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V.V. Shevchenko, A.N. Minko, M. Dimov

IMPROVEMENT OF TURBOGENERATORS AS A TECHNICAL BASIS FOR ENSURING THE ENERGY INDEPENDENCE OF UKRAINE

The paper defines the directions of improving turbogenerators as the basis for ensuring the energy independence of Ukraine. The analysis of the state, problems and prospects for the development of modern electric power industry. ***Goal of the work*** *is to identify promising directions for sustainable development of the national electric power industry in order to ensure energy security of Ukraine, to conduct a comparative analysis of electricity sources, to confirm the need to improve the main sources – turbogenerators.* ***Methodology****. During the research, an analytical analysis of the electricity sources, which are installed at power plants in Ukraine and the world, was carried out, taking into account the growth of the planet's population and its energy activity. Cyclic theory was chosen as the theoretical basis for forecasting. On the basis of this theory, global development trends, advantages and disadvantages of currently used sources of electricity - thermal (including nuclear) power plants and stations that operate from renewable energy sources - have been established. A review of literary sources on the methods of the energy sector forecasting the development, including the development of the energy sector in Ukraine, has been carried out.* ***Originality****. It has been established that due to the active growth of the planet's population, with the increase in its energy activity, obtaining electricity from renewable energy sources is not enough, that for the next 20-30 years nuclear power plants will be the main sources of electricity. The internal and external threats to the energy security of Ukraine, directions of development of turbogenerator construction, ways to improve turbogenerators, to increase their energy efficiency, power per unit of performance, to increase the readiness and maneuverability factors, and overload capacity have been identified.* ***Practical significance****. The need to continue the modernization and improvement of the turbogenerators of nuclear power plant units, as the main sources of electricity, has been proved. The directions of their improvement are established: increasing the power in the established sizes, making changes to the design of the turbogenerators inactive elements, replacing the cooling agent to keep Ukrainian turbogenerators at the world level, improving auxiliary systems, improving and increasing the reliability of the excitation system, introduction of automatic systems for monitoring the state turbogenerators. Possible limits of use, advantages, disadvantages and problems of using renewable energy sources for Ukraine have been established.* References 43, tables 3, figures 5.

Key words: **electric power industry, energy independence, turbogenerator, energy saving, ecology, technical diagnostics, weight and size indicators, power increase, renewable energy sources.**

У статті проведено аналіз стану, проблем та перспектив розвитку сучасної електроенергетики. Визначено напрямки її розвитку з урахуванням вибору техніко-економічного сценарію розвитку, супутніх факторів і їх взаємного впливу. Метою роботи було визначення перспективних напрямків сталого розвитку національної електроенергетики щодо забезпечення енергетичної безпеки України, проведення порівняльного аналізу джерел електроенергії, підтвердження необхідності вдосконалення основних джерел – турбогенераторів. Визначено внутрішні та зовнішні загрози енергетичній безпеці України. Встановлено переваги і недоліки, світові тенденції подальшого використання сучасних джерел електроенергії - теплових (включаючи атомні) електростанцій і станцій від поновлюваних джерел енергії. Встановлено, що в зв'язку з активним ростом населення планети і зі збільшенням його енергетичної активності електроенергії від поновлюваних джерел енергії буде недостатньо, що найближчі 20-30 років основними джерелами електроенергії будуть атомні електростанції і це підтверджує необхідність проведення робіт по вдосконаленню турбогенераторів. Встановлені напрями вдосконалення конструкцій турбогенераторів і систем охолодження. Зазначено, що вдосконалення турбогенераторів вимагає одночасного підвищення ефективності і систем, що забезпечують їх роботу: систем постачання газом, водою і маслом, системи збудження. Показана необхідність повного впровадження автоматичного контролю стану турбогенераторів, використання прийомів сучасної технічної діагностики найбільш напружених вузлів і елементів як в режимі online, так і при проведенні планових і аварійних ремонтів. Підтвердження необхідності проведення робіт по вдосконаленню вітчизняних турбогенераторів викликано появою в загальній енергосистемі України нових типів електроенергетичних джерел, які користуються активною державною підтримкою. Відзначена перспективність використання поновлюваних джерел енергії з точки зору зниження екологічних проблем, але лише для індивідуальних споживачів. Проаналізовані переваги, недоліки і проблеми використання поновлюваних джерел енергії, які найбільш прийнятні для України. Бібл. 43, табл. 3, рис. 5.

Ключові слова: **електроенергетика, енергетична незалежність, турбогенератор, енергозбереження, екологія, технічна діагностика, масогабаритні показники, підвищення потужності, поновлювані джерела енергії.**

В статье проведен анализ состояния, проблем и перспектив развития современной электроэнергетики. Определены направления ее развития с учетом выбора технико-экономического сценария развития, сопутствующих факторов и их взаимного влияния. Целью работы являлось определение перспективных направлений устойчивого развития национальной электроэнергетики с целью обеспечения энергобезопасности Украины, проведение сравнительного анализа источников электроэнергии, подтверждение необходимости совершенствования основных источников – турбогенераторов. Установлены достоинства и недостатки, мировые тенденции дальнейшего использования современных источников электроэнергии – тепловых (включая атомные) электростанций и станций от возобновляемых источников энергии. Определены внутренние и внешние угрозы энергетической безопасности Украины. Установлено, что в связи с активным ростом населения планеты и с увеличением его энергетической активности электроэнергии от возобновляемых источников энергии будет недостаточно, что ближайшие 20-30 лет основными источниками электроэнергии будут атомные электростанции и это подтверждает необходимость проведения работ по совершенствованию турбогенераторов. Установлены направления совершенствования конструкций турбогенераторов и систем охлаждения.

