International Journal of Human Capital in Urban Management
(IJHCUM)

Homepage: http://www.ijhcum.net/

ORIGINAL RESEARCH PAPER

Formation of the intelligent energy system based on digital technologies in urban management

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ARTICLE INFO

Article History:
Received 08 July 2022
Revised 01 October 2022
Accepted 03 December 2022

Keywords:
Digital technologies
Energy efficiency
Foresight methodology
Intelligent energy system
Smart City

DOI: 10.22034/IJHCUM.2023.01.01

ABSTRACT

BACKGROUND AND OBJECTIVES: The economic consequences of the introduction of digital technologies are projected both at the level of electricity market participants and at the level of the state as a whole. As a result of the introduction of intelligent electricity metering it is possible to achieve energy savings of 20 % and solve the problem of transparency of energy flows of the national economy (information asymmetry). The purpose of the work is to substantiate the organizational-economic management of the national integrated intelligent energy system of the country in the conditions of the digital economy.
METHODS: Statistical analysis for technical-economic analysis of the functioning of the national energy system, technological forecasting and foresight for assessment of future changes in the architecture of energy systems, economic-mathematical modeling and scenario analysis for comparative assessment of future development of separate energy technologies.
FINDINGS: Forecasting of development of macrotechnologies in the energy sector is carried out, points of bifurcation of competitiveness of various energy technologies are defined. Assessments of economic consequences of introduction of digital technologies in energy systems both at the level of energy market entities, and at the national level are carried out. In the presence of own generating capacity, the consumer becomes an active participant (producer) in the electricity market, which in turn reduces system technological losses and economic costs of suppliers in the expansion of energy grids.
CONCLUSION: For generation companies, the effect lies in reduction of operating costs of up to USD 2 billion annually by smoothing the load schedule in Slovakia. Significant results can be achieved in the electricity distribution sector, in particular by reducing electricity losses by 50 % and reducing equipment maintenance and repair costs by 10 %. It was suggested to consider the technological platform as a business model for the digital development of the infrastructural sectors of the economy, in particular, the digitalization of the energy infrastructure. The authors developed the structure and presented the opportunities of the technological platform for the introduction of an intelligent energy system in Slovakia. Proposals for the implementation of the concept of an intelligent energy network as part of the digital transformation of the economy of Slovakia were developed.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
42	4	3

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Note: Discussion period for this manuscript open until April 1, 2023 on IJHCUM website at the “Show Article.

INTRODUCTION

The rapid development of Information and Communication Technologies (ICT) leads to the gradual digitalization of many sectors of the national economy, including infrastructure, which includes the energy system of a country. Under these circumstances, the traditional methods of strategic planning and implementation of technological changes in the energy system of a country do not meet the modern requirements of an integrated combination of interests and efforts of the state and business. In network sectors of the economy, this in turn necessitates the expansion of scientific views on the processes of formation of supply and demand, as well as changes in existing approaches to market regulation of the monopoly type (Borlase *et al.,* 2017). The need for radical changes in the energy sector of a country is conditioned by new requirements to increasing the reliability and quality of the energy supply system of a country, increasing the level of its manageability under conditions of growing share of renewable energy sources (RES), growing level of cybersecurity of the energy system of a country (Sadeghi-Pouya *et al.,* 2017). The combination of these factors requires the development of an economic mechanism for the development of the intelligent energy system of a country. Directions and stages of the process of integration of information and communication technologies and electricity grids include conducting appropriate technological forecasting (energy foresight), determining the effects of technology implementation, determining bifurcation points, that is the terms of replacement of traditional energy technologies with alternative energy sources when the structure of the energy balance will change and the intellectual architecture of the energy system will develop (Cebulla and Fichter, 2017). The economies of the world leading countries are undergoing changes that affect the consumption of electricity (Ghodousi *et al.,* 2017). The problem arises as to the efficiency of energy production, supply, distribution and use (Cheng and Yu, 2018). Accordingly, a transformation of the energy sector is taking place, which is becoming global in nature, which should lead to significant changes in the energy sector and energy efficiency (Seljom and Tomasgard, 2017). The purpose of the work is to substantiate the organizational-economic management of the national integrated intelligent energy system of the country in the conditions of the digital economy. To achieve this goal, the following scientific tasks were set and solved: identify characteristics and areas of digital modernization of the national energy system; systematize possible threats, risks and evaluate the economic effects of digital modernization of the national energy system; suggest conceptual provisions for the management of the intelligent energy system of a country.

Literature Review

The following main trends in scientific and technological development can be identified (Bunn *et al.,* 2018): strengthening technology convergence; strengthening the diffusion of modern high technologies in medium-tech segments of the manufacturing sector; strengthening the impact of new technologies on management and organizational forms of business. Innovative technologies are being developed, which will largely determine both future markets and the competitiveness of countries (Filipović *et al.,* 2019). The key factor in the development of the technological paradigm 4.0 was the integration of information technology with technologies, which are basic for the development of the modern world in the field of energy, transport, biology, medicine, media, education and culture, defense and national security (Lund *et al.,* 2017). This paradigm fuels the design and development of new integrated energy and telecommunications technologies, biotechnology, nanotechnology, etc. The main result of the development of new technologies is the resource-saving potential of economic growth (Karjalainen and Heinonen, 2018). The identified trends and regularities prove that qualitatively new large-scale technologies are able to provide solutions to complex, unsolvable on the previous technological basis, economic, social and environmental problems (Richter *et al.,* 2018). The most promising areas of technology convergence are as follows (Solano Rodriguez *et al.,* 2017): nanotechnology and ICT; cognitive technologies and ICT; nanotechnology, materials science and ICT; energy technologies and ICT. In the future, these technologies will promote the emergence of new sectors of the economy and markets. The final formation of a complete set of converged technologies is expected no earlier than in 2020 (Saul and Gebauer, 2018). Currently, the level of uncertainty in the prospects for the development of the energy sector has increased significantly (Brown *et al.,* 2018). This is related to the fact that global participants in the fuel and energy markets give different assessments of energy development. Accordingly, opposite development strategies are developed. Scientists identify two main options for answering questions about the development of energy supply in the future. The first option is known as "energy efficiency plus" (Ilieva and Gabriel, 2019). It provides for the modernization of existing energy systems, which are based on centralized energy supply grids, large-scale generation and "carbon energy" (Fan *et al.,* 2018). The second option is a paradigm that involves the development of new energy, which should be based on renewable energy sources, energy systems based on a decentralized intelligent grid and "smart" infrastructure of cities (Aineto *et al.,* 2019). It is also planned to move to buildings with lower energy consumption and integrated technical solutions for autonomous energy supply. The leading countries already provided for the transition to a new type of real estate ("resource-producing") (Nerini and Strachan, 2017). In the existing studies in general the prospects of innovative development of electricity industry on the basis of digital technologies are proven, and it is determined that when using new methods of management of introduction of technologies, both consumers and energy companies will receive advantages (Wagner *et al.,* 2020). However, issues regarding possible risks, mechanisms for introduction of innovations in the industry in the context of the development of a competitive electricity market remain unresolved. The problems of balancing the interests and consolidating the efforts of stakeholders

