https://doi.org/10.33271/nvngu/2022-5/089

H. Pivniak[1],
orcid.org/0000-0002-8462-2995,
O. Aziukovskyi[1],
orcid.org/0000-0003-1901-4333,
Yu. Papaika[1],
orcid.org/0000-0001-6953-1705,
I. Lutsenko[1],
orcid.org/0000-0001-6406-2364,
N. Neuberger[2]

1 – Dnipro University of Technology, Dnipro, Ukraine, e-mail: Lutsenko.I.M@nmu.one
2 – Esslingen University of Applied Sciences, Geppingen, the Federal Republic of Germany

PROBLEMS OF DEVELOPMENT OF INNOVATIVE POWER SUPPLY SYSTEMS OF UKRAINE IN THE CONTEXT OF EUROPEAN INTEGRATION

Purpose. To analyse problems and features of the formation of perspective concepts and scenarios for the development of the latest structures of energy supply systems for Ukraine in the context of the energy transition and European integration.

Methodology. Theoretical studies, analysis, and generalization of scientific and practical results along with the comparative analysis.

Findings. The European Green Deal contributes to the wide development of relevant RES-based systems in the EU countries. Ukraine has also declared its active position regarding the issues of low-carbon development and “green” transition with the formation of relevant implementation scenarios until 2035, 2050, and 2070. The paper analyses the current state and structure of the electricity supply system in Germany and Ukraine on their ways to low-carbon development of the energy sector and economy. As a result of the conducted research, it is possible to determine further rational steps for effective transformation of the electric power industry according to the strategy of pragmatic or low-carbon development with further measures to modernize the nuclear and thermal energy sectors and moderate RES development. Development of rational structures of electric power systems of new technological order is a constantly relevant, science-intensive direction, which brings serious changes to the traditional raw-resource economy and energy industry.

Originality. The conducted comprehensive analysis of the current state and prospects for the development of the structure of electric power complexes of Ukraine and Germany makes it possible to formulate high-priority rational steps in achieving energy independence and energy security, taking into account low-carbon development of the national economy.

Practical value. The represented analytics can be used to ensure sustainable development of Ukrainian energy industry, to form an outlook on problems, prospects, and aspects of optimistic and pessimistic scenarios of the generation system development.

Keywords: *electric power, energy transition, low-carbon development, energy development scenarios*

Analysis of the problem state. One of the origins of the necessity in energy transition and transformation of the corresponding sector is a problem of energy-related hunger and overpopulation of the Earth. At the end of 2011, the number of world population was more than 7 bln people. At the same time, a stage of maximum annual population increment is a thing of the past as well; in particular, at the peak of its value within the period of 1990–2000, it reached about 8–84 mln people per year in terms of absolute values. That corresponds to the population of such country as Germany (Fig. 1) [1]. Nevertheless, the world population is growing; according to the UNO predictions, its number will be 9.7 bln people before 2050 and 10.9 bln up to 2100 (Fig. 2) [1].

Due to this fact, the following question is being constantly discussed: whether natural energy reserves will be enough and what is necessary to prevent possible energy collapse.

According to monitoring organizations in the field of energy resources and energy (e. g. Enerdata), total global energy consumption between 1990 and 2019 increased approximately by 1.64 times from 8,556 to 13,995 megatons of oil equivalent (Mtoe) (Fig. 3), annual growth of 2.2 %. (For reference: 1 toe = 41.868 GJ = 11.63 MWh). In this context, the largest increase in energy consumption during this period by 2.83 times, from 2,113 to 5,983 Mt, occurred in Asian countries – first of all, in China. For Germany and Ukraine, these indicators are represented in Fig. 4.

It should be noted that the global economic crisis that began in 2008 led to a slight decline in global energy consumption in 2009 compared to 2008 by 0.85 %. Subsequently, until 2019, an increase in global energy consumption was observed on average by 2 % per year.

In 2020, due to the global pandemic, a growth of energy consumption in the world decreased by 3.5 %. Energy consumption has reduced in almost all countries, except China, which accounted for 24 % of the international energy consumption. For example, the consumption fell by 7.6 % in the USA, by an average of 7 % in EU countries, by 6.5 % in Germany, by 4.8 % in Russia, and by 3.4 % in Ukraine.

Total global primary energy consumption in 2020 was 13,508 Mtoe. Of this total, only 15 % is electricity, although 38 % of the primary energy resources are used to produce this amount. Currently, electrical energy is used in all spheres of life, and it does not pollute the environment. Growth of the Earth’s population, progress of electrical technologies, and rapid development of electric vehicles will determine the growing needs for electricity in the near future.

The humanity uses actively different energy resources to ensure its vital activities. The need for these resources, which is constantly growing, is caused by two main factors – growing Earth’s population and rapid technological development.

Today, more and more attention is being paid to the need for high-quality and reliable energy supply to consumers, taking into account such factors as environmental friendliness of the processes of production, consumption, and disposal of products, including direct low-carbon development of the electric power industry itself. This allows solving the global problem of climate change on the planet, reducing harmful emissions into the atmosphere, and improving the ecological state of the environment.

To achieve the goals of climate neutrality, it is impossible to do without a radical approach to the issues of electricity production and transformation of power-generating systems towards the large-scale use of alternative and renewable energy sources (RES) with the use of quite developed technologies for the integration of relevant decentralized systems into electric power systems as well as networks of almost any countries.

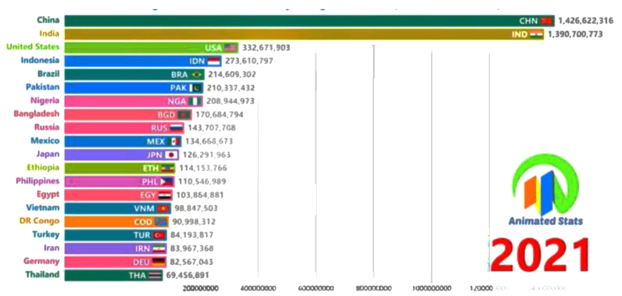


Fig. 1. Rating of the most populated countries in the world [1]

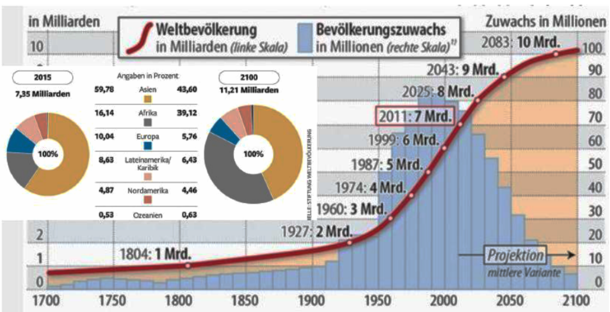


Fig. 2. World population and predictions of its development [1]

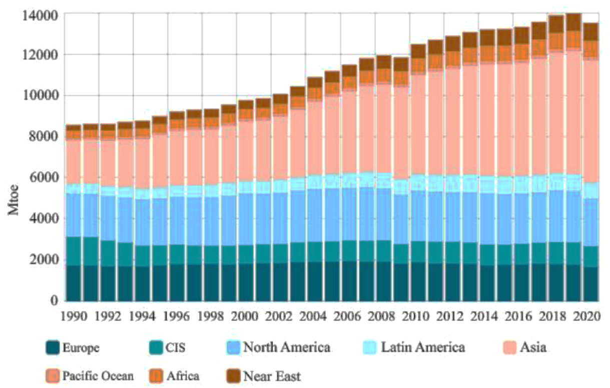


Fig. 3. Worldwide growth of energy consumption for the last 30 years [1]

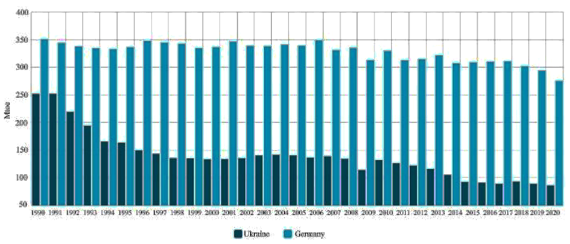


Fig. 4. Changes in energy consumption in Germany and Ukraine

The main problematic aspects of the mass re-equipment of the electricity generation system and the implementation of "energy transition" taking into account a 3D concept of the development of the electric power sector (decarbonization, decentralization, digitalization) in the short- and medium-term period in Ukraine are as follows:

- need to transform coal regions, whose population is connected with the processes of traditional energy (mining, processing, mineral dressing, logistic, machine-building, generating enterprises);
- retraining of personnel and creation of new branches of high-tech production;
- diversification of energy resources and their supply chains with the provision of a possible complete technological and "life" cycle of energy – from obtaining the required raw materials to disposal of products of the electric power sector;
- implementation of rational plans for the development of the electric power sector and electric power production systems through a systematic and adequate transition to low-carbon energy of the guaranteed energy supply;
- development of "green", smart transport – electric cars, electric buses, other municipal transport, taking into account the possibility of regulating the modes of energy system operation;
- development of nuclear energy, which is also defined by the EU as "green".

The specified stages cannot be implemented instantly and, according to German experience, take a period of 10–20 years. However, knowing the main issues, Ukraine can achieve the relevant results at an accelerated pace, taking into consideration the comprehensive support of both the EU and the leading countries of the world (G7) in terms of post-war reconstruction, restoration, and implementation of an intensive path of the national economy development.

Undoubtedly, the development of low-carbon energy is characterized by a number of features that should be taken into account to prevent the reverse effect that may manifest itself in reducing the energy system stability, intensifying the requirements for a share of highly flexible generation in order to compensate, for instance, forced deviations in the forecasting of RES generation or use of excessively produced electricity. A rational combination of various types of decentralized generation with highly intelligent systems of energy monitoring and management as well as dynamic pricing will make it possible to create stable structures of reliable and high-quality energy supply of objects and will contribute to the achievement of goals of energy security and energy independence of states from the policies or market conditions. This problem becomes especially relevant in terms of acute dependence of the electric power industry on imported energy resources, which is characteristic of the economies of Germany (natural gas and oil) and Ukraine, being a common factor. It should be considered while forming both foreign and domestic policy in order to avoid crisis situations typical for 2022, associated with military actions in Ukraine by the Russian Federation, and the necessary sanctions policy of Western countries regarding energy resources imported from the aggressor country.