Отмечено, что совершенствование турбогенераторов требует одновременного повышения эффективности и систем, обеспечивающих их работу: систем снабжения газом, водой и маслом, системы возбуждения. Показана необходимость полного внедрения автоматического контроля состояния турбогенераторов, использования приемов современной технической диагностики наиболее напряженных узлов и элементов как в режиме online, так и при проведении плановых и аварийных ремонтов. Подтверждение необходимости проведения работ по совершенствованию отечественных турбогенераторов вызвано появлением в общей энергосистеме Украины новых типов электроэнергетических источников, которые пользуются активной государственной поддержкой. Отмечена перспективность использования возобновляемых источников энергии с точки зрения снижения экологических проблем, но только для индивидуальных потребителей. Проанализированы преимущества, недостатки и проблемы использования возобновляемых источников энергии, которые наиболее приемлемы для Украины. Библ. 43, табл. 3, рис. 5.
Ключевые слова: **электроэнергетика, энергетическая независимость, турбогенератор, энергосбережение, экология, техническая диагностика, массогабаритные показатели, повышение мощности, возобновляемые источники энергии**

The following abbreviations are used in the work: **TG** – turbogenerator; **NPP** – nuclear power plant; **TPP** – thermal power plant; **CHP** – combined heat and power plant; **HPP** – hydroelectric power plant; **RES** – renewable energy sources; **WPP** – wind power plant; **OECD** – Member Countries of the Organization for Economic Co-operation and Development; **HTSC** – high-temperature superconductor; **LTSC** – low-temperature superconductor.

Introduction. In most countries of the world, the electric power industry is considered the most important sector of the national economy. Therefore, **the goal of this work** is to identify promising directions for sustainable development of the national electric power industry in order to ensure the energy security of Ukraine, conduct a comparative analysis of electricity sources and confirm the need to improve the main sources – turbogeneratots. Here, the main issue, one of the most serious problems for any national manufacturer, is energy saving [1-4]. The solution to the problem of energy saving is especially important for Ukraine, where at present the production of a unit of GDP on average consumes almost 3 times more energy resources than in European countries [1, 3, 5]. Energy saving is one of the most important factors contributing to an increase in the level of energy security, which is one of the most important elements of sustainable economic development for both exporting and importing countries of energy resources. Obviously, it is difficult to solve the problem of ensuring the energy security of the country if the energy supply is fully or largely dependent on external suppliers [3, 5]. For Ukraine, as well as for all countries, the main requirement when choosing directions for the development of the electric power industry is reliable and efficient energy supply to industry and the population, obligatory taking into account the requirements of environmental safety and social stability. The promising tasks of the energy sector are the same for all countries: it is the search for new sources and technologies for generating electricity, a continuous increase in generation volumes, an increase in efficiency in transmission and distribution, and a reduction in losses at all these stages [6-8].

When choosing directions for the development of the electric power industry, it is necessary to take into account the whole complex of factors and their mutual influence: the technical condition of electrical equipment, national directions and priorities for the joint development of the economy and industry; political, environmental, demographic problems; technological and resource capabilities not only of the electrical engineering industry, but also of related industries: turbine construction, enterprises for the creation of controlled reactors, mining and processing of uranium [5, 8].

At the present time it is necessary to choose: to continue the development of different directions or to develop one, specific direction; to improve and develop mono-energy with globalization on a national scale or to give priority to the development of poly-energy (mini- and micro-hydroelectric power plants, solar and wind energy, mini-CHP, etc.).

Since the end of the 90s of the 20th century in all countries, special attention (and government material support) has been paid to energy from RES, «green energy» [2, 5]. This is an important area, but it will not meet the growing needs of the world's population for electricity, which are constantly increasing, especially taking into account the continuous increase in specific energy consumption in all countries of the world (Fig. 1, Fig. 2, Table 1) [3, 9, 10].

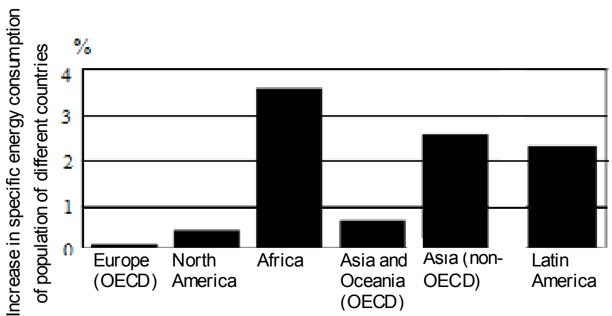

Fig. 1. Forecast of annual growth in electricity demand (specific energy consumption), 2010-2040

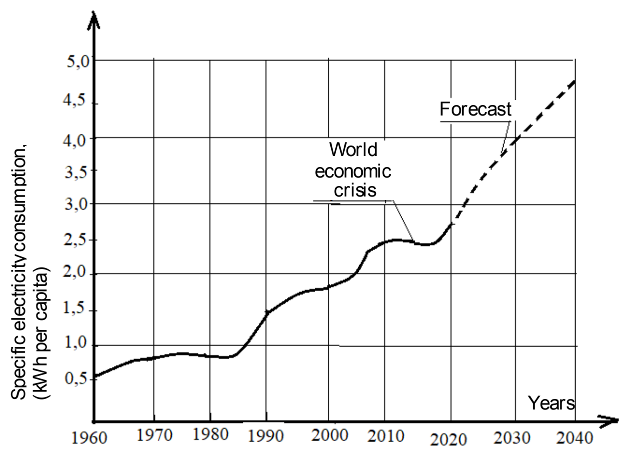

Fig. 2. Global growth in specific electricity consumption (kWh per capita)

Table 1

Existing and prospective population growth and demand for basic energy in 2030

No,	Indicator	World rates of population growth and demand for main types of energy, % to the level of 1970		
		1970-1990	1990-2010	2010-2030 (forecast)
1	Population	+1,8	+1,4	+1,0
2	GDP	+3,5	+3,2	+4,0
3	Electricity	+2,6	+3,2	+3,9
4	Electricity per capita	+0,5	+0,5	+0,7
5	Energy intensity of GDP	–0,9	–1,4	–2,0