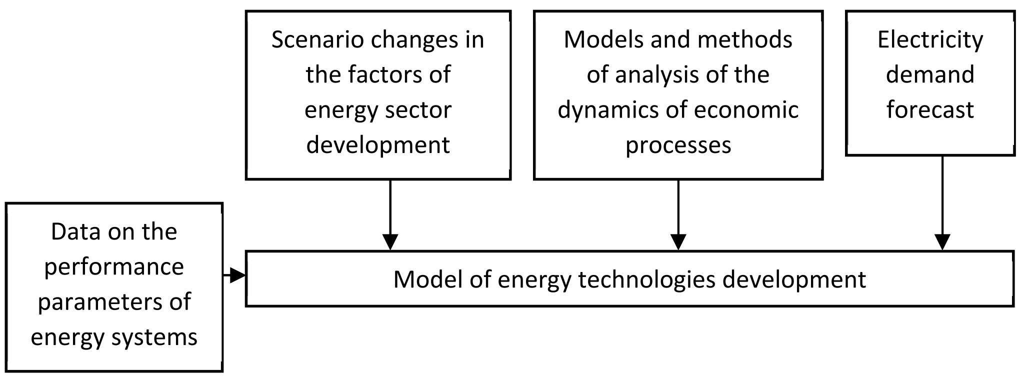

Fig. 1: Components of the process of model-scenario analysis of the development of energy technologies

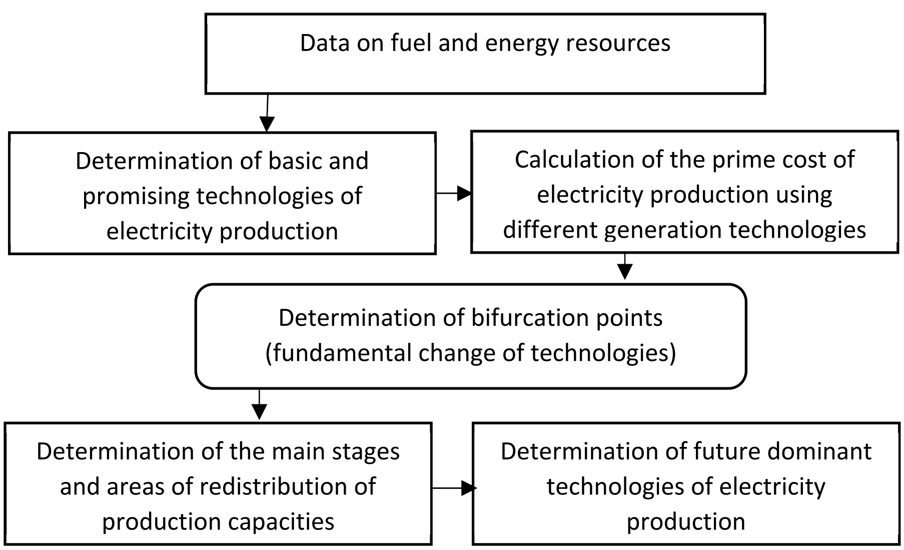

Fig. 2: Model for determination of the future dominant technologies of electricity production

in the process of developing the intelligent energy system of a country also remain insufficiently covered. Thus, further study is required in part of developing organizational and economic support for the process of innovative development of the energy system based on digital transformations. The current study have been conducted in Slovakia during 2015- 2021.

MATERIALS AND METHODS

The following scientific methods were used to achieve the set purpose: logical-historical method for the study of regularities of technological development of energy systems, structural and functional analysis for classification of the objectives of modernization of the energy system in the current conditions, factor analysis for systematization of economic threats and risks of fundamental changes in the architecture of future energy systems, statistical analysis for technical and economic analysis of the functioning of the national energy system, technological forecasting and foresight for assessment of future changes in the architecture of energy systems, economic-mathematical modeling and scenario analysis for comparative assessment of future development of separate energy technologies.

In the article, foresight is the main method of forecasting the formation of the energy system, which is a much more complex approach than traditional forecasting. With the help of technological forecasting, one gets information about the possibilities of new technologies, about their perfection and dynamics, about the possible terms of their transfer from laboratories to production (Al-Tarazi and Chang, 2019). It is a preparation for the decision-making process regarding the establishment of priorities in the field of science and innovation and provides for the involvement of informed participants from scientific, business circles and the public in technological analysis and dialogue. The forecast gravitates towards more specific and certain results based on the information available today. With the help of technological forecasting, one gets information about the possibilities of new technologies, about their perfection and dynamics, about the possible terms of their transfer from laboratories to production (Ashraf *et al.,* 2020). It is a preparation for the decision-making process regarding the establishment of priorities in the field of science and innovation and provides for the involvement of informed participants from scientific, business circles and the public in technological analysis and dialogue (Cai *et al.,* 2019). The forecast gravitates towards more specific and certain results based on the information available today. In addition to the advantages, foresight research has certain disadvantages (Choi *et al.,* 2018): the availability of financial resources and time (the larger the scale of the research, the greater the costs it involves); the necessary level of participation of experts and stakeholders (some methods, such as Delphi, allow for the interaction of large groups of participants, but such interaction will be rather fleeting; expert panels, on the contrary, allow for greater depth of discussion, but with a smaller number of participants; a combination of methods makes it possible to eliminate the indicated shortcomings, but requires large costs); combining a method with others as a basis or supplement to the main method (formal methods are rarely used alone, more often a combination of several methods is practiced). The existing model of calculation of prime cost and definition of development of macrotechnologies in the field of energy efficiency was adapted for modeling (Uniejewski *et al.,* 2017). Since the introduction of methods for management of electricity demand particularly affects the activities of thermal power plants, the main effect lies in reducing the use of units with a capacity of 200 and 300 MW by 20-30 % and fuel savings of 40-60 million tons per year from smoothing the daily load schedule, as well as passing the heating season (DeCarolis *et al.,* 2017). Model-scenario analysis of the development of energy technologies and assessment of their impact on the structure of electricity demand involves: representation of relevant aspects in world energy systems; formalization of models, data input; review of possible technology development using scenario analysis of built models. The components of the process of model-scenario analysis of the development of energy technologies are given in Fig. 1, and the conceptual diagram of the model, in Fig. 2.

