} will be replaced by the technological blocks T_{m=1...6}. However, in this case, the characteristics of the infrastructure will be used from Table 8.

In this regard, the mandatory quantitative changes in the technological blocks we considered and studied were evaluated in order to approach the required indicators by 2035 with the scenario modeling presented in Fig. 7.

In the frame of the negative scenario, the result of a strong investment gap, of an increased load as the straightforward consequence of an increased consumption, the deterioration of the environmental situation and the low level of technology introduction in the infrastructure shift in concert the reliability and the amount of accidents in the energy sector to the critical zone. Achieving the necessary level of infrastructure condition to meet the requirements of environmental safety becomes impossible.

The changes will be the most significant in availability and maintenance time because otherwise the infrastructure can become a deterrent to any innovative development and to the transition to the digital economy.

In the context of the positive scenario, one of the main factors in achieving indicators of infrastructure quality (in conventional units) is the introduction of technologies until 2030. Achieving the SDGs is possible as evidenced by the high indices of 8 indicators of the infrastructure:

- The reliability will be increased from 0.3 to 0.6, thus making the infrastructure more safe and more resilient. It is a prerequisite for achieving Sustainable Development Goal 11 - *Sustainable cities and communities*.

- The cost of ownership has been reduced from 0.9 to 0.4 and it will be closer to the required level. It is a prerequisite for achieving Sustainable Development Goals 11 and 12 - *Sustainable cities and communities and Responsible consumption and production*.

- The availability will increase from 0.4 to 0.6 and it will fully reach the required level. This will provide access to the energy for a large number of people. It is a prerequisite for achieving Sustainable Development Goals 7 and 10 - *Affordable and clean energy and Reduced inequalities*.

- Observability will increase from 0.2 to 0.7, which will improve the quality of monitoring and managing the infrastructure. It is a prerequisite for achieving Sustainable Development Goal 12 - *Responsible consumption and production*.

- The number of accidents will significantly decrease from 0.7 to 0.6. This has a direct impact on the environment. It is a prerequisite for achieving Sustainable Development Goal 13 - *Climate action*, but we believe that this decreasing to a value of 0.6 is good but not enough and more than other characteristics require additional programs to achieve this SDG.

- The maintenance time will decrease from 0.9 to 0.7. It is a prerequisite for achieving Sustainable Development Goal 7 and 12 - *Affordable and clean energy and Responsible consumption and production*. However, it also requires additional measures, since the required level of the indicator is 0.4.

- The throughput will increase from 0.55 to 0.65 and thus it will meet the demand for energy. It is a prerequisite for achieving Sustainable Development Goal 7 - *Affordable and clean energy*.

- *Environmental safety of energy infrastructure use will increase from 0.1 to 0.45*. It is a prerequisite for achieving Sustainable Development Goal 13 - *Climate action*.

Thus, technological improvement and energy efficiency can directly contribute to the 9th sustainable development goal – Industry, innovation and infrastructure. In addition, it will allow indirectly achieving the 5 Sustainable Development Goals: 7th SDG (Affordable and clean energy), 10th SDG (Reduced inequalities), 11th SDG (Sustainable cities and communities), 12th