Analysis of possible scenarios and directions for the development of world energy sector and energy sector in Ukraine. In the chosen model of technical and economic development of the state, different scenarios are possible: unfavorable (pessimistic), favorable (moderate), maximally favorable (optimistic) [8-10]. The most acceptable for Ukraine, given the existing internal and external factors, is, in our opinion, a moderate scenario, but its implementation also requires significant structural reforms. In the long term, the development of the domestic economy and energy sector will be determined by a combination of three principles – static, cyclical and dynamic [9, 11-14]. According to these principles, inertia of economic and energy development will prevail in Ukraine until 2050, followed by cyclical repetition at a higher level, and the dynamic principle makes us expect an acute complex crisis in the future, which will most likely be resolved by a complete change in the direction of energy sector development. Over the past 100 years, three such crises can be noted: the early 1930s, early 1970s, and the crisis of the late 2010s [9, 11].

The crisis of the early 1930s led to accelerated industrialization and a sharp increase in the demand for electricity and petroleum products for industry. The crisis of the early 70s was caused by the transition of the United States and Western Europe to the model of post-industrial development and the end of the Cold War. Here, private entrepreneurship became more active, the acceleration of the development of nuclear energy was noted, the demand for gas as the main fuel for the energy sector increased, etc. During the crisis, the growth rates of world energy consumption decline and may even become negative, but after the crisis, there is always a steady growth (Fig. 3) [9].

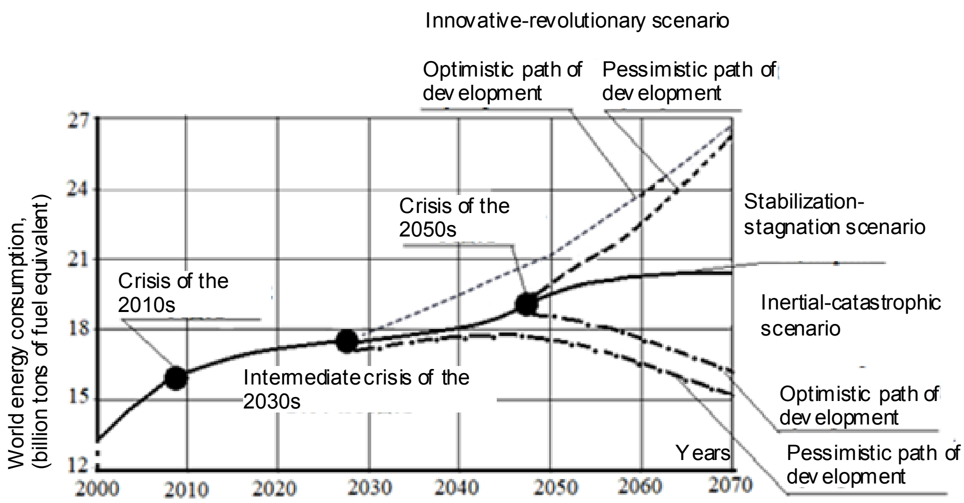

Fig. 3. Changes in electricity consumption under various scenarios for the development of the electric power industry

The crisis of the late 2010s caused the need to reevaluate and forecast new directions for energy sector development. The theory of cyclical development (N. Kondratyev theory of «long waves») was chosen as the theoretical basis for forecasting, which reduces forecasting errors, takes into account economic crises, energy saving and environmental safety requirements, increases the accuracy of identifying strategic problems and the volume of sufficient investments. According to this theory, the cycles of development of the economy, industry and energy sector have a duration of 50-55 years and are determined [9, 11] by:

1) accidental and temporarily acting factors (natural disasters, wars, accidents);

2) constantly acting non-cyclical factors (scientific and technological progress, demography, presence and availability of natural resources);

3) constantly acting cyclic factors (for TG these are electromagnetic and thermal effects, vibration, «aging»).

Analysis of the dynamics of energy sector development, taking into account the existing cyclicality, allows to expect the next crisis in the world economy and energy sector by 2040-2050, which will lead to new qualitative, intellectual, energy-informational levels in the energy sector [9, 14-16].

After overcoming the next crisis, each state should choose scenarios for the development of national energy sector from three possible options:

1) inertial-catastrophic;
2) stabilization-stagnation;
3) innovative-revolutionary.

Each scenario has its own characteristics and ways of resolving contradictions, its own scale of demand for energy resources, features of the development of technologies for the production of primary energy resources and their consumption (see Fig. 3). Each scenario is characterized by the presence of two stages: the first one, which retains a certain inertia of the previous scenario, and the second one, in which the inertia is exhausted, a period of stagnation begins with signs of a latent or explicit energy crisis, and then the energy sector goes into a qualitatively new state. At the last stage, innovations are introduced into science and technology, there is a maximum rise in industry, new issues are formed that must be addressed at the next stage (cycle) and which will determine further development [11, 12, 16].

The most progressive in terms of energy sector development is the innovative-revolutionary scenario. It assumes qualitative changes in modern directions by 2020-2030 by improving the technology for generating electricity, its transmission and final consumption. In this scenario, the key trends in the development of world energy sector will be an increase in investment activity, the development and implementation of new technologies, an increase in the share of electricity in the total amount of energy used, a radical reduction in energy consumption [4, 9, 14-16]. The innovative-revolutionary scenario presupposes the formation of a new type of energy sector in developed and developing countries; growth in the volume of electricity in total global final energy consumption from 21.7 % (2010) to 28.6 % (2030) and up to 36.8 % in 2050.