To build an economic-mathematical parametric model, a number of assumptions are made. Namely:

there is a set (vector) of technologies (Eq. 1):

$$v = V_i(f_i; C_i; r_i; h; g) \qquad (1)$$

where f_i — utilization factor; $C_з$ — primary fuel price; r_i — installed power; h_i — unit cost; g_i — emissions CO_2.

The following technologies are selected for the

calculations:
$V_1(f_1;C_1;r_1;h_1;g_1)$ – TPP (Thermal Power Plant), steam turbine with subcritical steam parameters;
$V_2(f_2;C_2;r_2;h_2;g_2)$ – TPP, steam turbine with supercritical steam parameters;
$V_3(f_3;C_3;r_3;h_3;g_3)$ – NPP (Nuclear Power Plant);
$V_4(f_4;C_4;r_4;h_4;g_4)$ – HPP (Hydro Power Plant);
$V_5(f_5;C_5;r_5;h_5;g_5)$ – Solar Power Plants (silicon cells);
$V_6(f_6;C_6;r_6;h_6;g_6)$ – Solar Power Plants (thin film cells);
$V_7(f_7;C_7;r_7;h_7;g_7)$ – Solar Power Plants (hub);
$V_8(f_8;C_8;r_8;h_8;g_8)$ – wind power stations.

The objective function is as follows (Eq. 2):

$$F = \sum_{i=1}^{m} \left(S_i \sum_j Y_{ij} \right) \quad (2)$$

where S_i — prime cost of electricity production using *i*-th technology, USD/kWh, which in turn is calculated by the formula (Eq. 3):

$$\begin{cases} S_{ij} = K_w + C_w + S_f + Z_w + S_{CO2_w} \\ O_a \sum_k \sum_i (Y_{ik}) \le N_a \\ \sum_i \sum_j Y_{ij} \ge U_j \end{cases} \quad (3)$$

where Y_{ij} - volume of electricity produced using *i*-th technology at *j*-th plant, $\cdot$kWh; K_w - specific capital costs, USD/$\cdot$kWh; C_w - operating costs and management, USD/$\cdot$kWh; S_f - fuel costs, USD/tons of oil equivalent; z_w - waste disposal costs, USD/$\cdot$kWh; S_{CO2_w} - emission permit costs, USD/$\cdot$kWh; U - demand for electricity, $\cdot$kWh; O_a - greenhouse gas emissions, t/$\cdot$kWh; N_a - target level of greenhouse gas emissions, tons.

The study information base is analytical materials of the International Energy Agency. The assessment of the Integrated National Energy and Climate Plan of Slovakia made by the EU in 2020 generally indicates a low level of ambition of the state by a number of main indicators, such as the share of RES in final energy consumption in 2030, energy efficiency, energy security, research and innovation (Slovak National Energy and Climate Plan, 2022). According to the statistical data of the Regulatory Office for Network Industries of Slovakia as of June 2020, the consumed electricity from renewable sources was 17.48% in 2019, while its total specific weight in the electricity balance was 18.42% (Slovak National Energy and Climate Plan, 2022). Biomass processing (5%) and hydropower (8.1%) are the main renewable sources of generation. Solar energy accounts for only 1.8% of electricity, while nuclear power plants produce more than 55% of all consumed electricity (Slovak National Energy and Climate Plan, 2022). Among the positive aspects of the plan, the presence of good examples of the interconnectedness of climate change and energy efficiency issues is noted. Particular attention is focused on the formation of measures at the local level by creating a network of regional energy centers. The presence of the specified problems in the development of the methodology to study the management of the creation of the intellectual energy system of the country actualizes the need to define all the components of the methodological framework of such a study as viewed by the authors. The basis of the indicated methodology will be formed by a number of assumptions (hypotheses). Hypothesis of environmental complexity: changes and their implementation are determined by the action of factors of the external and internal environment. Hypothesis of chance: change management, as a management process, has in its arsenal a list of tools and techniques, the use of which depends on the type of problems and change situations that have arisen. Hypothesis of integrity: changes and their effectiveness depend on the coordination and interaction of various control elements (subject, object, subject of management). Hypothesis of balance: for each level of the combination of factors of the change environment, a combination of control elements can be determined that will ensure the achievement of the change goals. The use of the assumptions (hypotheses) specified in the methodology is possible in two aspects: theoretical and applied (practical).

RESULTS AND DISCUSSION

Digital transformation of energy sector is a natural stage of development of energy systems in developed countries. However, in each of these countries, the areas of implementation of digital technologies are conditioned by national characteristics of energy systems. The presence of excess, but physically obsolete generating capacities, shortage of switching capacities, imbalance of logistics of primary energy supply, imperfect tariff policy, non-transparency of energy flows are the characteristic features of the energy system. At the same time, the use of RES (Renewable Energy Sources) is accelerated in the country. The introduction of a competitive electricity market provides for inclusion of qualified consumers in the system of market relations and significantly increases the requirements for information and software support of the energy management system. The diagrams for replacement of one equipment with another are presented by S-shaped curves. If it is not a case of replacing old equipment with new one, but a case of using new equipment performing the functions, which were not previously performed by it, the same type of growth curve is still used.