Thus, in its development, Ukraine can repeat and borrow German experience, especially in the field of energy efficiency, transformation of coal regions, and development of renewable energy; but one should also take into consideration the negative experience of dependence on energy resources of authoritarian countries with opaque economies, which use this factor to implement destructive foreign policy. Undoubtedly, the experience of implementing significant volumes of RES, considering their successful balancing, can and should be used in the development of this sector in Ukraine.

The structure of electricity generation and consumption in Germany and Ukraine. Instability of the political situation and constant fluctuation of prices on the primary energy market forces the countries to take measures to ensure their energy independence and security.

Germany has taken into consideration the importance of the aspect of low-carbon energy independence for a long time and has developed a long-term concept of the transition to non-carbon energy sources, calling it the "energy turn". The term "energy turn" was first used in 1980 in a publication of the Institute of Applied Ecology in Germany entitled "Energy turn. Growth and prosperity without oil and uranium" ("Energiewende. Wachstum und Wohlstand ohne Erdöl und Uran"). This paper proved the possibility of economic growth and sustainable energy supply without the use of nuclear energy – at the expense of renewable energy and increasing energy efficiency.

Over the past 20 years, the structure of German energy supply (Fig. 5) has undergone a significant transformation in favour of RES (wind, solar, bioenergy), whose share has increased substantially during this period. At the same time, it should be noted that in percentage terms a share of solar and wind energy in terms of installed capacity is equal [2]. That ensures a smaller negative impact on the energy system stability compared to the structure of RES in Ukraine, where the installed capacity of solar plants is four times greater than that of wind power plants. It is also necessary to pay attention to the one-and-a-half-fold increase in the consumption of natural gas in the Federal Republic of Germany, which, due to the lack of this resource of its own production, made the country dependent on the importer – the Russian Federation.

The structure of generating stations of the energy system of Germany and Ukraine by installed capacity is shown in Table 1.

Fig. 6 demonstrates dynamics of changes in the structure of electricity generation by sources (*a*) and a share of RES in total electricity consumption (*b*) in Germany over the past 30 years.

In case of Germany, one can trace clearly a rapid increase in the electric energy generation from RES and a dramatic decrease in the electricity generation over the past 15–20 years from the traditional energy resources, including nuclear energy, which, since 2022 by the decision of the EC, has been conditionally equated to "green" (together with natural gas) for some "transitional" period. That is why traditional types of fuel at power stations are diversified due to the increasing amount of electricity obtained by using natural gas.

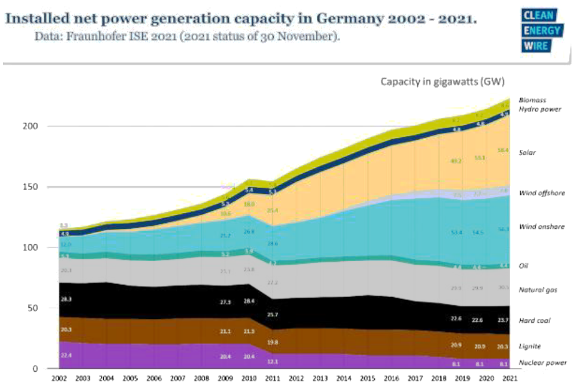
The analysis of absolute and percentage shares in electricity production (Fig. 7) makes it possible to conclude that the Federal Republic of Germany is moving successfully towards decarbonization of energy and economy: a share of electricity from RES as of 2021 is 42.4 %, natural gas – 15.3 %, coal power generation – 28 %, and nuclear – 12 %. However, a share of traditional plants, i.e. coal-fired ones, remains at a fairly high level and is commensurate in relative units with the generation structure of Ukraine by this component.

Table 1

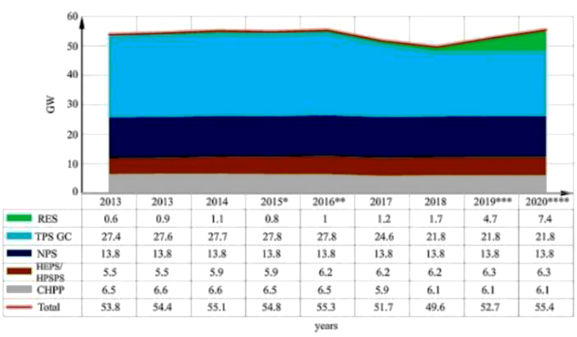
Installed capacity of the electric power stations in the energy system of Germany and Ukraine [2–4]

Type of electric power station	Ukraine	Germany	Ukraine	Germany
	Installed capacity, GW		Share in the structure, %	
Nuclear power station (NPS)	13.8	8.1	24.6	3.6
Thermal power station Generating companies (TPS GC) + Combined heat and power plant (CHPP)	27.9	44	49.6	19.7
Hydro-electric power station (HEPS)	4.8	4.9	8.6	2.2
Hydroelectric pumped-storage power station (HPSPS)	1.5	–	2.6	–
Solar-power station (SPS)	6.4	58.4	11.3	26.2
Wind-power station (WPS)	1.5	64.1	2.8	28.7
Biofuel-based stations	0.25	8.6	0.5	3.9
Oil	–	4.4	–	2.0
Natural gas	–	30.5	–	13.7
Total	56.3	223	100.0	100.0

In 2021, the volume of electricity production by power plants of Ukraine as a whole amounted to 156.6 TWh [4]. The main share in the total production during 2021 is as follows: NPS – 55.0 %, TPS and CHPP – 29.3 %, and HEPS and HPSPS – 6.7 %. According to the structure of electricity produc-

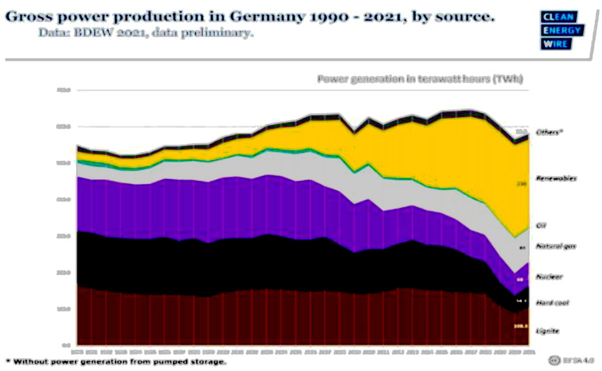


a

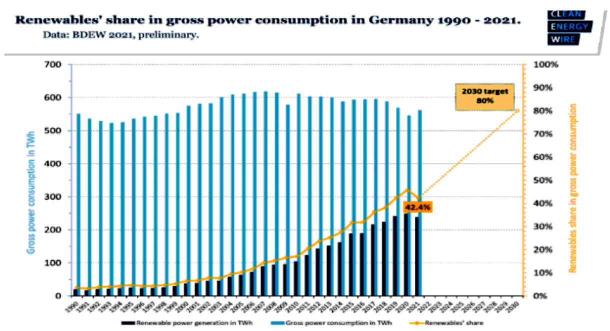


b

Fig. 5. Dynamics of changes in the installed capacity of energy systems in Germany (a) [2] *and Ukraine (b)* [5]

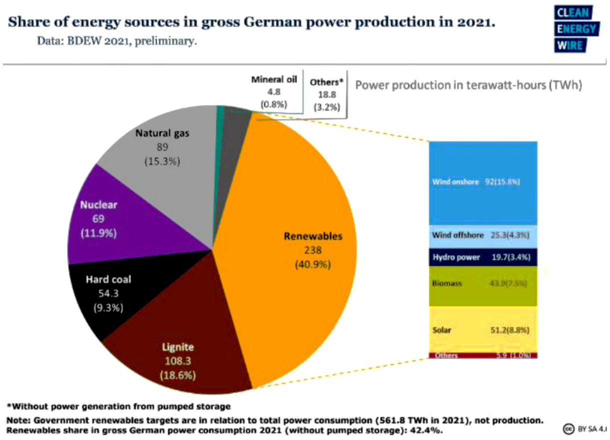


a

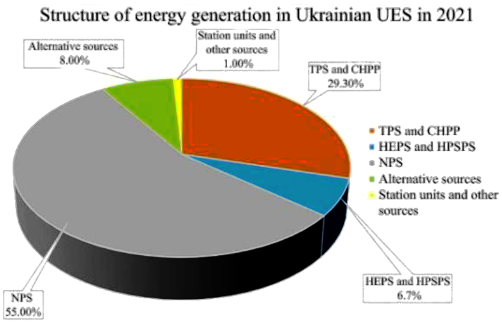


b

Fig. 6. Dynamics of changes in the structure of electricity generation by sources (a) and a share of RES in total electricity consumption (b) in Germany [2]



a



b

Fig. 7. Structure of energy generation in Germany (a) [2] *and Ukraine (b) as of 2021* [4]

tion (Fig. 7), in relative units, Ukraine exceeds the indicators of Germany by 5 times in terms of the NPS share; its indicators of generation from RES are inversely and proportionally lower.

Nevertheless, over the past five years, the renewable energy sector has increased significantly in terms of both installed capacity and electricity generation volumes, which together with generation from HEPS and HPSPS allowed reaching an indicator of 15 % in the overall energy balance. This demonstrates the possibilities of intensive RES development in the conditions of Ukraine and achieving the goals of low-carbon development and diversification of the fossil energy sources.

Moreover, a significant contribution to the national energy security is made by TPS and CHPP, which, in accordance with the strategies of low-carbon development and energy transition, are planned for gradual closure.

It should be noted that the total electricity production in Germany as of 2021 amounted to 577.4 TWh, which exceeds the similar indicator for Ukraine by almost 4 times and indicates intensive functioning of the industry and constant development of the national economy, considering that the energy efficiency of production processes and electricity consumption is up to 9 times higher than in our country.