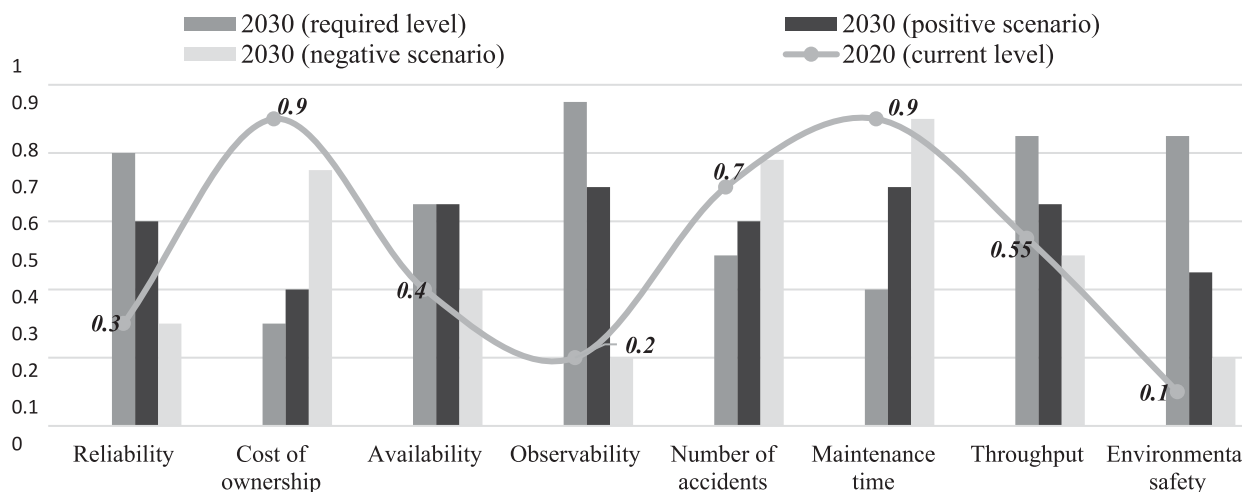


Fig. 7. Results of the modeling of the infrastructure condition modeling, taking into account scenarios, the impact of global challenges and technological changes.

(Responsible consumption and production), 13th SDG (Climate action).

In this regard, it is mandatory to strengthen and stimulate the companies of the electric grid complex to participate, strive and become more responsible in achieving the SDGs.

The main influence arises from specific technological blocks such as *Renewable Energy, Information Technology and Digital Technologies* (Fig. 8).

The rate of required technological changes R_m of technological blocks $T_{m=1...6}$ was calculated using the formulas:

$$R_m = \frac{1}{8} \sum_{j=1}^{j=8} \frac{L_j}{\bar{P}_j \text{ positive} \times \frac{1}{8} \sum_{j=1}^{j=8} Z_{mj}} \quad (10)$$

where L_j is the current level of the value of characteristics of the infrastructure from Table 9; Z_{mj} represents the average weighting factor of the influence of the technological unit on the characteristics of the infrastructure in accordance with Table 6; $\bar{P}_j \text{ positive}$ represents the value of the infrastructure characteristics $P_{j=1...8}$, which is obtained by taking into account the impact of challenges and of technological changes, calculated according to formulas (1)–(9).

It should be emphasized that the calculations use the infrastructure characteristics in the context of a positive scenario. Also, it should be noted that data can be also obtained for a negative scenario. The impact rate was calculated separately for each characteristics and an average value was obtained for improving the infrastructure as a whole.

Thus, technological changes are needed that can affect the observability, the cost of ownership and the environmental safety, in such ways that the infrastructure does not become a constraint to the development and to the different transition towards the digital economy.

The methodology in this article can be applied to conduct similar studies in other countries. We propose a methodology based on the example of the state of the infrastructure in the Russian Federation. The assessment of technological changes in the energy infrastructure should be done by scenario modeling using the method of brainstorming. To assess the scenarios and the state of the infrastructure, it is necessary to refer to the expert judgment based on the Delphi method. Based on the results of an expert survey using the Delphi method, it is necessary to determine the coefficients of the influence W_{ij} of global challenges $G_{i=1...6}$ and the weight coefficients Z_{mj} of the influence of technological blocks $T_{m=1...6}$ on the characteristics of the infrastructure

$P_{j=1...8}$. It should be noted that the list of 6 global challenges, block 6 of technologies and a list of 8 characteristics of the state of the infrastructure can be applied to any country. However, the coefficients W_{ij} and Z_{mj} in Tables 4 and 6 respectively will be changed according to the country or company. The new value of the characteristics of the energy infrastructure, taking into account the positive and negative scenarios, will be calculated using formulas (1)–(10). The value of the parameter X_i from Table 7 also remains unchanged and can be applied to any country.

3. Results and discussion

Based on the results of expert assessments, the coefficients of the mutual influence of the technological blocks and of global challenges on the signs of the state of the infrastructure were constructed. The indicators highlighted that our scientific approach makes possible to get access to the complex state of the energy system from the standpoint of reliability, quality, accidents and environmental risks.

3.1. Key technologies

Based on the simulation results, we identified the key technologies required to mitigate the negative impact of the aging of the energy infrastructure. We discovered that the largest amount of demand will appear in the field of digital and information technologies, as well as in the field of distributed generation based on renewable energy sources.