It seems most difficult to forecast the dynamics of operating capacity for thermal power plants. Considering the extremely wide variety of types and characteristics of existing Thermal Power Plant (TPP) equipment, as well as the high dependence of solutions on the dynamics of gas and coal prices, this problem has no clear solution and requires an integrated analysis of the following key factors (Drobyazko and Hilorme, 2021): age structure of existing equipment, most of which was introduced 30–50 years ago, and estimates of its physical wear; depreciation and non-competitiveness (unprofitability) of operation of existing capacities in the conditions of deep deregulation of the electricity market; comparative efficiency of investment solutions on reconstruction (modernization or replacement) of existing equipment or its dismantling with replacement by new, technologically advanced power plants taking into account the changing cost of fossil fuels. Analysis of the age structure of existing equipment and assessment of the dynamics of potential disposal of existing TPP capacities through natural physical wear allows to estimate the total amount of investment decisions on their reconstruction or replacement in the first approximation. The traditional criterion for assessing the scale of potential disposal is the "fleet life" of energy equipment, the value of which is determined by the operating life of the units of thermal power equipment of similar design, materials and operating conditions, which ensures their trouble-free operation in compliance with standard requirements for metal control, operation and repair (Henríquez *et al.,* 2017). In the general case, the concept of "fleet life" can be attributed to the power plant as a whole, separate units (boiler, turbine, steam pipeline) or their main elements. The forecast of dynamics of operating capacity of TPP is made taking into account the recommended investment decisions on reconstruction by standard groups of equipment. According to calculations, by 2030 of the operating capacities (103 GW) reaching the maximum physical service life, only one tenth (10 GW) is subject to final dismantling (Lopion *et al.,* 2018). As for the other capacities, effective decisions on their reconstruction can be implemented, and with that more than a half (55 %) of existing equipment can be replaced by technologically progressive equipment. Along with a quantitative comparison of the efficiency of different fuels and waste generated, it is important to consider the relative costs associated with the use of a particular fuel. The cost of construction of nuclear power plants is much higher than the cost of existing coal- or gas-fired thermal power plants. But the cost of nuclear fuel, including its necessary preparation, is less than the cost of oil, coal and gas. The actual cost of electricity generated by nuclear power plants will be almost the same as that generated by thermal power plants. Regarding investment in new generating capacities, design and capital construction costs are a determining factor. If low gas prices are projected in any area today, it is the main reason for the non-competitiveness of nuclear energy there. The presence of areas of electricity consumption away from sources of cheap coal is the main condition for increasing the use of nuclear energy for many countries. An important aspect of the development of nuclear energy is its dependence on the solvency of a country in the international market. Therefore, in countries such as Japan or France, where the choice is between importing large quantities of fuel and high capital construction costs on own territory, the decision can be made simply on the basis of international exchange (Yang *et al.,* 2017). Buying a thermal power plant abroad, for example in Japan, would lead to higher electricity prices and significantly reduce the foreign exchange reserves of the country, which will not happen when using less expensive uranium fuel. An agreed policy on the prices of carbon fuel burned for electricity generation, or significant taxes on it, will change the economic status of nuclear energy. For example, the price of USD 37 per ton of regular coal, or USD 29 per ton of brown coal, will increase the cost of electricity by one cent per kilowatt hour at constant prices for nuclear electricity (Lane *et al.,* 2018). It was noted above that the cost of nuclear power plants is higher than that of thermal power plants. Energy costs (that is the amount of energy invested in the manufacture of materials, fuel preparation, etc.) may also be higher. This is especially true for light water reactors, which require additional energy to enrich the fuel. Energy costs for manufacture of structures and initial loading of the fuel of the light-water reactor are approximately 1.5 % of the energy produced by the reactor, and taking into account subsequent fuel loads, this value will be less than one percent (Price and Keppo, 2017). In the worst case, when using expensive diffusion methods of uranium enrichment, it will be up to 4 percent. Although coal and uranium compete for the leading role in basic electricity production, some developed countries see their progress in their equal role. Also, it is necessary to take into account the fact that the cost of equipment is relatively constantly decreasing and solar energy has a high Levelized Cost of Energy (LCOE) value. At the same time, the quota cost is calculated. This indicator reflects a fixed tariff for electricity, which reflects the cost of its generation and at which the total discounted revenue from the sale of electricity to the final consumer is equal to the total discounted costs throughout the entire life cycle of the power-generating facility. It is the minimum price at which the electricity generated over the entire life of the power plant must be sold to reach its break-even point (NPV = 0). If the price of electricity is higher than the LCOE, it will give a higher return on invested capital (NPV > 0) than the adopted discount rate, while a lower price will not allow the project to pay off at the given discount rate (NPV < 0). Data for different fuel prices (for fossil fuels) or commissioning terms (for nuclear installations). 5 % discount factor taking into account the 30-year service life and an average load factor of 70 % (Drobyazko and Hilorme, 2022). The issue of fuel prices is a key factor for fossil fuels (Ketter *et al.,* 2018). Since in nuclear energy the ratio of fuel cost to total cost of electricity is low, the time of design and construction, and hence capital costs, is a key factor. Thus, increasing the load factor will be more advantageous for nuclear installations. In practice, the energy payback period is actually about six months. Hydropower is a clean source of energy. However, hydropower causes indirect greenhouse gas emissions, mainly during the construction and flooding of a water storage reservoir. This may be related to the decomposition of some part of flooded biomass (forests, peatlands and other types of soil) and the increase of aquatic wildlife and vegetation in the reservoir. Long-term socio-economic development of European countries provides for the concentration of efforts on the development of special tools allowing to combine science, production and state administration in various sectors of the economy and industry. Technology platforms are one of such tools. Ten years of experience in the creation and implementation of such EU platforms show their effectiveness in the context of accelerating innovative development at the level of separate sectors of the economy. In order to implement the mechanism for solving problems with regard to modern requirements for the functioning of the energy supply system on the basis of new advanced technologies, it is necessary to improve the system of forecasting, planning and consolidation of efforts.