Fig. 8 shows structures of electricity consumption by industry sectors and municipalities. The German structure is significantly different from the current Ukrainian model: in Germany, a share of industry prevails while consumption by the population is about 20–25 % of the total energy balance.

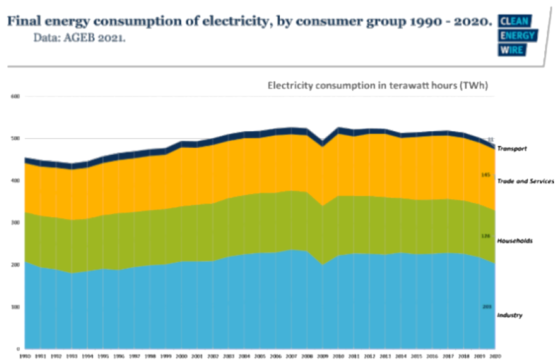
In Ukraine, the main consumers of electricity by category are as follows: industry – 52 bln kWh (43 %), population – 39 bln kWh (30 %), domestic households – 15 bln kWh (12.5 %), agriculture – 3.7 bln kWh (3 %), transport – 6.1 bln kWh, other nonindustrial consumers – 6.4 bln kWh, and construction – 1 bln kWh (Fig. 8).

Current decline in the industrial production and, accordingly, electricity consumption, caused by the Russian Federation hostilities in 2022 and destruction of the metallurgical giants "Azovstal" and Ilyich Iron and Steel Works in Mariupol is estimated at 30–40 %. Therefore, a share of electricity consumption by the population in relative units will grow significantly. Other critical infrastructure facilities were also destroyed or damaged – Kryvyi Rih CHPP, Chernihiv CHPP, coal supply routes to Zaporizhzhia TPS were damaged, which, along with Zaporizhzhia NPS and a significant number of RES facilities (solar and wind power plants) located within the temporarily occupied territory of Zaporizhzhia and Kherson regions.

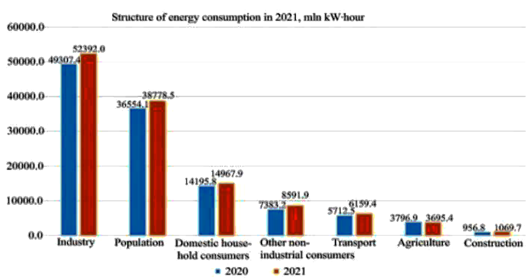
Integration of Ukrainian UES into the pan-European one and synchronization of the operating mode with ENTSO-E with complete separation from the energy systems of the Russian Federation and Belarus open up promising EU markets for our country. At the same time, Ukraine is becoming a market for suppliers from the EU, which will stimulate European integration changes in the energy sector, reconstruction of electrical networks to European standards. However, limited capacity of the intersystem networks of Ukraine and the EU, which is only 650 MW with Hungary, Slovakia, Romania, 235 MW with Poland, and 700 MW with Moldova, remains a problematic issue. This shows that Ukraine is physically unable to obtain significant diversification of electricity supply from the EU today.

The mentioned problems show the urgent need for decentralization of electricity production systems with the intensification of a rational transition to RESs by constant increase of their share and location according to the energy demand of consumers, which will contribute to improved operating stability of both power system and load nodes, increasing the energy efficiency of power supply processes. These principles can be implemented through the pragmatic implementation of a planned energy transition in the energy sector and economy of Ukraine using the best practices and experience of the EU countries and avoiding the main mistakes regarding the disordered and unbalanced development of RES systems, which are already felt in Ukraine, even with the existing share of renewable generation.

Sustainability of the energy system of Ukraine in the context of energy transition. The Ukrainian UES is still characterized



a



b

Fig. 8. Final energy consumption by the groups of consumers in Germany (a) [2] *and Ukraine (b)* [4]

by a negative tendency towards a considerable unevenness in a daily consumption curve. A configuration of daily electricity consumption in Ukraine as a whole is characterized by a load peak during the evening peak hours of the Ukrainian UES, a load drop during the night time zone hours, and almost uniform consumption of electric energy during the morning peak and semi-peak hours. At the same time, the unevenness of the daily load curve of Ukrainian UES ranges from 4.5–6.5 GW (Fig. 9).

Fig. 9 demonstrates the daily PSLC of the energy system of Ukraine per so-called regular days (the most loaded day in June and December) [6]. They show that the daily electricity consumption and production curves of the UES of Ukraine for different periods of the year are characterized by significant unevenness (mainly due to the increase in household and communal electricity consumption). The maximum electricity consumption in the summer is about 17 GW while the winter figure is about 23 GW of active power with the PSLC unevenness coefficient at the level of $\alpha_{irr} = 0.7–0.8$ (Table 2).

Fig. 10, *a* represents a mode of operation of energy sources; the mode provides a variable PSLC component of the energy system of Ukraine. As discussed above, such sources include primarily heat- and hydropower (power-generating units of TPS, HEPS, and HPSPS). Thus, maximum capacity of HEPS does not exceed 2.67 GW, which indicates a significant limitation in the capacity of this flexible component. Daily unevenness of the TPS capacity, used in the flexible mode being extremely inefficient for these stations, varies from 1.5–2.0 GW in summer to 3.0–4.0 GW in winter, which confirms the problem of low regulation ability of the energy system of Ukraine.

Use of renewable energy sources is shown in Fig. 10, *b*. It should be emphasized that currently the total level of power produced by these sources per day is already rather significant despite the share in the structure of generating capacities, being at the level of 1 %. It is extremely important to take into account its rapid recent increase, leading to so-called "green-coal" paradox.

Table 2

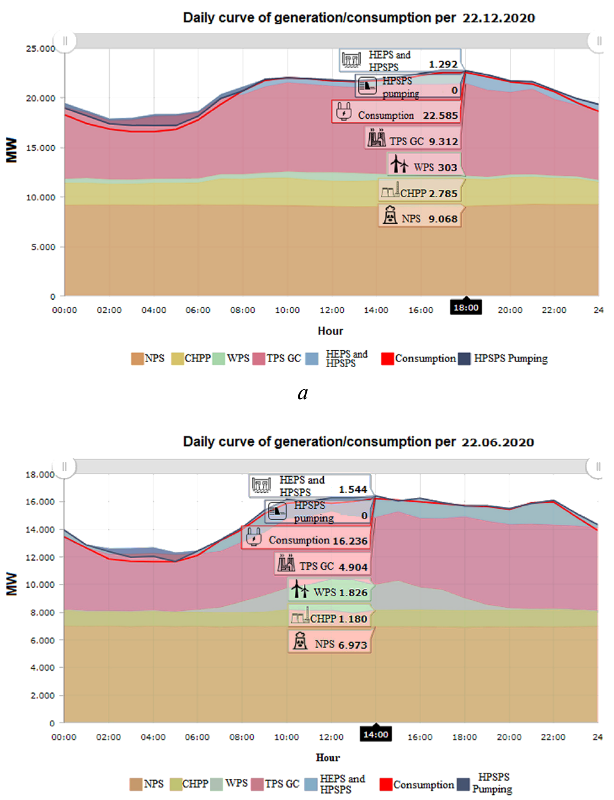
PSLC indices of the energy system of Ukraine per mode days

	Parameter							
	P^{Consum}_{min}, GW	P^{Consum}_{max}, GW	α_{irr}, r.u.	P^{TPS}_{min}, GW	P^{TPS}_{max}, GW	P^{HEPS}_{min}, GW	P^{HEPS}_{max}, GW	P^{RES}_{min}, GW
19.06.14	15.1	19.8	0.76	8.3	11.0	0.2	2.2	0.2
19.12.14	18.2	22.7	0.8	9.2	10.7	0.1	1.7	0.2
21.06.20	11.6	15.7	0.74	3.8	5.3	0.2	1.6	1.9
22.12.20	16.6	22.6	0.74	5.9	9.3	0.1	1.4	0.9
21.06.21	11.6	16.4	0.7	2.5	4	0.9	3	3.5
22.12.21	18	24	0.75	4	6.5	0.15	2	1.4

Regulation of the daily load curve of the Ukrainian IPS is complicated, especially in the context of disordered development of renewable energy sources. That is due to the fact that a significant part of basic power generation in Ukraine is covered by the operation of nuclear power plant units, which can operate safely only in a stable mode of electricity generation and, accordingly, do not participate actively in daily regulation of electricity consumption modes.

According to the joint research of SE NEC "Ukrenergo" and Tetra Tech ES, the maximum level of RES capacity in the energy system of Ukraine should not exceed 4,750 MW, of which wind generation is 1,750 MW, and solar generation is 3,000 MW in 2020. It was assumed that if this level is not exceeded, the Ukrainian energy system will be able to balance them at the expense of other traditional sources (HEPS, HPSPS, and TPS). Otherwise, the construction of highly flexible generation and batteries (energy storages) is necessary. In connection with the reduction of coal generation to compensate for renewable energy until 2025, there was a need to build 1,000 MW of gas power plants with quick start and 500 MW of energy storages.