3.1.1. Renewable energy sources

The global production of electricity based on renewable energy sources will increase to 40–50 billion kWh in 2030. The next stage in the development of renewable energy sources is the connection with other technological blocks. A large scale implementation of renewable energy sources is therefore possible, with a breakthrough in other adjacent areas, for example, the development of space renewable resources. It is a type of alternative energy, involving the use of solar energy to generate electricity, with the location of a power station in the earth’s orbit or on the Moon, which will be primarily available in countries such as the Russian Federation and the United States. The main way to support grid of technologies for renewable energy is the investment in generating projects of construction based on high capacities of production of renewable energy with guaranteed feedback on investment and a high degree of profitability from electricity consumers.

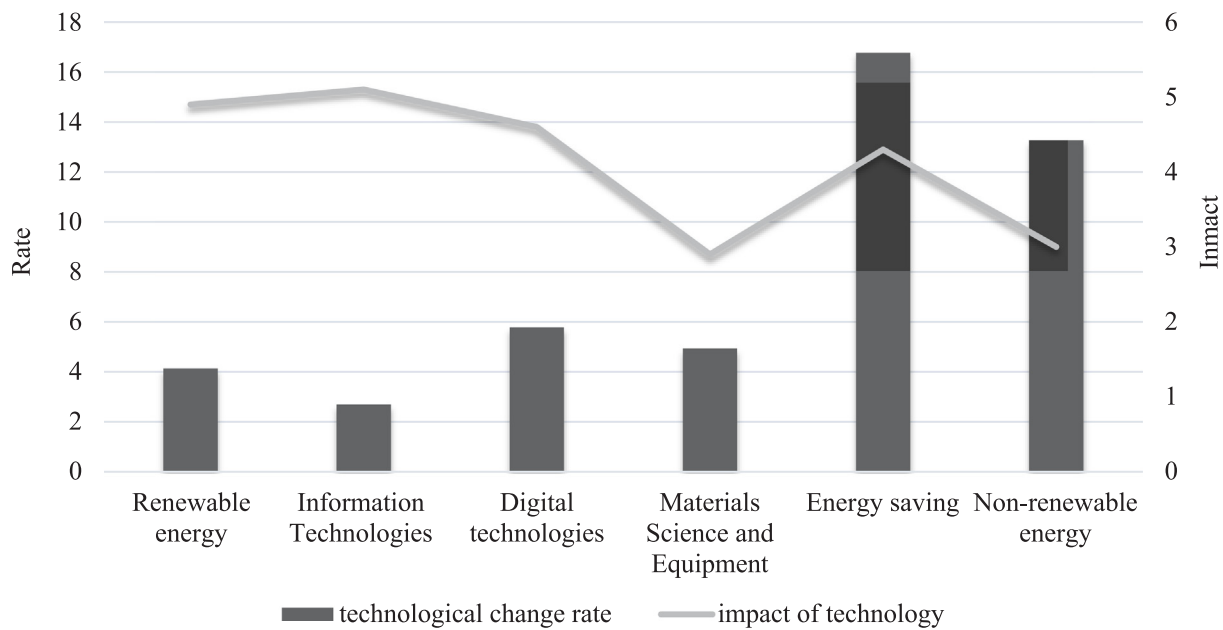


Fig. 8. Coefficient of the necessary technological changes and their degree of influence based on the simulation results.

3.1.2. Digital and information technologies

Today, the main strategic goals of the energy sector are the course towards energy saving and the introduction of information and digital technologies.

It can increase the interaction between the consumer and the system for the large-scale production of the energy. These technologies will serve as a basis for gaining more flexibility in integrating various systems for energy resources. Digital and information technologies such as internet of energy (IOE), big data and cloud computing, have a highly positive influence for changing the state of the infrastructure of energy sector:

1. The concept of Internet of Things (IoT) & Internet of Energy (IoE) will enable better decision making, flexible energy transactions, intelligent distributed automation, and real-time supply as well as the balancing of demands. This will provide remote control of elements of the electrical network and power plants. It is a prerequisite for creating emergency control devices and to relay protection with self-diagnostics, remote control and parameterization functions. Virtual power plants with aggregated services of consumers based on IoT will balance the load. Moreover, IoT will enable the integration of distributed sources and facilities for the production of an intermittent generation of renewable energy.