Thus, it is substantiated that the development of integrated intelligent energy systems has a system nature of energy transformation and requires consolidation of efforts of all stakeholders: state institutions, energy business and research institutions. This form of cooperation in matters of technological development is called a “technological platform” (Drobyazko *et al.,* 2020). The corresponding organization plan of interaction of institutions in the course of digital modernization of energy systems is suggested in the paper (Fig. 3). The availability of these resources to the growing population of the world and the capacity of ecosystems for permanent and sustainable self-healing depend to a large extent on the efficient use of resources in the production and consumption of goods, services and technologies used in these processes. In these conditions, industrialized countries must find an adequate response to formulate their energy strategy in the medium and long term. Three pillars of energy policy, namely: competitiveness, sustainable development and security of energy supply should be the basis for planning future prospects. New participants from other sectors of the economy are entering the energy market. In particular, companies that are leaders in the field of information and communication technologies are becoming participants in energy markets and investing in the development of alternative energy. Based on these observations, it can be argued that the convergence of information technology with technologies that are basic for the development of the modern world is a key factor in the development of economic sectors. This paradigm fuels the design and

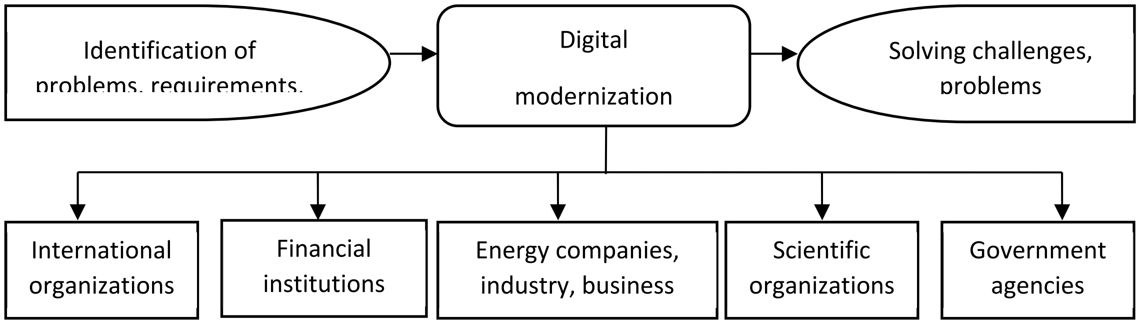

Fig. 3: Communications of institutions in the process of digital modernization of energy systems

development of new energy information technologies (Drobyazko *et al.,* 2021). The process of digital energy transformation is global in nature and is related with the convergence of information-communication technologies and energy technologies, which leads to the formation of integrated intelligent energy systems and synergy effects. The main result of the application of new technologies is the use of resource-saving potential of economic growth. Currently, the role of energy consumers, who can become its producers, is changing. Thus, consumers not only buy energy resources in the centralized energy system, but also buy capacities for energy production. This allows to increase the self-regulatory role of consumption, to mobilize the technologies of decentralized energy production, to increase the value of local resources, as well as to move to "smart consumption" in cities. It can be argued that the scenario of transition to new energy is already justified in the leading countries of the world. The following should be considered as preconditions for the introduction of intelligent energy system technologies: electrification of energy demand, increase of renewable energy sources in the energy balance, growth of demand for digital technologies in the field of energy supply, construction of real estate with much lower consumption of energy resources. This provides for maximum flexibility and informatization of energy systems, including generating capacities. The identified trends prove that qualitatively new, large-scale technologies can provide solutions to complex economic, social and environmental problems that cannot be overcome on the basis of the previous technological base and methods of technological forecasting and planning of development of energy supply systems. Therefore, new strategic planning tools are gaining ground in the leading countries. These include: foresight, strategic technology plans, technology roadmaps, technology platforms, problem-oriented scenario analysis, methods of adaptive management and technological forecasting, etc. The results of studies are used to make decisions on promising areas and priorities of energy development. The use of energy foresight is caused by the following factors: crisis of existing relations in the energy supply system; consequences of financial and economic crises of recent decades; emergence of structural and functional imbalance, which leads to the accumulation of contradictions and new bifurcations; new system of design and production of equipment and materials with predetermined properties, which is a promising way of technological modernization of energy systems. To obtain results regarding the transition to a new quality conditions of the system operation, that is to determine the bifurcation points and to calculate the prime cost under different conditions of application of advanced technologies of intelligent metering and flexible transmission systems in the bulk electrical system for leveling the imbalance of generation and consumption of electricity modeling was carried out. Scenario conditions for the development of electricity production include prices for the following fuels: oil, natural gas, and coal. Natural gas will undoubtedly play a major role in meeting global energy needs for at least the next two and a half decades. Global demand for natural gas, which declined in 2009 due to the economic downturn, has been resuming its growth trajectory, characteristic of gas for a long period of time, since 2010. This is the only type of fossil fuel for which demand is higher in all scenarios in 2035 than in 2008, although growth rates are completely different.

With the long-term rise in oil and gas prices, interest in coal as an alternative energy source is only growing in the world. According to the US Department of Energy, after 2020, coal in general will become the fastest growing fuel for power plants, significantly outpacing gas. In Western European countries, where fuel costs and consumer properties are taken into account, the gas/coal/fuel oil price ratio is 2/1/2.8 (Lane *et al.,* 2018). Market pricing mechanisms should eliminate serious distortions of domestic gas prices and gradually bring the energy price ratio to the level formed in other countries. The key criteria for selecting the future structure of generating capacities are the efficiency of capital investments in various types of generation, which determines the minimum cost of electricity for the consumer (including reimbursement of capital and all other costs of generation and transmission), as well as energy security, general economic efficiency, existing constraints in terms of connections and environmental consequences. The comparative analysis of the economic efficiency of different types of generation will be primarily determined by the specific capital investments for the construction of different types of plants and fuel costs (Table 1).

Comparison of cost characteristics of energy generating technologies (Table 2). The expected reduction in the cost of alternative energy sources is fundamentally dependent not on time but on the cumulative effect of mass production, which in turn requires the development of the market for these technologies. Most technologies can reduce investment costs by 30–60 % of the actual level by 2024 and by 20–50 % in the period after 2040 reaching its peak development. Particular attention should be paid to bifurcation points. It can be assumed that after 2025 the cost of electricity produced using renewable energy sources, especially solar ones, will be significantly reduced.