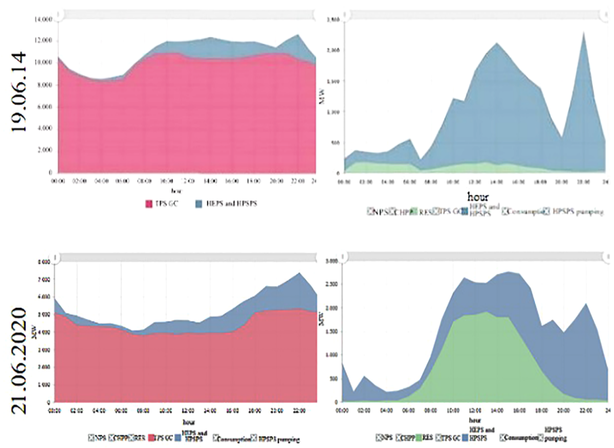
At the level of 2022, more than 6 GW of solar power stations (SPS) and about 1.7 GW of wind power stations (WPS) are already operating in the energy system of Ukraine [3]. In 2022–2023 (before the start of the Russian Federation hostilities), construction of another 2–3 GW of wind power stations in the south of Ukraine was expected to be completed as well



a

b

Fig. 9. Typical daily power-system load curves (PSLC) in Ukraine per 22.12.2020 (a) and 22.06.2020 (b) with the structure of peak coverage sources [6]



a *b*

Fig. 10. Mode of ES operations with the sources providing variable component of PSLC (a) and renewable energy sources (b) [7]

as an increase in the power of the SPS was to continue. In other words, the energy system of Ukraine is in an unstable mode of operation, which causes the forced withdrawal of NPS capacities into reserve during the periods of significant solar activity (March-October), periodic limitation of the generation of RES facilities due to a threat to stable UES operation [8].

Within the recent 10 years in Ukraine, after the provision of state support in the form of a "green tariff", RES generation has developed quite rapidly (Table 3, Fig. 11). In 2019, the amount of electric energy generated by RES in the overall structure of electric energy production reached 3.6 %, or 5.5 bln kWh (e.g. the entire export of electric energy to the countries of Eastern Europe from the Ukrainian UES in 2019 was equal to 5.8 bln kWh), in 2021 this indicator exceeded 5 %.

The problem of imperfect forecasting of electricity production and disordered growth of the RES share in the energy balance, their location according to the economic interests of investors, not according to the technical needs of a specific energy node of Ukrainian energy system, leads to the corresponding consequences and the "green-coal" paradox: if you do not limit RES without introducing new flexible facilities, you will have to reduce basic load of NPSs and increase it for GC TPS.

Fig. 12 shows the data on the error in forecasting the electricity production from RES, being about 30 % (450 MW as of 2017), which according to the indicators of 2022 may amount to about 3 GW of capacity. That will have to be covered promptly by flexible generation, being still not available now in Ukraine, while regulation and balancing continues to be carried out by pulverized coal power units of TPS GC, which has the opposite effect on the issue of greening of electricity production processes.

Fig. 13 shows the projected scenarios of the Ukrainian energy system by limiting nuclear or coal generation at RES capacity exceeding 3 GW. It can be argued that already in 2020, these scenarios became relevant, since the installed RES capacity was about 7 GW, being currently twice higher than the figures predicted for 2025. It can be seen from the figure that the possibility of using NPS capacity without its limitation as well as reducing coal generation, is available only if there is a fast-acting reserve of 2,000 MW based on gas turbine installations in combination with 1,000 MW of storage capacity of the corresponding energy storage units. However, flexible generation, which is modelled for use, is completely unavailable today. In addition, it should be noted that the transition to flexible energy sources using natural gas as fuel does not solve the problem of import substitution and diversification of the dependence on energy resources.

Currently, NEC "Ukrenergo" is considering two main options to solve the problems of energy system balancing by means of energy storage construction. The first one involves location of 200 MW of energy storage in one place, the second one mean location in several places with the division into 4–5 parts. The cost of this project is currently estimated at EUR 154 mln. An active dialogue with foreign partners concerning this issue is already underway.

The proposed ESS volumes are clearly insufficient today. To maintain the balance of energy systems and create a flexible power reserve, the most effective storage systems capable of smoothing out the daily and peak load changes are considered to be hydroelectric pumped storage power station (HPSPS)

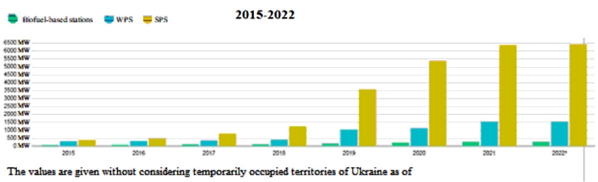


Fig. 11. Dynamics of commissioning of RES generation facilities [3]

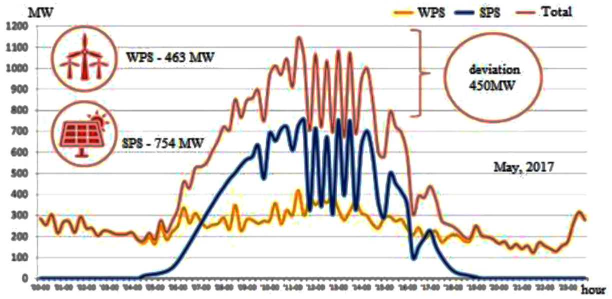
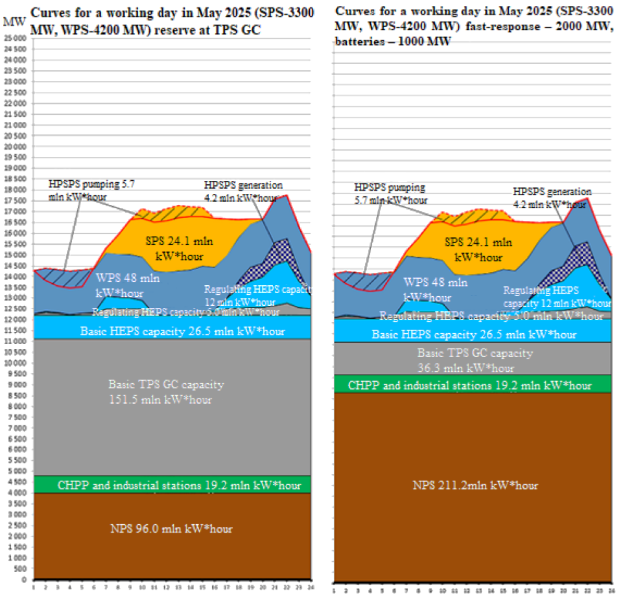


Fig. 12. Problem of forecasting the accuracy of electricity production from RES [3]



a *b*

Fig. 13. Predicted scenarios for limiting nuclear (a) or coal (b) generation at RES capacity > 3,000 MW (May 2025) [5]

Table 3

Dynamics of the commissioning of RES [5]

RES technology	Increment relative to the previous RES year, 2013–2020, MW							
	years							
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019***	**2020****
WPS	108.9	137	–81.1	–123.6	20.4	60.6	704.3	900
SPS	245.6	18.6	–222.9	98.9	300.4	466.4	2,666.92	2,100
BioEPS	0	35.4	17	10.2	34.3	1.8	37.8	20

[9]. One should also implement alternative solutions and methods for balancing the operating modes of local micro- and macrogrid systems, e.g. with the help of electric cars etc.

Since the power system load curve is the sum of consumer load curves, it can be balanced only with the help of regulator consumers who are able to limit or transfer some part of their electrical load from one hour of the day to another [10]. Therefore, various economic, organizational, and technical measures should be applied to stimulate, first of all, consumers, to level the load curve and demand for energy.

A problem of ensuring the flexible part of the power system PSLC during the day can be solved by increasing the flexible capacities for the electric energy production not at the expense of pulverized coal blocks of thermal power plants but by introducing new highly efficient technologies for the use of renewable energy sources (wind, solar, and hydropower) or innovative solutions for the use of potential consumers-regulators, to which it is expedient to include, e.g. rapidly growing electric mobility. The use of electric vehicles as such consumers-regulators of electric power in electric networks is a new challenge for both the developed countries of Europe and Ukraine, especially considering the erosion of Ukrainian energy security since 2014. The generating sources available in the power system are actually at the stage of exhausting their physical capabilities to ensure daily regulation and rational modes of power plant operations. For this reason, complete or partial modernization of plants is necessary in the near future along with the introduction of new highly flexible facilities. The introduction of steam-gas or gas-turbine plants for this purpose is very limited due to small amount of domestic gas and high price of imported gas. Use of electricity storage systems, e.g. electric vehicles with charging and discharging stations for load regulation, development of hydropower (HPSPS and micro-HEPS), introduction of demand management technologies will mitigate significantly the negative consequences of the problem concerning unevenness of the power system PSLC in Ukraine due to the exclusion of the corresponding TPS capacity from the operation in a flexible mode with a simultaneous increase in the basic NPS load.

In addition, the listed technologies will contribute to overcoming the "green-coal" paradox caused by the rapid development of RES, i. e. solar energy, whose share is about 80 % of the installed capacity in the overall RES structure and introduce significant unevenness even in the system of electric power generation (Fig. 10), comparing the years of 2014 (the beginning of RES development) and 2021 (passing the first peak of RES development). According to the data given in Table 2, regarding the standard daily generation-consumption curves, it is possible to trace the RES generation increase during the last 5–7 years by 7 times in the winter period and, accordingly, by 17 times in the summer period.

According to the 2019 Report on the Assessment of Compliance (Sufficiency) of Generating Capacities in Ukraine (NEC "Ukrenergo"), the unified electric power system of Ukraine was created to work under fundamentally different conditions than those in which it has to function today [5]. Modern conditions dictate new requirements, under which it is impossible to ensure the reliable and safe operation of the Ukrainian energy system in its current state. The most significant factor in the transformation of UES operating conditions in Ukraine today is rapid introduction of power plants with non-guaranteed power (ENP) based on renewable energy sources (RES), which are not accompanied by the parallel introduction of regulating capacities with the appropriate characteristics and volumes. The development of highly flexible generation sources with the capacity of 4 GW, including the ones on the basis of electricity storage systems (ESS) with a volume of at least 2 GW, is necessary to ensure opportunities to provide the Ukrainian UES with the necessary regulatory reserves to meet compliance requirements in the perspective of 2030 [5].

Without the implementation of appropriate measures to support the required level of basic and semi-peak generation in the UES of Ukraine, a deficit of generating capacities from 2.5 GW in 2025 to 9 GW in 2030 is possible, i. e. already from 2025, the energy system will not meet the requirements of sufficient generating capacities. This requires urgent improvement of the legislative and regulatory framework for regulating activities in the electric power sector, i.e.: ensuring the investment attractiveness of the development of support for traditional generation and introduction of the demand management tools [5].