2. The concept of Big Data will enable better decision makings, acceleration of business process control, increased observability of grid infrastructure. Big data comes from embedded systems, devices, infrastructure sensors. This increases the observability of equipment parameters and electrical power regime. Operational data can provide a basis for the use of artificial intelligence (AI) in the tasks of predicting the risks of violation of the conditions for the safe operation of energy facilities.

3. The concept of Cloud Computing will allow computers to receive and to process a huge amount of information about energy infrastructure. It will allow to analyze the condition of the equipment based on diagnostic data. Cloud Computing is responsible for storing and analyzing data, as well as managing data and users.

These technologies are combined into the following technological solutions:

(a). *Digital substations operating at 35–110 kV*. This requires minimal size and implementation cost, built-in measuring and intelligent capabilities (integrated functions of protection and

automation, monitoring, accounting and data transmission) in the Plug and Play ideology. This technology will be effective in reducing the capital expenditures.

(b). *Active-adaptive network*. We mean the optimization of the network topology and the implementation of algorithms for automated control of power lines based on the principles of automatic allocation of the lowest possible damaged sections of power line in order to minimize the number and duration of outages. This technology will be effective in reducing the capital and the operating expenditures. It will also reduce the index of the system average interrupt duration and the index of the system average interrupt frequency.

(c). *Smart measuring system*. This concerns, as part of an integrated decision support system – an energy management and energy monitoring system with a commercial dispatcher function and online monitoring of commercial loss centers. This technology will be effective in reducing the power losses.

(d). *Integrated support system of decision*. We are talking here about a unified information system for operational–technological and situational management. It ensures the creation of a model single network based on the requirements that determines the standards for information exchanges between the different actors which are the electrical distribution systems and a complex of applications of SCADA (system of supervisory control and data acquisition); DMS (system of distribution network management); OMS (system of outage management); OTM (an interconnected network of operational and technological management). This technology will be effective in reducing the operating expenditures.

Smart ways have to be found for monitoring, for controlling and for optimizing the energy savings primarily related to the rising cost and demand for energy. The emergence of digital production is capable of changing the approach of consumers to the energy supply. The network infrastructure must adapt itself to customer requirements, which continue to grow steadily. Based on AI, it is possible to build not only a dynamically controlled system, but one can also integrate various energy resources. AI will allow to build a unified dispatching of gas, water, heat, hydrogen, electricity. The integration of energy and distributed generation based on AI will allow systems to be more secure, energy efficient, flexible, environmentally friendly and sustainable. It reinforces the focus on the combating of climate change throughout the

energy and resource supply chain. This is why the management of the energy has become an important part of an integrated sustainable development strategy.

3.2. Future directions and suggestions for development of energy infrastructure

Scientific and technological progress in the energy sector are currently living a tremendous momentum. The degradation of competencies in this industry will practically catch up with the IT sphere by 2030 and will have about 2–3 years lifespan. In this regard, the launch of the new personnel training with “ready to work” skill sets in the digital power grid complex should have started fairly ago. It is important to note that the digitalization should take place simultaneously with the modernization of the laboratory base, with the ad-hoc formation of the required number of students (technicians, engineers) by teachers having the ad-hoc knowledge in dedicated universities.

The main directions for digital technologies should be focused on the following conditions:

- the improvement of equipments, technologies and technological processes through the introduction of known and new scientific knowledge;
- the wide availability of information (receiving, transmitting, exchanging data);
- the updating of the list of creating of the professions demanded in line with the intellectualization, the digitalization and the automation of work processes;
- the retraining of specialists and training of new personnel.
- the advanced training for employees in the area of cybersecurity, with access to the information system.
- an additional support in the form of investment programs from the state for equipment suppliers.
- the Changes in the law on the transfer of personal data for Big Data technology.