It can be expected that by 2050 developing countries will reach the modern energy consumption standard of the countries of Europe and the USA, equal to 5 MWh per capita per year. Quantitative differences will decrease, but qualitative differences will increase, because it can be assumed that after 2030 in developed countries the formation of new generation energy systems based on smart grid technologies will begin. And, despite the unpopularity, the role of nuclear energy can be expected to increase: almost twice by 2030 and four times by 2050, since only NPPs, as sources of electricity, will be able to provide its required volume [6, 8, 10, 14, 17]. It is expected that in this case the development will receive: «thermal» reactors of 3-4 generations; fast reactors; reactor plants B-392, which use new solutions to increase the design life of the reactor pressure vessel up to 60 years; «small nuclear energy» which will somewhat reduce the consumption of uranium («uranium problem») and problems of storage and processing of spent nuclear fuel. It can be considered that the next 20-30 years nuclear power industry – highly productive, with a low level of emissions of substances that pollute the atmosphere, and with practically unlimited reserves of fuel – will be the main source of electricity [16, 18, 19].

At the same time, for Ukraine, the innovative-revolutionary scenario for the development of energy sector, economy and industry is unattainable in terms of technical, economic and political indicators. According to macroeconomic indicators, Ukraine is one of the poorest European countries with low incomes, which leads to the absence of a social and economic foundation for sustainable development. According to the International Finance Corporation [12, 17], the energy intensity of the gross domestic product (GDP) per USD 1 in our country is approximately 2-3 times higher than in developed European countries. Therefore, it can be argued that a stabilization-stagnation scenario of development is most likely for Ukraine [9, 18]. Here, while there are no new sources of electricity and sustainable systems for its storage, nuclear energy should be continued to develop and thermal energy (TPPs, CHPs) should be maintained in working order with the obligatory compliance of the national environmental policy with world requirements: the Kyoto Protocol (2005) and the Climate Conference in Paris (Paris Agreement, 12 Dec. 2015) [18-20].

It should be noted that there are threats to the energy security of Ukraine, both internal and external. Morally and physically obsolete electrical equipment of the power complex, outdated technological lines for the manufacture of new equipment, dependence on the export of both equipment and fuel resources, deficiencies in maintenance, diagnostics and repair have led to the fact that the power system of Ukraine has one of the largest losses of electricity in the «generation – transmission – distribution – consumption» cycle, that raises the question of the country's energy security. For example, energy losses in distribution networks reach 25 % [5, 21].

Internal factors include:

- excessive energy intensity of GDP, which has grown by 1.5 times in recent years. Energy costs for the manufacture of the main types of electrical products in Ukraine are 3.5-9 times higher than in the developed countries of the world [4, 16, 22];
- depreciation of fixed assets of the fuel and energy complex [16];
- insufficient investment in the electric power industry, including in the development of electrical engineering and in the renewal of equipment for power plants, in scientific research, in the improvement of technological processes at industrial enterprises and in the education system [4, 23];
- imperfection of the regulatory framework for the industry in market conditions, the crisis of payments at all levels [4, 13].

External factors include a high level of monopolization in the electric power sector, unregulated by state supplies of imported fuel and energy resources and electrical equipment [16, 24], as well as the dependence of nuclear energy, the main supplier of electricity in Ukraine, on imports of nuclear fuel and equipment, and existing storage problems of spent nuclear fuel and nuclear waste [8, 16, 24]. More distant problems of nuclear power should also be noted: the decommissioning of NPPs units that have worked out the service life (taking into account the possible extension of this period), and the tasks of their subsequent maintenance. This is a common problem that is being addressed all over the world.

It can be concluded that the direction of development of the electric power industry is clearly national in nature, but it is obvious that in any scenario of development and any technical and economic state of the country, work should be continuously carried out to improve the TGs – the main sources of electricity for a very long time [16]. For the electric power industry of Ukraine, during the construction of new units and the modernization of the operating ones, it is necessary to use TGs of a larger unit power, to continue work on their improvement. This will provide the country with a sufficient amount of electricity, i.e. will ensure its energy independence, as well as TGs will become an item of export to many countries of the world, which will preserve the importance of Ukrainian products in the world market [16, 25].

Such an assessment of the future of the nuclear power industry may raise questions and objections against the background of the general enthusiasm for «green» energy. But already in 2018, the IAEA revised its forecasts for the development of nuclear power. The IAEA predicts an increase in energy production at NPPs until 2050: under the optimistic scenario – 3969 TWh in 2030 (11.5 % of the total world electricity production) and 6028 TWh in 2050 (11.7 %). Under the pessimistic scenario, these figures will amount to 2732 TWh in 2030 (10.3 % of the global electricity generation) and 2869 TWh in 2050 (5.6 %) [8, 10, 13, 26].

Today there are 450 operating NPP power units in the world. According to experts, the expansion of power at the present time, as well as the near and long-term growth prospects, are characteristic mainly for Asia. Of the 34 reactors under construction, 19 are located in Asia, and 28 of 39 recently commissioned reactors, which were connected to power grids, are located there [26]. Most of the power units are operated in the USA (100), France (58), Japan (43), Russia (36) and China (36). The total generating power of the NPPs is over 392 GW. Since 2018, the commissioning of new power has amounted to 302 GW, 117 GW have been decommissioned, as a result, the net increase in installed NPPs power is 185 GW [10, 24]. According to forecasts, by 2030, the total power of nuclear installations (with innovative-revolutionary scenario of development) will increase by 88 % [24].

The disasters at the Chernobyl nuclear power plant (1986) and at the Fukushima-1 nuclear power plant (2011) led to a rethinking of the idea that nuclear generation is a safe way to generate electricity. As a result, the Japanese authorities decided to work on the closure of all nuclear reactors in the country. Germany, which before the disaster was one of the largest consumers of nuclear energy, has now closed 8 of 17 reactors. Other European countries have also scaled back their plans to develop nuclear power. However, this did not force some countries to abandon plans to build NPPs in addition to existing HPPs and TPPs (coal and gas). In a number of countries where hydrocarbon resources are scarce, nuclear power is perceived as an efficient and economical way to generate electricity. The World Nuclear Association (WNA) states that more than 45 countries are actively striving to develop nuclear programs [10, 18, 24, 26].