As a result of full-scale invasion and aggression of the Russian Federation against Ukraine, there was an accelerated complete separation of our energy system from the unified energy system of the CIS countries and integration into the European electricity transmission system ENTSO-E. As a result, there is an urgent need to diversify energy resources and ensure the stability of Ukrainian energy system, which requires significant transformation in the system of electricity generation, transition to low-carbon or generally climate-neutral technologies for the production of electricity. This is expected to cause the second stage of peak development of the RES sector; however, with the need to shift the emphasis somewhat towards the construction of systems with the ability to balance and store electric energy (ESS), transition from the alternative sources of non-guaranteed power (solar, wind energy) to the systems with guaranteed output of electric energy according to the defined power generation pattern (PGP). Such systems will be in demand both at the macro level and in microgrid systems of decentralized generation in order to maximize consumer satisfaction in places of energy demand. In addition to balancing the generation and consumption modes, the RES development is also related to promising plans for the production of "green" hydrogen, using appropriate technologies, including for the purpose of "absorption" and effective use of RES generation surpluses, rational integration of electric vehicles and charging infrastructure into the electrical networks of municipalities, whose principles are demonstrated below.

Methods of using electric vehicles in microgrid systems. An increase in the number of electric vehicles makes them an important component of the electricity supply system both at the regional level and at the level of the entire country. The development of electrical networks with electric vehicles, the development and use of Smart Grid technologies for them is carried out taking into account additional requirements and restrictions regarding the charging modes of traction batteries of cars in order to ensure their effective integration into the hybrid power supply system [11–13].

Today, there is a technical possibility of integrating electric vehicles into the electric network when using them to regulate the power system load [11]. However, in terms of Ukraine, there is no legal mechanism as well as scientific, technical, and economic substantiation for the implementation of this technology.

A sufficient number of electric vehicles operating in parallel in the load regulation mode is similar in their operation mode to a network with hydroaccumulating power plants, which can be used for the purpose of balancing both power consumption modes and "absorption" of excess unregulated generation of RES [14].

To assess the expected technical impact of electric vehicles as consumers-regulators in the electrical networks of settlements, the real operating modes of the consumers of the utility sector and basic electrical equipment were analyzed, which made it possible to assess adequately the predicted advantages and disadvantages of implementing V2G and G2V technology, taking into account the expected energy as well as economic and ecological efficiency of their introduction in market conditions [15].

Levelling of PSLC of the local electric network consumers due to the use of electric vehicles is fundamentally similar to the system-wide one. However, in each individual case, both structure and power of the flexible potential source, its impact on the existing power supply system should be determined [16].

It should be noted that the total PSLC of the energy system of Ukraine (and other countries) is formed by all electric energy consumers, among which industrial enterprises and public and household objects (population, service sector) should be singled out. According to various estimates, the electricity consumption of public and domestic consumers in percentage terms is 30–40 % of the total system consumption. It means that such consumers as the public have a significant influence on the PSLC indicators of the power system, which causes interest in the assessment of their regulatory ability [11], especially if there is an electric vehicle and the potential of its interaction with the network using V2G/G2V technologies.

Use of electric vehicle batteries as the sources of electrical energy to cover power system load peaks can bring additional economic effect to the owner [11, 17]. Their amount depends on the legal framework, conditions and requirements of the regulations in a specific country. Currently, there is no legislative framework for the possibility of involving electric mobility in load regulation in Ukraine, and its elaboration should be based on conducting appropriate research in the specific conditions of V2G technology implementation.

Currently, Ukraine is a regional leader in the number of electric cars. Dynamics of the development of electric mobility in Ukraine is one of the highest in Europe. According to the data represented in [18, 19], the expected increase in the number of electric cars by 2024 will be about 250,000 cars (Fig. 14), which requires preliminary substantiations to ensure the appropriate charging infrastructure and readiness of electric networks to integrate powerful consumers in terms of distribution networks of the populated areas of Ukraine. Today, a share of electric cars in the total fleet of vehicles is about 1 %, and with forecast dynamics, this indicator will be at the level of 5 %, being not enough to solve the global issue of using the potential to ensure the power system stability. Speeding up the pace is possible under the condition of a transparent procedure for the material motivation of car owners to buy and use electric cars according to V2G/G2V technologies to take into account promising technologies not ex post but to ensure their implementation and development of technologies along with EU countries. In 2022, the demand for electric vehicles in Ukraine has increased significantly due to high cost of traditional fuels (gasoline, diesel) caused by the war. In some EU countries it has also grown due to the legislative policy regarding the complete ban of vehicles with internal combustion engines (ICE) in the near future. The Verkhovna Rada of Ukraine and the Ministry of Infrastructure of Ukraine are also creating prerequisites for the increase of electric vehicles by developing draft laws on tax incentives for production localization and banning the import of vehicles with ICE from 2030. In 2021, the Law of Ukraine "On amendments to the Tax Code of Ukraine and some legislative acts of Ukraine on stimulating the development of the electric transport industry in Ukraine" was adopted. The relevant initiatives will also have a positive effect on the development of electric mobility of our own production, which will further actualize the research tasks in this sphere.

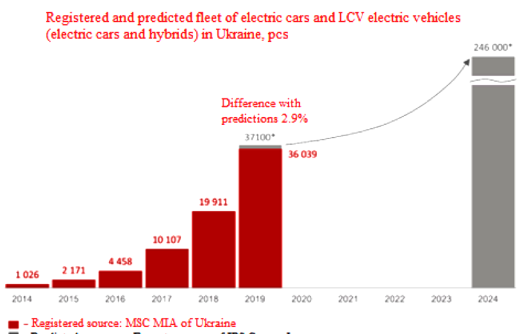


Fig. 14. Registered and predicted fleet of electric cars and hybrids in Ukraine until 2024 [19]

This will stimulate acceleration of the forecasted indicators and makes the issue of rational integration of the relevant innovative infrastructure extremely relevant both from the scientific and practical viewpoints.

Levelling of the electric load curves by filling night dips with shifting loads to day and night hours can be carried out using state regulation measures, intra-industry incentives, and on the basis of power consumption management directly at the consumer, e.g. at the expense of regulatory consumers: such consumers, in the structure of which there is electrotechnological equipment that can operate in the mode of adjusting the load curve according to the UES needs.

A consumer-regulator can and should provide relevant services on a paid contractual basis. Abroad, this area of electricity consumption regulation was called "demand side management", which combines technical (consumer-regulator) and economic (demand, management) components. In a number of countries (Australia, the United Kingdom, the United States, etc.), certain automated power demand management projects have been developed and are being implemented in order to reduce the UES peak loads.

Regulation of power consumption modes can make electric vehicles rather efficient consumers-regulators [11]. Battery charging at night is capable of filling the night-time dips in electrical load and preventing an increase in its peak values during the day.

Levelling of the PSLC of electric network consumers due to their use of electric vehicles is fundamentally similar to the general system (HPSPS). Nevertheless, in each individual case, both structure and power of the flexible potential source should be determined [20].

The most accurate way to determine the flexible source power is to use real data on electricity consumption, which will allow developing a pattern for the use of electric vehicles in a specific case of a typical load mode of a substation, taking into account typical consumers of the area of the city under consideration. In terms of widespread introduction of electric vehicles and sustainable use of V2G technology, this alternative active load compensator should be taken into account when designing an electrical network.

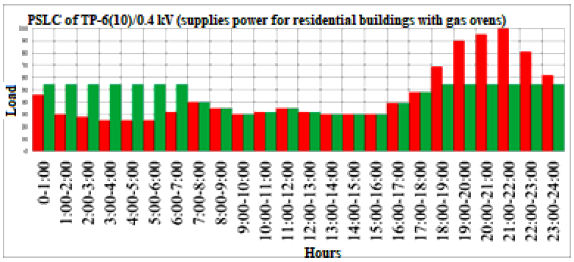
The most potential places for the location of charge-discharge stations in cities are parking lots of residential areas or department stores (malls), etc. [21].

The use of V2G technology can be an effective measure for the cases of increased loads in electric networks as it can be compensated by distributed generation from the decentralized sources (batteries of electric cars) [11, 22].

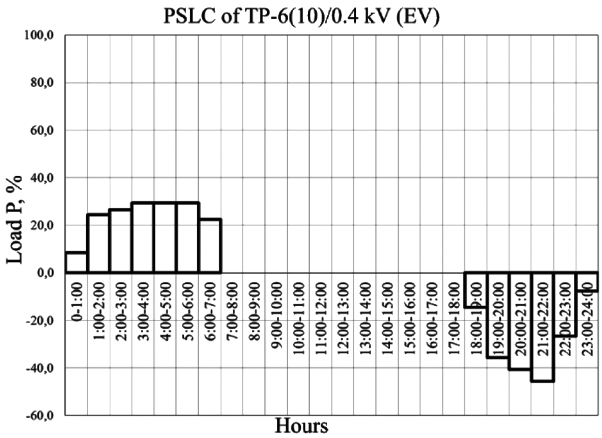
In view of the fact that residential transformer substations (TS) TP-6 (10)/0.4 kV are located in the centres of electrical loads, the charge-discharge station should be located as close as possible to the transformer substation in order to meet the optimal technical and economic indicators of operation, which will contribute to the minimization of electrical losses energy in power cables, satisfactory indicators of the quality of electric energy according to the voltage deviation criterion, and minimal capital investment in the object's external power supply system. Use of the station and its power at the stage of development of alternative active compensators is limited to the flexible part of the TS PSLC, taking into account the uniform charging of electric vehicle batteries during the night dip periods.

The results of modelling on levelling PSLC of typical consumers are presented in Fig. 15.