The digital technologies and the social sector can be both controlled and efficiently managed to ensure a convenient sustainable development. Satisfying the needs of the present days also requires to reach a reliable and sustainable balance with the wills of all stakeholders. The balancing of interests should be automatic and transparent. These transformations will be facilitated by the creation of specialized digital platforms. *It is proposed to create a self-organizing energy platform called EnergyRF (Fig. 9).*

Automation in the digital platform goes through the entire life cycle, up to the liquidation of a power facility or participant. The systematic search for the efficiency in the use of resource and the detection of any waste management in the perspective to reduce the burden on the environment become highly manageable. The integration of a transparent economy, of a fair governance, the possibility of an action from the side of the government action, taking advantage of a good degree of education and using the best of the science will make progress towards sustainable development goals. Being already at the design stage of infrastructure facilities, such indicators like service life, repair management, disposal and reuse become apparent.

The consumer is a key partner of the platform. The formation of a smart consumer through digital technologies is a key challenge. Thus, one of the main goals is to ensure the interaction of the personal energy of each customer with its production and realization, due to energy saving. *We propose to form a unified legislative, regulatory, social system of rules that form a safe, affordable, high-quality energy supply to all participants. It can be contribution to the SDGs, especially within the rational consumption and production of energy.*

In this regard, the following is proposed:

- To provide an opportunity for active consumers (prosumers) independently organizing their work and choosing the type and the method of energy consumption and generation;
- To establish the conditions for the interaction of a new participant to a given market (both on the part of an individual person - a prosumer and on the part of enterprises) with its already existing actors;
- To change the mechanism of payment for the use of energy in order to stimulate the development of technologies for energy saving, in the perspective of ensuring the quality and reliability of consumption;
- To introduce a preferential value added tax (VAT) for key technologies implemented by representatives of the private sector at all levels;
- To orient banks to develop profitable offers, with a low rate for representatives of actors operating in the areas of large businesses with the aim to build trusting relationships bridging the public and private sectors.
- To form priorities, mobilization and coordination of the activities of research projects in the field of renewable energy, digital technologies, materials and equipment;
- To promote energy conservation and the development of digital advisors in energy-saving behavior and energy-saving technologies.
- To develop models and mechanisms for effective international and cross-sectoral interaction in order to enhance cooperation and intensive development of best practices.
- To encourage the creation of networking platforms for the interaction of all.

Thus, the experience of digitalization shows that the speed of modernization of the infrastructure will increase not only within the enterprise, but also in the chains of value to which this enterprise belongs. The development of the technical infrastructure is an important, but it is not a sufficient condition for the digital transformation of the energy sector. This transformation includes changes in mindset, leadership style, incentive systems for innovation and the introduction of new business models to improve the performance of the employees of the energy sector, its customers, suppliers and partners. *A more difficult stage for the transformation of the company is the restructuring of all industry processes, the development of personnel competencies and the formation of trusts to the new digital technologies.*

3.3. Classification of technologies by the demand level and the need for financial and policy support

The main task for reforming the energy sector at the world's scale is to attract additional external investments in the industry to upgrade the infrastructure, to maintain the functioning of power grids and to ensure energy security. By avoiding investments in network upgrades, grid companies will certainly be able to keep their costs down in the short term. But at the end, something will fail and the consequences of these will be unpredictable. It is also unprofitable to build up excess network capacity. Technologically redundant networks will operate with a high degree of reliability, but today cost-sensitive environment, over-caution is an expensive strategy. *Therefore, it is necessary to make the power grid complex modern, flexible and reliable, which currently requires additional investments. This approach will allow grid companies to resolve the dilemma between risk of disaster and will avoid inadequate and hazardous spendings.*

The results of the classification of technologies for attracting investments are presented in Fig. 10. This classification is made under the scenario of moderately high hydrocarbon prices in the period up to 2030. The size of the bubbles characterizes the normalized significance of this technology.