One of the additional factors confirming the need to build new NPP units is the inadmissibility of the construction of TPP units, because it is the TPP emissions that determine the main threat to the environment. It should be noted that for countries with developed nuclear power, technologies for the disposal of radioactive waste are less expensive than technologies for the disposal of waste from TPPs, aimed at reducing harmful emissions to the required levels [18, 27].

Generating electricity from renewable energy sources (RES) can be considered a promising alternative. According to the forecast of the World Energy Council (WEC), the share of energy from RES by 2025 will account for 1150-1450 million tons of standard fuel (5.6-5.8 % of total energy consumption) [8, 13]. It is expected that the share of certain kinds will be: biomass – 35 %, solar energy – 13 %, hydropower – 16 %, wind energy – 18 %, geothermal energy – 12 %, ocean energy – 6 %. It was planned that by 2030 alternative sources could provide up to 40-50 % of the energy of the current level of its consumption, that the largest increase in electricity production until 2040 will be determined by the developing countries of Asia (up to 45 % of world electricity generation [15]) and that by 2040, global electricity production from RES will exceed 50 %. It is assumed that in European countries the share of RES (including hydropower) will reach 68-72 %, and only RES (excluding hydropower) will provide 51-56 %. So. Europe will become the second region after Central and Latin America, in which by 2040 more than half of the electricity is expected to come from non-fossil fuels (all types of RES including hydro resources) [12]. At the same time, according to the forecast, coal is expected to remain the dominant source of generation in developing countries in Asia by 2040; in North America, the Middle East and Africa – gas TPPs; in South and Central America, the first place will remain for the generation of electricity at hydroelectric power plants, and only in Europe, RES can become the main ones. Therefore, the assertion that mankind has no future without alternative energy sources to nuclear energy is, in our opinion, too categorical, but this only once again emphasizes the need to search, research and introduce new sources of electricity, for example, hydrogen energy or controlled thermonuclear fusion energy.

The main disadvantages of RES should be considered the low specific density and inconstancy of electricity generation, dependence on weather conditions, time of year and day, low efficiency (with the exception of hydroelectric power plants), high cost with low unit power of power plants. The inconstancy of primary energy resources (wind, sun), up to a complete absence, makes it necessary to install and maintain additional energy accumulators and/or backup sources. As a result, the cost of the generated energy turns out to be high even in the absence of a fuel component in the final price of electricity.

The low specific power of RES requires an increase in the number of power units. For example, the average annual value of the specific power of solar panels for the sunniest regions of the world (taking into account seasonal and weather fluctuations) does not exceed 250 W/m^2, and in Ukraine, the average density of solar radiation on the earth's surface at noon on a clear day is about 120 W/ m^2. In our latitudes, even in cloudless weather, solar panels rarely operate at full capacity, on average this figure is 50-60 % in summer and 10-15 % in winter, i.e. a 275 W panel will generate about 140-145 Wh on a summer day. On average, in Ukraine, a solar panel with power of 1 kW in a year generates 1100 kWh of electricity (Fig. 4) [2, 16, 28]. Similarly, wind energy has a low specific power: the average specific energy density of the wind flow, as a rule, does not exceed several hundred W/ m^2. At a wind speed of 10 m/s, the specific energy density will be about 500 W/ m^2.

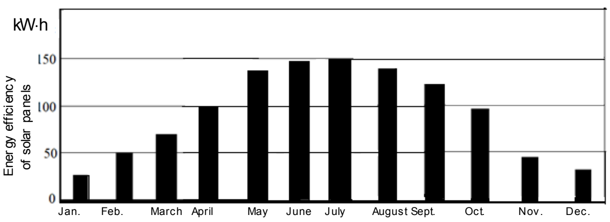

Fig. 4. Average electricity generation by solar panels in Ukraine per 1 kW of installed power

In Ukraine, only in some regions (4 % of the territory) a steady wind speed («wind rose») is 4-4.5 m/s, so the specific energy density is insignificant, up to 100 W/m^2. For comparison, the energy density of a water flow with speed of 1 m/s is about 500 W/ m^2, and the density of the heat flow, which «presses» on the walls of steam boilers at TPPs and NPPs, reaches several hundred kW/ m^2 [16, 29, 30].

The COVID-19 pandemic (2020-2021) has changed the forecasts for the development of the electric power industry, caused more disruptions in the energy sector than any other event, and its consequences can be expected to be felt for years to come. Currently it is difficult to assess how the current crisis will affect the development of the electric power industry: whether it will accelerate or slow down the creation of a safe and sustainable energy system. The pandemic is not over yet, which introduces uncertainty in energy consumption issues, and it is probably too early to predict important decisions in the field of energy policy. In addition, the economic crisis is causing significant changes in the strategic orientation of energy companies and investors, in the activity of energy consumers. The World Energy Prospects Program [3, 12, 21] contains two possible scenarios: optimistic (The Stated Policies Scenario, STEPS – a forward-looking policy scenario) and pessimistic (Delayed Recovery Scenario, DRS). According to STEPS forecast, global energy demand will recover to the level of the beginning of the pandemic by early 2023, but in the event of a protracted pandemic, an even larger decline is expected (according to DRS) and demand will only recover by 2025.

Before the epidemic, a forecast was made that electricity consumption for the period 2019-2030 will grow by 12 %. The growth forecast has now changed to 9 % (STEPS) or 4 % (DRS). And this growth will mainly be driven by developing countries (China, India). In countries with developed economies, the demand for electricity is decreasing, investments in the energy sector and in the production of new equipment are decreasing, and the volume of construction work is decreasing [24]. But under any scenarios and features of the current period, all researchers predict an increase in energy consumption. Therefore, it can be argued that for the next 20-30 years, with all the understanding of the problems of nuclear energy, the daily, sustainable supply of electricity to the population of the planet will be provided by NPPs, i.e. by TGs installed on units [8, 13, 19, 24].