Modelling the modes of using electric vehicles applying V2G/G2V smart technologies for a typical residential area shows the possibility of reducing the estimated maximum



a



b

Fig. 15. PSLC of TP-6(10)/0.4 kV for a residential area of the city with buildings up to 10 floors:

a – comparative PSLC (red – output PSLC; green – when using electric cars); b – modelling the mode of using a group of electric vehicles applying V2G/G2V technology

power grid load by 45 %, or 1.8 times, which creates prerequisites for the effective selection of network equipment and its further use in accordance with the nominal parameters. Use of the proposed principles makes it possible to reduce additionally the electrical energy loss in electrical networks by 7–10 % compared to the existing ones; it also helps increase the carrying capacity of electrical networks and avoid their overloading and failure during disordered charging processes.

On the contrary, irregular modes of charging batteries of electric vehicles can cause an increase in electricity consumption and growing unevenness of the total electric load curve. In turn, this requires construction of additional generating capacities of power stations with an inefficient operating mode. At the same time, rational use of electric vehicles as the consumers-regulators with regulated modes of electricity consumption allows reducing the unevenness of electric load curves (Table 4), improving a structure of generating capacities with long-term optimization of development, and increasing their operational indicators as well as achieving a pronounced environmental effect.

Aspects of the energy transition for the EU and Ukraine. In December 2019, the European Commission presented the European Green Deal, an ambitious policy package aimed at making the European Union's economy environmentally sustainable. The goal is to achieve climate neutrality by 2050 and turn the transition into an economic and industrial opportunity for Europe [23].

Table 4

Comparison of PSLC indicators of the district without/taking into account the use of electric vehicles

	α_{irr}	T_{max}, hour	P_{avg}, r.u.	P_{rms}, r.u.	K_{gf}	K_{max}
Without considering EV	0.25	3975.8	0.454	0.510	0.454	2.20
Considering EV	0.55	7303	0.45	0.47	0.83	1.2

In 2019, the EU imported over €320 bln worth of energy, and over 60 % of EU imports from Russia were energy. A massive reduction in this flow would restructure the EU's relationship with key energy suppliers. Such countries as Russia, Algeria, and Norway will eventually lose their main export market. Europe accounts for about 20 % of the world crude oil imports. A greener Europe will depend more on imports of products and raw materials that serve as a source of clean energy and environmentally friendly technologies. The Green Deal will have an impact on Europe's international competitiveness [23].

However, most importantly, the Green Deal is a foreign policy, because climate change is a global problem. Decarbonisation that would only focus on Europe would not help mitigate global warming as Europe accounts for less than 10 percent of global greenhouse gas emissions. The worst part is in the fact that if the Green Deal simply shifts Europe's greenhouse gas emissions to its trading partners, it will have no impact on climate change. Although for this reason alone, the EU is likely to push very hard for ambitious multilateral agreements to curb global warming and subordinate some of its other goals to this top priority. The European Commission has already acknowledged that it will need to either export its standards or create a border regulation mechanism to maintain European competitiveness and prevent carbon leakage.

To make Europe environmentally neutral by 2050, the European Green Deal must pursue one main goal: to change the way energy is produced and consumed in the EU. Almost three quarters of the EU's energy system relies on fossil fuels. Oil dominates in the EU energy complex (with a share of 34.8 %), followed by natural gas (23.8 %) and coal (13.6 %). The share of renewable energy sources is growing but their role remains limited (13.9 %) as well as nuclear sources (12.6 %).

This situation will change completely by 2050 if the European Green Deal is successful. Nevertheless, the changes will be gradual. Fossil fuels will still provide around half of the EU's energy in 2030, according to European Commission forecasts but fossil fuels differ in intensity of pollution. The use of coal – the most polluting element in the energy mix – must be reduced significantly by 2030, while oil and, especially, natural gas can be phased out later. Most of the changes to oil and gas will occur between 2030 and 2050. During this period, oil is expected to be almost completely excluded, while natural gas will provide only a tenth of the EU's energy in 2050 (Fig. 16) [23].

According to the data by Bruegel/ECFR (Eurostat 2020), dependence of EU countries on the natural gas importers is illustrated as follows (Fig. 17 [23]).

Germany. The energy transition of the Federal Republic of Germany in the perspective of 2030–2050 (Fig. 11) also envisaged further consumption of gas as a more environmentally friendly energy resource compared to coal and oil [23]. Current intermediate stage of the implementation of the low-carbon development policy has turned out to put the Federal Republic of Germany in even greater dependence on the Russian Federation. That is used by the respective importing country in solving geopolitical disputes and problems to its advantage by creating an energy collapse.

Today, the energy transition concept refers to the course taken by the German government to abandon gradually both hydrocarbon and nuclear energy along with its almost complete transition to renewable energy sources. Germany has become one of the few countries that has committed to transition to a carbon-neutral economy by 2050 at the legislative level. (Law on expanding the use of renewable energy sources dated July 21, 2014).

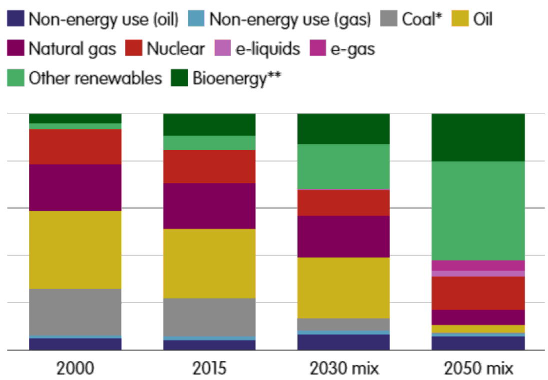


Fig. 16. EU energy mix evolution (55 percent lower emissions in 2030 compared to 1990 and climate neutrality in 2050) [23]

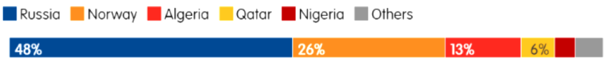


Fig. 17. EU imports of natural gas by main trading partners, 2018 [23]

In early 2020, the German government passed a resolution to close all nuclear power plants by the end of 2022 and abandon completely coal-fired power plants by the end of 2038.

The abandonment of these traditional energy sources results in the need for an equivalent replacement, which can only be provided by the development of renewable energy sources (wind, solar, hydropower, generation from biomass and biogas, geothermal energy) and a forced increase in the use of natural gas. Energy generation using clean sources, including gasless ones, should make up 80 % of the total volume by 2030 and 100 % by 2050.

According to experts' assessments, the energy turn provides the following significant advantages for the Federal Republic of Germany:

- reducing dependence on the import of energy carriers;
- stimulating the development of technological innovations and "green energy";
- reducing the risks of using atomic energy;
- fighting against monopolies in the energy sector;
- fighting against climate changes.

In terms of Germany, the energy transition concept involves comprehensive development of many components of the new energy system, the main of which are:

- new generating capacities;
- new electrical networks;
- an increasing number of energy storage devices;
- large-scale implementation of the intelligent power supply systems;
- integration of the German energy system into the pan-European system.

The energy transition concept is the most acceptable and scientifically based one for the implementation of the strategy of "effective transformation" of the energy industry of Ukraine, adopted at the legislative level by the National Security Strategy of Ukraine, approved by the Decree of the President of Ukraine dated September 14, 2020 No. 392. The main positions are determined by the following steps [24]:

- introduction of a full-fledged highly competitive market environment in the energy industry, formation of a favourable investment environment;
- maintaining the energy sector sustainability and ensuring energy security of Ukraine;
- consistency and transparency of energy policy and decision-making by state bodies;
- use of new technologies for energy production, transportation, storage, and consumption, use of renewable and local energy sources, digitization of energy use, which allows bringing energy production sources closer to the consumer and balancing the operating modes of energy systems;
- synchronization of the operating modes of the United Energy System of Ukraine and the energy systems of EU countries actually means disconnection from the energy system of the Russian Federation;
- implementation of energy saving and energy efficiency programs in households, housing and communal and budgetary spheres.

Analysis of the trends in the world energy development shows that the key factors are the reliability of energy supply, energy security, energy efficiency and environmental harmonization. At the same time, increasing the level of energy efficiency is a strategic direction for reducing the energy intensity of the economy [25].

One of the main driving forces for the development of the energy industry in the period of 2020–2040 will be prevention of global climate changes due to systematic reduction of greenhouse gas emissions. The key role in the successful solution of urgent energy problems, including meeting the growing demand, increasing energy efficiency and reliability of energy supply with environmental improvements, will be determined by innovative energy technologies. They are aimed at the development of "smart" power grids (Smart Grid), technologies of "smart" accounting and calculation systems (Smart Metering), demand management (Demand Response, DR), devices for storing energy and charging electric vehicles, etc. [25].

Distributed generation is the most important sector of global energy in the future. It is a system of energy production and transmission, which involves a large number of consumers, who at the same time are producers of electricity and heat for their own needs, and have the ability to transfer excess energy produced to the general network. Improvement of the technologies and increased attention to environmental issues according to the Paris Climate Agreement along with the exhaustion of energy resources (especially coal and oil) will change the structure of demand for primary energy resources and require a review of traditional approaches, principles and mechanisms of the energy system operation. It will also require development and implementation of new modern technologies based on renewable energy sources, capable of ensuring sustainable development, improving consumer properties and efficiency of energy use [25].

Among the innovative projects of the transmission system operator SE NEC "Ukrenergo", which are related directly to aspects of the energy transition in Ukraine, it is appropriate to single out the following [26]:

- SCADA/EMS modernization of national and regional control centres;
- creation of a system for forecasting generation from RES;
- pilot projects of V2G technologies (joint operation of networks and electric vehicles), VPP (virtual power plant), a detailed study on the consumption structure and Demand Response (demand management).

Energy accumulators based on lithium-ion batteries (LIBs) reduce the impact of generation stochasticity on network reliability during the introduction of renewable energy sources. The energy accumulator reacts immediately to the changes in the consumer load, and, depending on the needs, accumulates or releases it under the conditions of dispatching the operation of generation facilities [9].