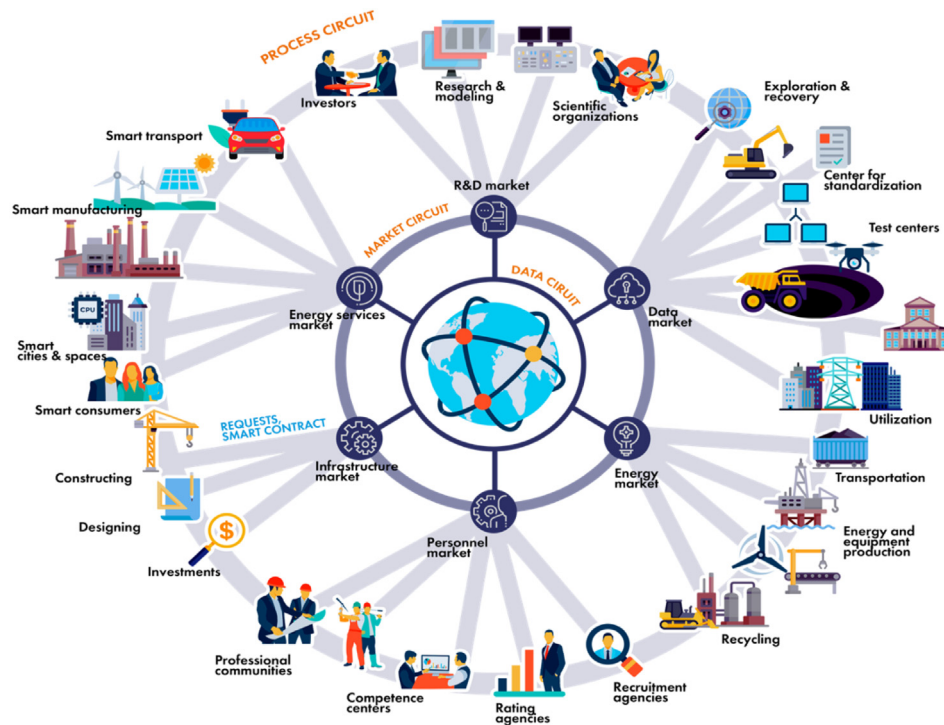


Fig. 9. Development of platform “EnergyRF”.

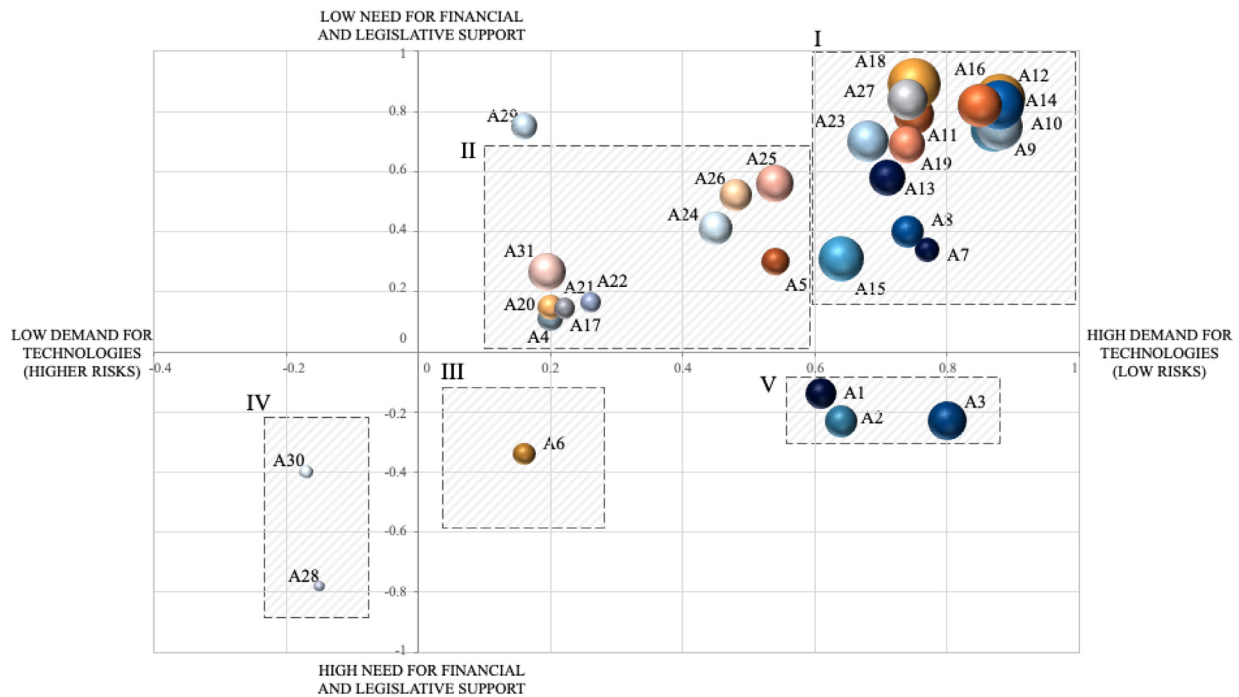


Fig. 10. Classification of technologies by the level of demand and the need for financial and government support based on the results of our modeling. The name of the technologies is presented in Table 5.