The main directions and problems of creating modern TGs. In world practice, since the middle of the last century, the unit power of the TGs has increased by 7-7.5 times, from 200 to 1500 MW, and if we count from 1898, when Charles Brown (since 1971 Abegg and Rauhut) produced the first 6-pole TG with power of 100 kVA, the power increased by 15000 time. At the same time, the dimensions and weight of the TGs increased, which at a certain moment created the problem of their creation and transportation by rail and determined the task of minimizing the volume and weight with increasing power. Until 2000, the insufficient power of the electric networks also limited the power of the TGs, since in the event of an emergency shutdown of a powerful generator, problems arose with the stability of the network. At present, the total power of electric grids has become higher, they have become more resistant to sudden switching off of generating units, and an increase in the power of TGs has become possible. The prospect of increasing power is also confirmed by international practice (Siemens, ABB Alstom Power, Hitachi, General Electric, Westinghouse): in Great Britain and the USA they are designing 2000 MW TGs, in France two TGs with power of 1550 MW are already operating, General Electric is developing two TGs with power of 1750 MW for Chinese NPPs. It should be emphasized that all world Companies are oriented on 4-pole generators [16, 30-33].

To increase the power, it would be logical to increase the dimensions and weight of the machines, but, as indicated, this complicates their manufacture and transportation, and increases the cost. Therefore, the increase in power is currently being considered without changing the dimensions. The design takes into account the technological capabilities of related industries: the capabilities of metallurgical enterprises, turbine-building enterprises, enterprises for the creation of controlled nuclear reactors, the possibility of transporting TGs to the consumer [34-36]. The increase in power is also expedient from the point of view of economic indicators. For example, the total mass, cost and losses of several TGs are always greater than the mass, cost and losses of one machine of the same power. It is calculated that when using one TG instead of several, the power of which is equal to the power of one TG, the mass, cost and losses decrease approximately $\sqrt[4]{m}$ in comparison with the same indicators m of TGs of lower power. On the example of TGV-300-2 turbogenerator, the possibility of increasing the power from 300 MW to 500 MW by changing the electromagnetic and geometric parameters of the structure (within acceptable limits) with practically the same dimensions is shown [16].

Hundreds of TGs operate at the power plants of each power system, i.e. any TG on the unit operates in parallel with other generators in the power system. For stable operation, all of them must generate consistent voltage, otherwise equalizing currents will arise between machines operating in parallel on the same electrical network. For this, the rotors of all generators must rotate at synchronous speed and at each moment of time occupy a certain angular position. In case of loss of stability, there is a massive shutdown of generators, the power system «falls apart». It is because of this that a major accident occurred in the United States in 1965 [37]. 7 states with a population of about 30 million people were left without electricity, the damage exceeded USD 100 million. The only part of the power system that was not affected is the area of Fort Erie near Buffalo, Ontario, which was powered by old generators with frequency of 25 Hz. For 5 minutes, chaos reigned in the power distribution system in the northeastern United States, as due to overloads that cascaded throughout the network, the TGs were disconnected by the protection system.

Unfortunately, the higher the power of the TG, the less «stable» it is in parallel operation. This is because with the growth of the unit power of the TGs, they try not to change their mass and dimensions. In powerful TGs, the rotors become relatively lighter, less inertial and, therefore, less stable in emergency modes (Table 2). With each new step in increasing the TG power, the problem of reducing stability becomes more and more urgent and requires additional research.

Table 2

Data of the TGs of power 63-1200 MW

TГ	Power, MW	Rotor mass, t	TG mass, t	Ratio of the rotor mass to the total mass of the TG, %	Manufacturer
TVF-63-2	63	25,4	123,6	20,6	JSC «Electrosila»
TVF-110-2E	110	28,9	151	19,1	
TVF-120-2	120	30,8	179	17,2	
TVF-200-2	200	41,8	265	15.8	
TGV-200-2	200	48,7	321	15,2	SE «Plant «Electrotyazhmash»
TGV-200-2M	200	48,1	256	18,1	
TGV-300-2	300	55,8	364	15,3	
TVM-300-2	300	50,4	333	15,1	JSC «Electrosila»
TVV-320-2	320	55,1	340	16,2	
TVV-500-2	500	65	444	14,6	
TVV-800-2	800	84,0	615	13,7	
TVV-1000-2	1000	86,5	641	13,5	
TVV-1200-2	1200	96	670	14,3	

Figure 5 shows the tendency of change in the relative rotor mass (the ratio of the rotor mass to the total mass of the TG, %) with a change in the TG power.

The decrease in the stability of the system due to the relative decrease in the mass of the rotors of the generators is compensated by the use of high-speed thyristor excitation control systems and automatic voltage regulators: with smaller mass of the rotor, its inertia decreases and during transients (or at a short circuit) the rotor of the TG begins to «swing», i.e. the stability of its parallel operation with the electric network decreases, but the automatic excitation control system increases the excitation current. Here, electromagnetic forces increase in the generator, which, as it were, connect it with other TGs, which protects the power system from collapse.