Stationary energy storage systems using lithium-ion batteries for Ukrainian residents are in most cases expensive and impractical for simple implementation as an autonomous power source. However, their effect can be more significant in terms of combined use in case of dual battery use, e. g. for V2G and G2V technologies of electric vehicles, which will improve significantly both the effect for an individual user and for the energy system as a whole, under the condition of rapid development of electric mobility, for which Ukraine is rather favourable.

Basing on the results of studies concerning the agreement of energy development forecasts with economic development forecasts, NEC “Ukrenergo” formed three representative scenarios for the development (strategy) of supply and demand for the energy system of Ukraine (Fig. 18) [5].

The first strategy is the pragmatic development scenario of (PDS): it means implementation of solutions for the economy and energy development, with an overview of the real resource, economic, and personnel potential for the economic development while meeting the requirements for the RES development according to the NES with the extension of trends in RES development for the perspective of 2050 year in accordance with the predicted certain trends. The PDS envisages preservation and development of the traditional Ukrainian economic sectors with gradual development of import-substituting solutions as well as innovative and new production of products, goods, and services.

The second strategy is the low-carbon development scenario (LDS): it involves achievement of the neutrality of the national economy in the context of GHG emissions at the level of 2050, i. e. at least 50 % of electric energy is produced using RES. The economic development involves gradual closing of energy-intensive industries that use organic fuel due to implementation of a strict environmental policy – growth of payments for GHG emissions and pollutants, which will make them uncompetitive.

The third strategy is the energy transition scenario (ETS): its main difference from LDS is refusal of the nuclear energy development.

A peculiarity of the LDS and ETS formation is that along with the scenario determination of the development of RES-based electricity production, a gradual reduction of the capacities of CHPP and TPS with their decommissioning at the level of 2030–2035 is meant.

According to the given economic and energy development strategies for Ukraine, two scenarios are foreseen – an optimistic one, corresponding to PDS and LDS, and a pessimistic one, corresponding to ETS. It would seem that the energy transition scenario should, on the contrary, be optimistic – decarbonization, environmentalization, energy independence from fossil resources; however, capital ownership in the re-equipment of energy systems, abandonment of traditional energy resources, including nuclear energy, will lead to economic and social imbalance, which will have a corresponding social resonance.

We will analyse in more detail the corresponding scenarios in the context of their impact on the electricity structure and its functioning.

Nuclear energy. The nuclear power industry of Ukraine has the potential to maintain its position in the electricity market of Ukraine by selling the cheapest electricity and extending the life of existing power units. The two main scenarios for the further development of nuclear energy (Table 5) assume the following [5]:

- the optimistic one (PDS, LDS) – development of atomic energy is envisaged while maintaining the capacity of nuclear power plants at a level that corresponds at least to their existing capacity;

- the pessimistic one – refusal of the development of nuclear generation in the future and closure of NPS power units after the excess resource exhaustion (ETS).

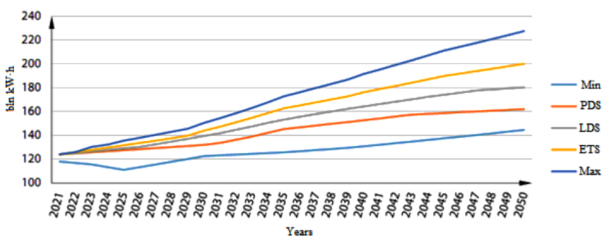


Fig. 18. Prospective demand for electric energy according to the development strategies [5]

Thermal energy. Development of electricity supply to the market by existing TPSs will be determined by the possibility of implementing the National Emission Reduction Plan (NERP) and the expediency of supporting the operation of power plants with low installed capacity utilization coefficients (ICUC) as well as state energy policy, since during the LDS and ETS implementation, no generation on organic fuel is expected [5].

The indicators of the optimistic and pessimistic scenarios of the thermal energy development are given in Table 6.

Hydropower. Today, hydropower plays a key role in the context of ensuring the operational security of the UES of Ukraine to compensate for the variable and difficult-to-predict fluctuations of generation from renewable sources. Therefore, its further development is extremely important, especially in view of high pace of introduction of energy generation from RES. When considering the development of hydropower, it is taken into account that today the sources of investment are not defined and there is significant opposition from public and environmental organizations to the development of hydropower in Ukraine [5].

In view of the above, two scenarios for the development of hydropower have been formed:

1) basic scenario (minimum development of hydropower);

2) optimistic scenario (maximum development of hydropower).

Table 5

Structure of generating capacities of NPS according to the scenarios, GW [5]

Scenarios	2021	2025	2030	2035	2040	2050
Pessimistic scenario, including:	13.8	13.8	13.8	10	6	2
available energy power units	13.8	13.8	13.8	10	6	2
Optimistic scenario, including:	13.8	13.8	13.8	>14.18	>14	>14
available energy power units	13.8	13.8	13.8	12	9	2
new facilities	0	0	0	>2.18	>5	>12

Table 6

Structure of TPS generating capacities according to scenarios, GW [5]

Scenarios	2021	2025	2030	2035	2040	2050
Pessimistic scenario, including:	18.4	8.8	2.5	0	0	0
available energy power units	–	–	–	–	–	–
Optimistic scenario, including:	18.4	18	16.1	16.1	16.1	16.1
available energy power units	18.4	13.17	4.57	2.1	2.1	2.1
reconstructed or new flexible facilities	0	2.83	9.53	12	12	12
highly flexible facilities with quick start	0	2	2	2	2	2

According to the optimistic scenario of the development of hydropower, the offer of electric energy produced by large HEPS and HPSPS is based on the Hydropower Development Programme approved by the CMU [27] with the adjusted terms for the introduction of HEPS and HPSPS capacities (taking into account the available plans and the terms of necessary development of networks based on the proposals, as noted by "Ukrhydroenergo" PJSC [28]) as well as the completion of Tashlytska HPSPS.

According to the basic scenario of hydropower development, it is assumed that only the existing projects of the near future will be implemented, i.e.:

1) reconstruction of the Dnipro cascade HEPS;

2) construction of Kakhovska HEPS-2;

3) increasing the capacity of Dniester HPSPS due to the commissioning of the *4th* hydrounit;

4) increasing the capacity of Tashlytska HPSPS due to the commissioning of the *3rd* hydrounit.

Table 7 shows the structure of generating capacities at HEPSs and HPSPSs according to these scenarios.

RES-based energy. In view of high interest of investors in the construction of new RES-based generating capacities, technical conditions have already been issued for the connection of new RES-based facilities at the level of about 11 GW [25]. Thus, it can be expected that under acceptable conditions of pricing of electric energy for this generation type, the potential of its development in Ukraine is very high.

The basic scenario is adopted in accordance with the requirements of the NES for electric energy production with the extension of the trends laid down in the NES until 2050.

The optimistic scenario is based on the assumption of further development of RES-based facilities at the current rate of growth.

Along with this, in the context of the declared goals of sustainable development and policy of energy transition [29] from the existing energy system to an energy system built on the latest principles and technologies for abandoning the use of fossil organic fuels, a share of RES-based generation at the level of 2050 should be no less than 50 % in the production of electrical energy when implementing scenarios that provide for the support of nuclear generation at the level of at least 14 GW, and a further transition to 70 % of the use of renewable energy sources to solve the tasks of supplying electricity to own consumers in the event of refusal of further nuclear energy development in the country.

However, it should be noted that even with significant WPS and SPS capacities in Ukraine, the latter do not play a significant role in ensuring maximum loads in the heating season, while even when using power transfer systems from PSLC zones, in which there is a surplus of electrical energy, to zones where there is its shortage. This is due to the fact that the compatible maximum loads occur in the evening hours in winter, when there is no generation from SPSs, and low temperatures in this period are characteristic of the areas with high atmospheric pressure, when the probability of the wind absence is high. Taking into account current trends in the development of RES-based generation and structure of the issued technical conditions for their connection, 3 scenarios of the development were formed, which correspond to different strategies of the country's electricity supply in the future. The structure of generating capacities of Res-based power plants, according to these scenarios, is shown in Figs. 19–21 [5].

With an increase in the demand for electric energy, all things being equal, the need to limit the capacity of power plants operating with the use of RES decreases, and solution to their balancing problems is simplified. At the same time, the situation is reversed when demand decreases.

In order to ensure fulfilment of the requirements of sufficiency along with the increasing demand for electric energy for the scenarios that correspond to NES and low-carbon development, the most expedient, from the viewpoint of transmission system operators (TSO), is the increase in NPS capacities. And for ETS, it is necessary to increase generation capacity of RES operating on biomass and gaseous fuel, and electrolysis systems for the production of "green" combustible gases – hydrogen, methane etc. to meet the requirement for zero GHG emissions at the level of 2050 [3].

The comparative analysis of supply and demand development scenarios shows that the implementation of LDS and ETS is not very realistic.