Globally, in 2035, coal will be the leader among energy sources used for electricity generation, although its share in electricity generation will be reduced from the current 41 % to 32 %. Significant growth in coal-based electricity production in non-OECD countries will be partially offset by its lower production in OECD countries. Globally, the transition to nuclear energy, renewable energy and other low-carbon technologies is expected to reduce emissions per unit of electricity produced by one third by 2035. According to the scenarios of electricity industry development, the total electric capacity of nuclear power plants may increase significantly in the world by 2050. Although coal and uranium compete for a leading position in basic electricity generation, some developed countries see their progress in their equal role. Solar and wind energy will become the main competitors of nuclear energy by 2030. The rate of reduction of the cost of solar energy generation and the development of energy storage technologies suggest that in 20 years the capital costs for solar energy generation, even in the basic mode, will be lower than those for nuclear energy. Table 3 contains the results of scenario modeling regarding the motion of bifurcation points, and as a result of reducing the generation volumes for certain technologies Thermal Power Plant (TPP); Wind Power Plant (WPP); Hydro Power Plant (HPP); Nuclear Power Plant (NPP); Solar Power Plant (SPP) and replacing one technology with another.

According to modeling results, one can see that the increase in fuel costs affects the development of technologies for alternative sources of electricity, especially solar energy. Also, growing specific fuel consumption is a significant factor. This is especially true of outdated TPP technologies. So, an economic-mathematical model is developed that allows to perform scenario modeling of energy technology development, both in the world as a whole and for a separate country. Based on the modeling results, the bifurcation points were identified, which would allow you to determine the areas and stages of the development of macro-technologies in the field of energy and to outline further transformations in the field of energy and energy efficiency (Fig. 4). By the modeling results one can also trace the stability or insignificant growth of electricity generation from traditional sources and a significant increase in the amount of electricity generation using technologies based on alternative sources. The first stage involves the introduction of digital technologies in the existing energy systems. The second stage involves the creation of a decentralized energy system operating together with a centralized energy system. The world leading countries are currently undergoing this stage. Distributed generation and the energy system become equal in the process of providing a consumer with electricity. The organization of interaction between the main energy system and the distributed generation system is carried out in energy system management. Competition is beginning to take effect in the retail

Table 1: Basic energy technology parameters

Parameter	Parameter
Coal-fired power plants	
Discount rate, %	8
Efficiency, %	36.7
Annual operation time, hours	7446
Specific investments per kW of installed capacity, USD	1300
Service life, years	40
Project start period, months	48
Fuel price, US dollars/MMBtu	1.2–1.5
MW production cost, USD	42
Combined cycle power plants	
Discount rate, %	8
Efficiency, %	53
Annual operation time, hours	7446
Specific investments per kW of installed capacity, USD	500
Service life, years	40
Project start period, months	24
Fuel price, US dollars/MMBtu	4.42
MW production cost, USD	41
NPP	
Discount rate, %	8
Efficiency, %	32.8
Annual operation time, hours	7446
Specific investments per kW of installed capacity, USD	2000
Service life, years	40
Project start period, months	60
Fuel price, US dollars/MMBtu	-
MW production cost, USD	67

Made by the author based on data from (International Smart Grid Action Network, 2018)

electricity market. The third stage lies in creation of a hybrid energy system in which a significant amount of electricity is generated by decentralized power plants together with centralized generation. Therefore, it is advisable to develop a program for the introduction of new technologies in the electricity industry and the development of important facilities in this area. When modernizing the energy system, mutually beneficial and comprehensive interaction with innovative companies of small and medium business is one of the important areas of cooperation of electricity companies with the entities of the innovation environment. Partnership relations should be formed and developed within the framework of subjects and projects defined by the sector development strategy. For the electricity industry, the import substitution program is considered as the main mechanism for implementing certain goals of the energy strategy in the context of digital transformations. Implementation of the import substitution program allows to achieve a

Table 2: Estimated cost of new capacities and prime cost of electricity

Technology	Investment, US dollars/kW	Prime cost, cents/ kW・h
Coal-fired TPPs:		
steam turbines with chemical absorption of gases	1850	6.79
steam turbines with supercritical steam parameters	1675	5.70
integrated coal gasification combined cycle plant	2100	6.73
hybrid combined cycle units with integrated coal gasification and high-temperature solid oxide fuel cells	2100	6.00
with integrated coal gasification based on coal water mixture	1620	3.35
combined cycle units with circulating fluidized bed (pressurized fluidized bed) and desulfurization	1400	5.26
Gas-fired TPPs:		
Combine-cycle plants with chemical absorption of exhaust gases	800	5.73
Combine-cycle plants with chemical absorption of exhaust gases and combustion in oxygen	800	5.41
Hybrid TPPs based on a combination of CCGT and high-temperature solid oxide fuel cells	1200	5.39
Modernization of steam turbine TPPs based on gas turbine superstructure	300-550	5.00
NPP (with decommissioning inventory)	1200-2500	2.50-6.00
NPP (extension of service life)	250-390	2.50-6.00
Large-scale hydropower	1000-2500	1.00-8.00
Small-scale hydropower	800	6.00
Renewable power plants: Biomass power plants	226	7.60
Geothermal power plants	2500-5084	6.50-30.80
Solar power plants (photovoltaic)	5000	15.00-50.00
Wind power plants	1370	3.60

Calculated by the authors based on data from (International Smart Grid Action Network, 2018)

Table 3: Results of scenario modeling for the motion of bifurcation points

Scenario	TPP with supercritical steam parameters	WPP	HPP	NPP	SPP
Basic scenario	2012	2014	2011	2029	2045
+ 10 % of fuel cost	X	2011	X	2024	2041
+ 10 % of quota cost	X	X	X	2028	2044
Quota cost up to 50 $/t	X	X	X	2029	2040
Specific fuel costs + 5 %	X	X	X	2022	2033
TPP capital costs + 10 %	X	2013	X	2027	2044
SPP (silicon) capital costs ± 10 %	X	X	X	X	2042

Calculated by the authors based on data from (International Smart Grid Action Network, 2018)