To maintain the characteristics of domestic TGs at the world level, in addition to the above tasks, additional research is needed to ensure trouble-free operation of TGs

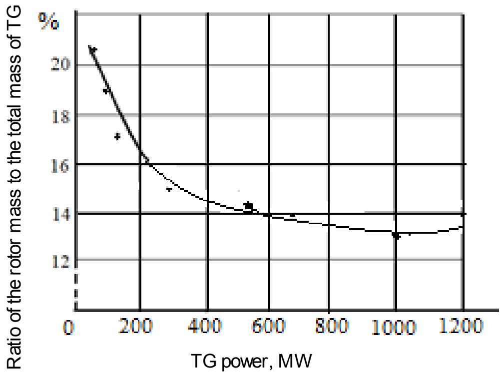

Fig. 5. Dependence of the ratio of the rotor mass to the total mass of the TG, depending on the power

in transient modes associated with «peaks» and «dips» of power consumption, operation in modes of reactive power consumption, it is necessary to reduce maintenance and repairs costs to ensure the reliability and durability of individual units and parts. Increasing the efficiency of the TGs also requires improving the supply systems (gas, water and oil supply systems), improving and increasing the reliability of the excitation system, introducing automatic systems for monitoring the state of the TG, using the methods of modern technical diagnostics of the most stressed joints and elements both in online mode, and during scheduled and emergency repairs.

The current stage is characterized by the emergence of new types of TGs, steel grades and insulating materials, the development of new methods of extending the service life of TGs installed at TPP and NPP units [23, 36]. To establish the pre-emergency state of the TG, identify defects, and exclude long-term downtime due to emergency shutdowns, it is necessary to introduce complex diagnostic systems [25, 30]. Work continues to further increase the power per unit of performance due to the introduction of new electrical insulating materials, forgings with higher strength characteristics, electrical steels with lower specific losses, to intensify the cooling of windings and cores [30-32].

Also, when creating modern TGs, it is necessary to comprehensively solve scientific problems related both directly to TGs and to systems of excitation, regulation, control and protection [16, 31]. When developing new designs, it is necessary to take into account the peculiarities of the power system operation and, accordingly, the operation of the TG in non-nominal modes: with «peaks» and «dips» of the load, operation with the condition of ensuring the balance of active and reactive energy in the network, etc. The TGs installed at power plants are not designed for such operating conditions: they are not maneuverable enough and are limited in solving the issue of reactive power regulation; have terms of operation exceeding the terms established by the manufacturer. The latter causes additional problems: «aging» of insulation and wear of structural materials, decrease in mechanical reliability and integrity of laminated stator cores, fasteners, etc. [16, 36]. Therefore, when designing a TG, additional requirements should be established:

- ensuring increased maneuverability of the TG with the possibility of at least short-term consumption of reactive energy from the network. The consumption of reactive energy should be limited only by the stability of the generator operation in the power system, and not by thermal and mechanical processes in the machine;
- ensuring high controllability, the possibility of regulating the TG rotation frequency (up to short-term asynchronous modes) while maintaining power, ensuring their stable connection with the grid in order to increase the economic and operational performance of the power plant [27, 31];
- ensuring the possibility, when carrying out repairs and modernization of TGs, to increase their power in the established size, improve the cooling system, make the necessary changes in the design of inactive elements of the TG using modern calculations, technologies and new materials.

Developers of modern TGs should:

- to maintain constant technical indicators when changing operating modes of the power system, to know the permissible limits of TG participation in maintaining the balance of active and reactive power;
- when increasing the power of the TG in the process of their modernization, to achieve the preservation of dimensions for the use of existing foundations and supporting systems;
- to improve the TG cooling system, carry out work on the replacement of cooling agents, in particular, in TGs with power of 300 MW and more, to replace explosive and fire hazardous hydrogen with air [30];
- to ensure the competitiveness of TGs, continue work to reduce their specific weight (kg/kW) by improving the design of the inactive zone [7, 36];
- to improve the programs for assessing the technical condition of TGs to determine the possibility of extending their service life, establishing the necessary and sufficient amount of repair work;
- to continue researching the prospects of installing asynchronized TGs at TPP units in parallel with operating synchronous TGs to increase the reliability and stability of their operation and the operation of the system [16];
- to improve the system of targeted training and retraining of specialists of all levels (skilled workers, engineers), solve the issues of ensuring the economic interest of power plant workers to keep them in the national electric power industry [23].

It should be noted that the creation of modern TGs is necessary not only for TPPs and NPPs. The creation of new types of TG is also necessary for modern wind power. Increasing the power of WPPs requires an increase in the power of generators. This increases the weight of the machine, which must be installed at an ever greater height. For example, a 12 MW WPP tower (Haliade X, General Electric) has height of 260 m [28, 40]. For such installations, the issue of reducing the weight of each element and, first of all, the generator is one of the main tasks.

The use of TGs with magnetoelectric excitation (with excitation from permanent magnets) instead of electromagnetic excitation does not solve this problem. A promising solution can be considered the use of generators with HTSC windings, which will reduce the weight and dimensions of superconducting generators by 3-4 times in comparison with conventional generators of the same power. A generator with HTSC windings for a WPP with power of 8 MW will have diameter of 3 m and weight of 120 tons, while a conventional («warm») TG of the same power will have diameter of 9 m and weight of 450 tons, i.e. the weight of the TG with HTSC windings will be 3 times less. Besides, the cost of the WPP will also decrease from 6.7 to 3.2 million USD. According to the studies carried out, the weight of additional cryogenic equipment for different designs of the HTSC generator is less than 4 % of the total weight of the generators, i.e. the additive is insignificant [38, 39].

Also, when TGs with superconducting windings are used for WPPs, the production areas required for their installation will decrease, which are usually very significant. Thus, an offshore WPP SG 14-222 DD (power 14 MW, working diameter 222 m, length of one blade 108 m) requires the area of $39\cdot 10^3$ m^2 [21, 28, 40]. (For comparison, the area of one NPP power unit with a 1000 MW generator and with a VVER-1000 reactor is about $9.1\cdot 10^3$ m^2). Some parameters of WPPs with a TG with power of 10 MW with different types of superconducting windings are given in Table 3.