As a result of the classification, all technologies were distributed in five areas:

Area I – These technologies are highly demanded and of significant interest in the domestic and foreign markets.

Area II – These technologies are expected to increase in demand, but it will mainly be driven by the domestic demand from the Russian Federation and from the countries of the Eurasian Economic Union.

Area III – In this area, transport and a number of accumulation technologies complementary to each other are concentrated.

Area IV – These technologies that are locally in demand, with the very high degree of risk of a significant decrease in demand and the need for constant subsidies.

Area V – These technologies of distributed and gridded renewable energy which play a significant role and on the horizon until

2030. There will be significant demand for them, especially in foreign markets.

4. Conclusion and policy implications

Population growth, its urbanization and the exponentially increasing amounts of information are increasing the demands on energy infrastructure. Based on an expert survey and a scenario modeling, we have demonstrated that digital and information technologies are still developing *too* slowly, albeit they will have the greatest impact on the state of the energy infrastructure. The introduction of modern technologies such as the Internet of Things, Artificial Intelligence, Big Data, Cloud Computing will double the reliability and the observability of the infrastructure, they will increase the availability of it by no less than 50%. This will reduce the risk of accidents, will increase the infrastructure service time and will increase the likelihood of the environmental safety. However, digital and information technologies are not enough to raise the parameters of infrastructures to the required level by 2030. These technologies are certainly the key technologies, but it is necessary to develop all the complementary technological blocks, including the renewable energy, materials sciences and equipment, energy saving and the non-renewable energy.

In order to consolidate these technologies, we conceive an adapted and self-organizing energy platform. One of the key task is the formation of new markets, simultaneously with the integration of emerging and the transformation of the existing ones. The already existing energy markets and the infrastructure markets will be transformed within the digital platform. All the users of this digital platform will have access to investments and to the ownership of energy facilities. The intellectualization and the modernization of the energy infrastructure will affect the cost of the energy that will be consumed. It will generate a substantial additional income. Today, the profits earned by the organizations selling the power and by the producers of electrical energy are limited by the solvency of the consumers and by the price of energy resources. The current system of pricing tariffs, which today not only covers all the necessary costs of power supply companies, but also includes additional profits, must be completely reorganized through the introduction of digital technologies.

In the document, we also describe concrete measures to shape the smart consumer. The emergence of new subjects of consumption and the return of unused reserved capacities will avoid to create additional network capacities, which are today financed by increasing the tariff for the population and more generally by the end-user, namely by the final consumer.

For these reasons, the policy of energy needs to promptly reshape into dynamic and more iterative approaches with different platforms to balance public and private interests, to better enhance welfare, innovation and safeguard public interests from their exploitations (Duch-Brown and Rossetti, 2020). The policy initiatives need to pay particular attention to meeting the needs of the consumer. This necessarily requires finding a reliable, sustainable balance between the needs of all stakeholders. The balancing of interests should be automatic and transparent. The creation of industry digital platforms will drive this transformation. This is mandatory for the effective transformation of all energy sectors.

In summary, the impacts of technological changes in energy efficiency create prerequisites for curbing the rise in electricity prices and for reducing the deterioration of the infrastructure. This will be made possible by increasing the efficiency of the using of generating and network capacities, by reducing the need for new capacities, by reducing energy losses, and via the emergence of new markets, including for users. This will improve the quality of life of the population and will allow the transition towards a more developed society and a prosperous economy as the basis for a sustainable development.

CRedit authorship contribution statement

M.Yu. Shabalov: Conceptualization, Formal analysis. **Yu.L. Zhukovskiy:** Methodology, Data curation. **A.D. Buldysko:** Visualization, Investigation. **B. Gil:** Supervision, Writing - review & editing. **V.V. Starshaia:** Writing - original draft, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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