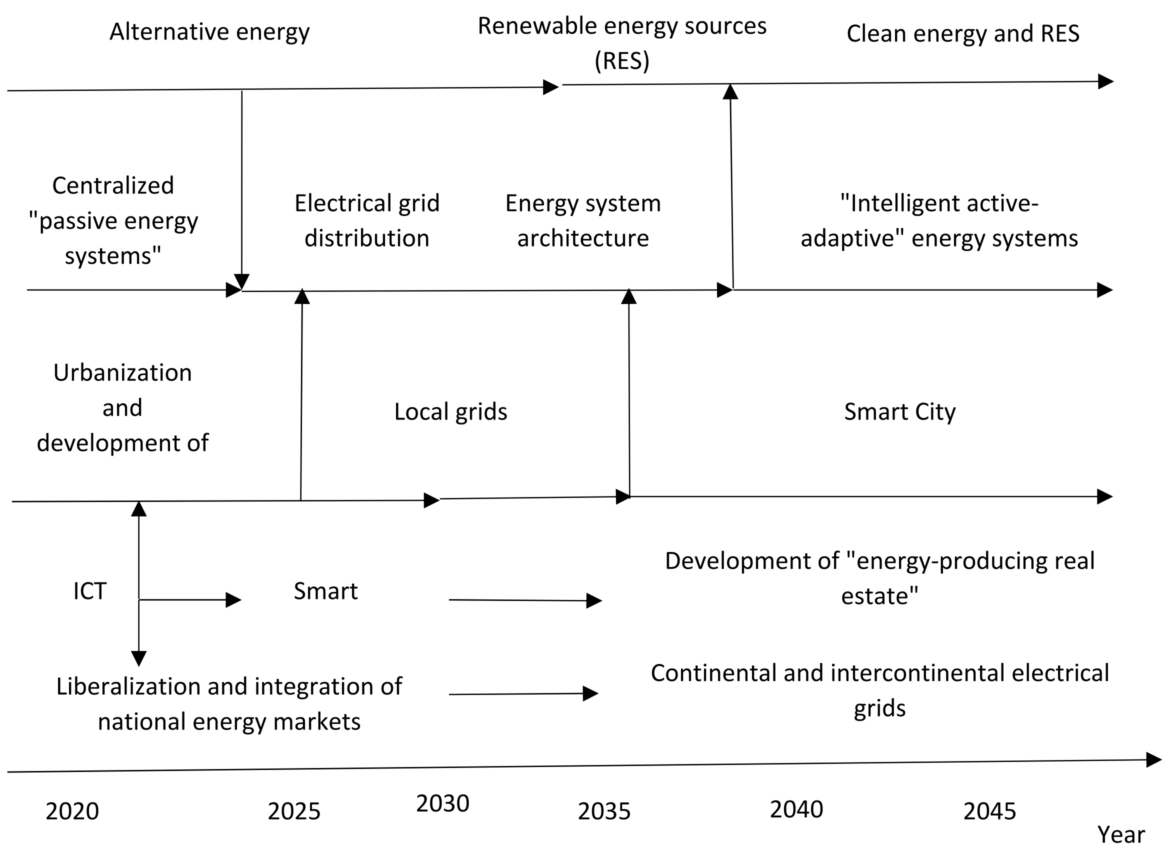

Fig. 4: Development in the field of energy sector and energy efficiency based on digital technologies (author's forecast based on Foresight methodology)

set of goals that affect not only electricity companies, but also companies in the fields of mechanical engineering, instrument making, chemical and other industries.

This trend can give a powerful impetus to the economy of the country towards innovative development. The management of the import substitution process should have an integrated and system nature. It is necessary to take into account the different goals and interests of the parties involved, which give rise to different economic relations between the parties involved in the process. Therefore, it is necessary to consistently and carefully build a system of economic cooperation with them. A special place in the formation of the system of economic cooperation is occupied by methods of stimulating manufacturers and suppliers of equipment, which must be adequate to the capabilities of energy companies and provide the necessary level of interest of contractors. It is necessary to use the developments of a system and integrated approach to building the systems of economic cooperation of electrical companies with equipment suppliers for the purpose of implementation of innovative programs based on import substitution and propose an effective system of benefits (preferences) to encourage economic cooperation.

Discussion

In pursuit of the goals and objectives of innovative investment programs, electrical companies place special demands on partners for product localization, its innovative component, as well as their general impact on the modernization of the country. In such an integral part of the institutional environment as an ideological sphere, it is necessary to propose a scientific concept that would become an integral part of the national idea of creating and implementing intelligent energy systems, a kind of national doctrine of building a energy-efficient, energy-ecological and energy-saving society. There arises a need to form a stable consciousness and behavior of the government, institutions, organizations, people and other subjects in the new mode of energy use. Institutional changes should provide for: creation of new legal norms that set priorities for energy saving at all levels of their use; attracting investments for the implementation of new energy systems; planning both at the state level and at the enterprise level for the implementation of all elements of intelligent energy systems; change of organizational structure of management within firms and the organizations, which would meet new requirements of energy consumption; introduction of new forms of state-private partnership. Thus, institutional changes should contribute to the creation of a system of incentives for the introduction of norms of intelligent energy systems in every sphere of society. The following main trends in the development and implementation of new technologies can be identified:

- Wide use of methods of strategic planning and process management using methods of forecasting of innovation and technological development (Ghodousi *et al.,* 2017);
- Orientation to set long-term goals, in particular, reduction of energy and water consumption, greenhouse gas emissions and waste in production and consumption, etc. (Solano Rodriguez *et al.,* 2017);
- Proper organization of monitoring of results and evaluation of progress as a precondition for preventing the scattering of funds and reducing investment risks (Ilieva and Gabriel, 2019);
- Active involvement in the whole process of research and development of experience and funds of business associations as the main consumer of new technologies through the mechanisms of state-private partnership and the creation of technological platforms, joint technological initiatives (Wagner *et al.,* 2020);
- With that, the ratio between public and private funding changes in favor of private investors closer to the end of the innovation chain, that is to the stages of introduction and distribution of technologies (DeCarolis *et al.,* 2017).