Table 3

Parameters of WPPs with different types of TGs with power of 10 MW with superconducting windings

Parameter	TG with windings of LTSC conductors Nb_3Ti (General Electric)	TG with windings of HTSC conductors (AMSC – American Superconductor)	TG with windings of LTSC conductors MgB_2 (Kalsi Engineering)
Rotational speed of WPP blades, rpm	10	10	10
Rated voltage of the generator stator winding, kV	3,3	0,69	4,5
Rated current, A	1750	–	1360
Cooling medium operating temperature, K	4	80	30
Mass of the generator with additional cryogenic equipment, t	143	150	52,5
Outer diameter of the generator, m	4,0	4,5-5	5
WPP diameter, m	160	190	150
Cost (as for 2018), thousand USD	4963	–	3168,0

For the NPPS, such disadvantages as the problems of storage and disposal of spent nuclear fuel are known. But RES also have similar problems – the issue of recycling spent installations and their individual elements. Utilization of large WPPs, especially their blades, is a difficult task. The blades are designed to withstand extreme weather conditions: frost, heat, hurricane winds. According to the Bloomberg New Energy Finance research Company, starting from 2022, in Europe alone, it will be necessary to dispose of approximately 3800 wind turbine blades annually [28, 42].

Researchers note that dismantling and disposal of small onshore WPPs is a difficult, but to some extent already worked out procedure, but dismantling of large offshore WPPs has yet to be mastered. In UK they calculated the costs of dismantling out-of-date offshore wind farms (located offshore). According to the optimistic forecast, it will be necessary to spend 1.85 billion USD, according to the pessimistic one – more than 5.2 billion USD.

It can also be expected that the appearance of large areas of wind farms can affect the natural movement of air masses, will facilitate the process of mixing warm and cold air. And solar panels will reduce the reflectivity of the Earth's surface. All this will lead to climate change and new environmental problems.

Since 2009, the EPR (European Pattern Recognition) project has been operating in Europe under the name «PV Cycle». Under this program, since 2014, self-disposal of solar panels has become mandatory for all manufacturers (EU Directive 2012/19/EU Waste Electrical and Electronic Equipment, WEEE) [41, 43]. Centers for the collection of «solar» waste were established. Some panels are considered hazardous due to lead or cadmium, and because it is impossible to determine the degree of danger, experts advise to consider all solar panels dangerous. Since 2020, all solar panel manufacturers that trade in the US markets must participate in the solar energy waste collection program (EPR project). Therefore, the main problem for the use of solar panels is to ensure that the costs of production and disposal are commensurate.

The disadvantages of renewable energy should also include the features of the operation of generators from RES on the overall energy system, the impact on its stability. Due to the instability of generating electricity from RES, the number of different types of power plants with renewable sources should be limited. This, in particular, concerns ensuring the stability of dynamic processes in power supply systems and, accordingly, changes in the organization of dispatch control. The general energy system cannot use large RES without increasing the number of maneuverable powers. A significant introduction of RES, if it is not accompanied by the installation of additional sources of energy storage, requires additional power control systems to balance the constant fluctuations in energy production and consumption. Also, an increase in the number of power plants from RES in the power system will lead to a reduction in the contribution to the energy supply of traditional power plants, which is good, but will complicate the ability to regulate the frequency and voltage in the event of loss of generation or load [2, 40]. Balancing electricity consumption and maintaining the voltage frequency in the grid are the main technical problems in power systems with significant installed RES power. In Ukraine, according to the calculations of Ukrenergo, the maximum installed power of solar and wind power plants, which the unified energy system can accept without deviations in operation, is 3 GW [2, 3, 21].

Conclusions.

For the sustainable development of the Ukrainian electric power industry and ensuring its energy security, it is necessary:

1. When choosing technical and economic solutions for the development of the electric power industry, one should focus on the stabilization-stagnation scenario with an increase in investments in the implementation of environmental programs.

2. To carry out work on the construction of new units and on the improvement of electrical equipment of operating nuclear power plants, as the main sources of electricity for the next 20-30 years. During the construction of new nuclear power plant units, it is necessary to introduce new types of reactors, more advanced equipment, new technologies for generating, transforming, transmitting and distributing electricity.

3. To continue work to improve the turbogenerators: increase their power (up to 1500 MW and more), use new designs of excitation systems, introduce modern cooling systems, etc. For the installed turbogenerators, expand the service and post-repair tests program, carry out modernization using modern technologies and materials in order to extend the service life, use a comprehensive online monitoring of the technical condition of the turbogenerators.

4. To maintain in working order, modernize the electrical equipment of thermal power plant units to ensure sustainable energy supply to consumers until the launch of new nuclear power plant units and the creation of industrially significant plants from renewable energy sources. The construction of new thermal power plant units is impractical due to the significant impact on the environment.

5. To continue work on the development of the electric power industry from renewable energy sources. For power plants from renewable energy sources that operate on the unified energy system, install sources of flexible powers, which will ensure stable operation in transient modes, and improve the dispatch control system. It is necessary to continue work on solving environmental problems that may arise when using renewable energy sources, in particular, on the issue of recycling elements of installations that have worked out the established service life. To supply energy to individual consumers in Ukraine, it is advisable to develop solar and wind energy (with power of up to 100 kW).

6. To resume investigations on the use of high-temperature superconductors to create electrical equipment (turbogenerators and other elements of the power system) with superconducting windings.

Conflict of interest. The authors declare that they have no conflicts of interest.

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V.V. Shevchenko[1]*, Doctor of Technical Science, Associate Professor,*
A.N. Minko[2]*, PhD,*
M. Dimov[3]*, PhD,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
2, Kyrpychova Str., Kharkiv, 61002, Ukraine,
e-mail: zurbagan8454@gmail.com (Corresponding author)
[2] Research and Production Company with Limited Liability «Ecopolymer»,
42-a, Tobolska Str., Kharkiv, 61072, Ukraine,
e-mail: alexandr.minko@i.ua
[3] Trakia University,
8600 Yambol, Bulgaria.
e-mail: milendimov@protonmail.ch

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