European regions play a key role in developing innovative solutions, building new value chains and cultivating markets for sustainable energy solutions. Today, the EU is actively looking for additional ways to solve problems that may arise in the future. The EU actively promotes innovation and sustainable solutions by participating in research projects, testing new technologies or creating pilot projects. Thus, the EU forms the future of energy policy. The European Union develops innovative technologies that reduce energy consumption and the depletion of key finite resources and fuels such as coal, crude oil and natural gas (Dwijaksara *et al.,* 2019). It should be noted that by ensuring this, the EU will transform electricity into thermal energy and vice versa, and due to the implementation of the innovation and development program, new opportunities were created for the transformation of the energy sector. Europe is confident in promoting a common energy policy based on competitive, sustainable and safe components. Therefore, the largest EU countries play an important role in the development of the energy sector. The European Union helps member states finance energy efficiency plans through the EU budgets and financial institutions (Epoh and Mafini, 2018). Decarbonisation of building heating and industrial process heating policies will have important implications for future demand for natural gas. Reducing carbon emissions and achieving industrial sector targets by 2050 will largely depend on a combination of energy efficiency, thermal electrification and Carbon Capture and Storage (CCS) (Giama and Papadopoulos, 2018). Therefore, the EU is confident in the goals approved by its member states. The EU goals aimed at energy efficiency and the use of endogenous energy sources are also reflected in the programs and legislation of EU member states. The EU coordinates the policies of the countries of continental Europe, introducing programs aimed at the transition to renewable energy sources and increasing the competitiveness of the economy. The EU also emphasized the EU renewable energy needs and the importance of photovoltaic facilities for 100 percent decarbonisation of the energy sector (Kot, 2018). Therefore, the cost-effective means of achieving emission reductions and the transition to renewable energy are a combination of technologies and investments in R&D of renewable energy strategies, the implementation of existing projects and new ones related to environmentally sustainable economic growth. As mentioned above, the transition to renewable energy is one of the main problems not only of the EU policy, but also of the whole world. Therefore, the energy sector is a guarantee of economic stability and growth of the countries of the European Union. The new Energy Sector Strategy (ESS) promotes secure, affordable and sustainable energy through the transition to a market-oriented energy sector. The main sense lies in the expansion of alternative energy sources (Lopes *et al.,* 2019). Therefore, the issue of energy is central to the long-term energy strategy of Europe, as it contributes to reducing greenhouse gas emissions, reducing the energy imports of Europe and making it more independent. This fast-moving economic sector provides the EU and the region with new 'green' jobs, opportunities to export energy with high added value and increased competitiveness in the production of goods and services, thereby helping to contribute to technological leadership. The European Union is on the "green" pass. Europe is going from a fossil fuel-based energy system to a low-carbon, fully digital and complex system.

CONCLUSION

Areas for improving the methods of managing the demand for electricity using digital technologies were suggested. A systematization of possible threats, risks and an assessment of the economic effects of the digital modernization of the national energy system were carried out. It was proven that progress in the creation of the intelligent energy supply system of the national economy depends on a number of organizational-economic factors. A sectoral analysis of the features of the digital transformation process in solving separate tasks of the energy industry development of a country was carried out. The necessity of implementing a new mechanism for the effective development of promising sectors of the economy was identified.

The technology platform should provide a link between research and development, business, public and state interests to form a long-term development strategy. Important areas of project implementation and international scientific and technical cooperation should be dealt with by separate groups as the main components of the technological platform. It is also advisable to use the institution of business reputation in the process of joining new participants to the technology platform. The organizational and legal aspects of the creation of the technological platform and the regulation of its work as a communication tool of various program participants deserve special attention. The limitation of the study lies, first of all, in the use of the principles of foresight study. Also, this study is possible when taking into account the principle of ceteris paribus. This means that the coincidence of economic interests of the alpha stakeholders regarding the implementation of projects of energy saving technologies is required. Alpha stakeholders form their requirements in accordance with the goals and motivations and influence the project based on their interests, professional competencies and the degree of involvement in its implementation. Based on these assumptions, the prospects for further research are the development of strategies and measures to achieve energy efficiency and energy saving at all levels of the economy.

AUTHOR CONTRIBUTIONS

S. Drobyazko performed an experimental design and analyzed the data. T. Hilorme defined the concept and methodology of the research. S. Nesterenko ranked the data into tables and figures. Z. Shatskaya performed the literature survey.

ACKNOWLEDGEMENT

This study was carried out within the framework of the research project [TDCAPS 2021-2026] "Temporality of Digital Civilization as an Attribute of a Public System", The European Academy of Sciences Ltd, London, UK.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS (NOMENCLATURE)

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
$C_з$	Primary fuel price
CO_2	Carbon dioxide
C_w	Operating costs and management, USD/kWh
EU	European Union
Eq.	equation
ESS	Energy Sector Strategy

f_i	Utilization ratio
Fig.	Figure
g_i	Emissions CO_2
GW	Gigawatt
h_i	Specific cost
HPP	Hydro Power Plant
ICT	Information and Communication Technologies
K_w	Specific capital costs, USD/kWh
kW	Kilowatt
LCOE	Levelized Cost of Energy
MBTU	British Thermal Unit
MW	Megawatt
N_a	Target level of greenhouse gas emissions, tons
NPP	Nuclear Power Plant
NPV	Net Present Value
O_a	Greenhouse gas emissions, t/kWh
OECD	Organization for Economic Cooperation and Development
RES	Renewable Energy Sources
R&D	Research & Development
r_i	Installed capacity
S_{CO2_w}	Emission permit costs, USD/kWh
S_i	Prime cost of electricity production using i-th technology, USD/kWh
SPP	Solar Power Plants
S_f	Fuel costs, USD/tons of oil equivalent
t	tonne
TPP	Thermal Power Plant
U	Demand for electricity, kWh
US Department of Energy	United States Department of Energy, DOE
US dollars	United States dollars
v	vector
V_i	vector i-th technology
WPP	Wind Power Plant
Y_{ij}	Amount of electricity produced using i-th technology at j-th plant, kWh
Z_w	Waste disposal costs, USD/kWh
$	Dollars
%	Percent

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HOW TO CITE THIS ARTICLE

Drobyazko, S.; Hilorme, T.; Nesterenko, S.; Shatskaya, Z., (2023). Formation of the intelligent energy system based on digital technologies in urban management. Int. J. Hum. Capital Urban Manage., 8(1): 1-16.

DOI: 10.22034/IJHCUM.2023.01.01

url: https://www.ijhcum.net/article_698020.html