This is primarily due to the fact that the implementation of relevant strategies requires significant investments and state support. Thus, the EU has developed the European Investment Plan "Green Deal" [30], which is also called the "Sustainable Europe" investment plan, being the investment basis of the "New Green Deal". In order to achieve the goals set by the "European Green Deal", it is

Table 7

Structure of generating capacities at HEPSs and HPSPSs according to the scenarios, GW [5]

Scenarios	2021	2025	2030	2035	2040	2050
Optimistic scenario, including:						
HEPS	4.8	4.9	5.20	5.45	5.87	6.00
HPSPS	1.65	2.25	3.4	4.37	4.37	4.37
Basic scenario, including:						
HEPS	4.8	4.9	5.0	5.0	5.0	5.0
HPSPS	1.47	1.95	1.95	1.95	1.95	1.95

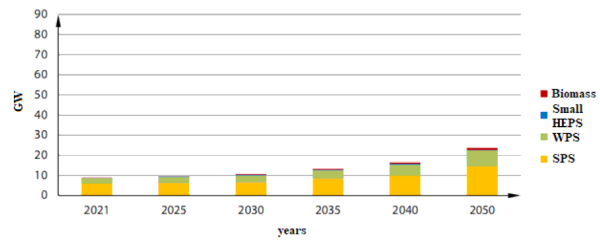


Fig. 19. Structure of RES-based facilities according to PDS [5]

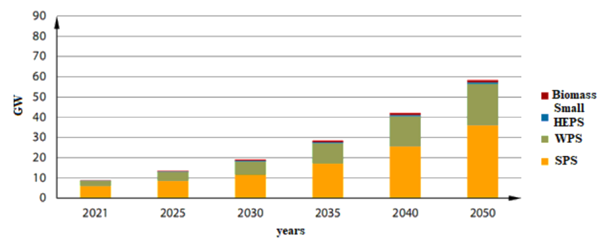


Fig. 20. Structure of RES-based facilities according to LDS [5]

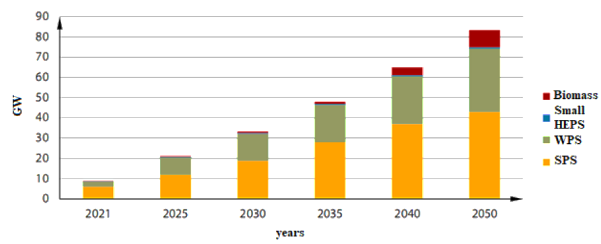


Fig. 21. Structure of RES-based facilities according to ETS [5]

planned to attract at least EUR 1 trln of investment over the next decade.

The concept of the "Green transition" of Ukraine [29] assumes that approximately 5 % of the national GDP per year is needed for its implementation. At the same time, the model calculations of the TSO for the formation of agreed forecasts of the economy and energy development for LDS and PDS show that their potential implementation is possible only under the following conditions:

1) no restrictions for the possibility to attract investments and credit resources for the national economic development;

2) significant interest of investors in the creation of high-tech industries in Ukraine, both for import substitution and for export of corresponding products;

3) possibility of exporting domestic products, goods, and services in the volumes necessary for the implementation of these scenarios, i.e. foreign currency receipts in the country must be sufficient to ensure a positive balance of payments;

4) almost complete localization of the industries necessary for increasing the capacities of RES-based power stations and technologies for balancing them and transferring/utilizing their power. While implementing LDS and ETS, it is necessary to introduce such systems with a total capacity of about 5 and 8 GW, respectively, as early as 2025, which, according to TSO, is unlikely from the viewpoint of necessary investments for the creation of corresponding industries and time for their implementation;

5) rapid increase in natural gas production in the country. However, a significant increase in its production in the country is possible no earlier than in 5–10 years, with significant investments in the development of gas production;

6) gradual reduction of production in energy-intensive sectors of the economy with significant GHG emissions.

According to TSO estimates, the fulfilment of all the listed conditions is unlikely [5]. This is due to the need to service and repay loans necessary for radical technological and structural restructuring of national economy and energy, the rise in prices for electric energy in terms of unavailable compensators in the form of domestic production.

The main arguments regarding the expediency of implementing the development scenarios and the proposal according to LDS and ETS are their high efficiency with a significant increase in payments for GHG emissions and a stable decrease in the necessary investments in construction, first of all, SPSs, leading to lower prices for the electric energy produced by them than on its production at traditional power plants, and on a significant reduction of the necessary investments in the implementation of demand management measures [5].

Conclusions.

1. The comprehensive analysis of current state and prospects for the development of the structure of electric power complexes of Ukraine and the Federal Republic of Germany helps formulate high-priority rational steps in achieving energy independence and energy security, taking into account environmental friendliness and low-carbon development of the energy sector and economy of our country, as a developing country, since there is an opportunity to adopt experience of leading countries in terms of diversification of energy resources, focusing on the obligations regarding climate neutrality and avoiding mistakes in making previously untested decisions.

2. The experience of the Federal Republic of Germany regarding the implementation of significant RES volumes, successful forecasting of generation and balancing, can and should be used undoubtedly in the development of this sector in Ukraine. That will allow solving the problem of power system stability due to disordered growth of the RES share in the energy balance of Ukraine. Further RES location purely by the economic interests of investors, and not in accordance with the technical needs of a specific energy node of the UES of Ukraine, is unacceptable both from the standpoint of stability of the operating modes of load nodes, and according to the principles of building decentralized power supply systems, overcoming a problem of the "green-coal" paradox.

3. If there is no significant increase in flexibility of the energy system of Ukraine and introduction of technologies for the use of excess electrical energy, further accelerated capacity of RES-based power stations will have negative consequences due to limited power of nuclear power plants to eliminate emerging power surpluses. To maintain static stability of the power system and create a flexible power reserve, there is an urgent need for the development of HEPSs and HPSPSs, an increase in ESS volume as well as alternative methods of balancing the operating modes of local micro- and macrogrid systems based, for example, on the use of electric vehicles as consumers-regulators and active electrical load compensators.

4. Rational integration of electric vehicles and charging infrastructure into the electric networks of municipalities using V2G/G2V technologies can be an effective measure in case of increasing loads in electric networks due to natural gas shortage and transition to electric heating. Modelling the modes of using electric vehicles with V2G/G2V smart technologies for a typical residential area shows the possibility of reducing the estimated maximum load of the power grid by 1.8 times, which creates prerequisites for reducing the emergency operation of existing networks. On the contrary, unordered modes of charging electric vehicle batteries can cause a growth in electricity consumption and increase the unevenness of total electrical load curves. This, in turn, requires construction of additional generating capacities of power stations with an inefficient mode of operation.

5. Germany's abandonment of nuclear energy by the end of 2022, increased share of alternative sources in the total electricity consumption, being 50.4 % as of 2020, and reduced harmful emissions into the atmosphere (as of 2020 – 40.8 %) are indisputable positive aspects of the energy transition strategy implemented by the Federal Republic of Germany. However, the energy transition of the Federal Republic of Germany in the perspective of 2030–2050 provided for the replacement of traditional energy resources with natural gas as a more environmentally friendly fuel compared to coal and oil, which has currently placed the Federal Republic of Germany in significant dependence on the Russian Federation, which this importing country uses in solving geopolitical disputes and problems by creating an energy collapse. This fact must be taken into account and avoided when implementing the energy transition for all countries.

6. Currently, the energy transition for the conditions of Ukraine corresponds to the pessimistic scenario, and implementation of its principles in full with the achievement of carbon neutrality will cause a social and economic resonance in society, since the achievement of the relevant goals is impossible without a radical approach to the issues of electricity production and transformation of electricity generating systems towards large-scale use of alternative and renewable energy sources with the use of technologies for their integration as decentralized systems. To ensure fulfilment of the requirements for sufficient sources in case of growing demand for electric energy for scenarios of pragmatic and low-carbon development, NEC "Ukrenergo" considers it expedient to increase the capacities of nuclear power plants; in terms of energy transition, it is necessary to increase the capacities of RES generation on biomass and gaseous fuels as well as electrolysis systems to produce "green" hydrogen.

7. Rapid growth of RES capacities as well as need to implement technologies for increasing flexibility of Ukrainian UES and ensure sufficient capacity of traditional generation for reliable PSLC coverage will lead in the long run to increased electricity prices. At the same time, for economic reasons, implementation of LDS and ETS is unrealistic, since the existing economic potential of Ukraine is not

enough to achieve ambitious goals of economy decarbonization, following the example of the most developed countries. The implementation of comprehensive support for the post-war recovery of Ukraine, including the energy field, will ensure a balanced energy transition in accordance with the described scenario.

8. Integration of Ukrainian UES into the pan-European one and synchronization of the operating mode with ENTSO-E with complete separation from the energy systems of the Russian Federation and Belarus open promising EU markets to our country. At the same time, Ukraine is becoming a market for suppliers from the EU, which will stimulate European integration changes in the energy sector as well as reconstruction of electrical networks according to European standards and requirements. The represented analytics can be used to ensure sustainable development of Ukrainian energy industry, to form an outlook on problems, prospects, and aspects of optimistic and pessimistic scenarios of the economy and energy industry development.

References.

1. *World Energy & Climate Statistics – Yearbook 2022* (2022). Retrieved from https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.

2. *Germany's energy consumption and power mix in charts* (2022). Retrieved from https://www.cleanenergywire.org.

3. *Installed power capacity of IPS of Ukraine* (2022). Retrieved from https://ua.energy.

4. CG "Scientific and Technical Union of Power Engineers and Electrical Engineers of Ukraine" edition of the STUPE (2022). *"Enerhoinform-Informenerho" No. 605. On the main indicators of the operation of the FEC of Ukraine FOR JANUARY-DECEMBER 2021 No. 605.* Retrieved from https://www.ntseu.net.ua.

5. *Report on the assessment of compliance (sufficiency) of generating capacities in Ukraine – 2019* (2019). Retrieved from https://ua.energy/?page_id=13075.

6. *Dispatch information of "NEC "Ukrenergo" PJSC* (2022). Retrieved from https://ua.energy/diyalnist/dyspetcherska-informatsiya/.

7. *Schedules of production and consumption of electricity in the energy system of Ukraine* (n.d.). Retrieved from https://ua.energy/diyalnist/dyspetcherska-informatsiya/dobovyj-grafik-vyrobnytstva-spozhyvannya-e-e/.

8. *Clarifications on the limitation of generation of SPP and WPP from January 1, 2020* (2020). Retrieved from https://ua.energy/zagalni-novyny/roz-yasnennya-shhodo-obmezhennya-generatsiyi-ves-ta-ses-7-sichnya-2020-roku/.

9. Golovko, I., & Astakhova, T. (n.d.). *Briefing of the Centre for Environmental Initiatives "Ekodiya". Why should Ukraine develop decentralized energy even today?* Retrieved from https://setech.in.ua/ru/potchemu-v-ukraine-sleduet-razvivaty-detsentralizovannuyu-nergetiku-uzhe-segodnya/.

10. Kalinchyk, V.P., & Skachok, O.V. (n.d.). *Evaluation and analysis of methods for levelling load curves of production systems.* Retrieved from http://ela.kpi.ua/jspui/bitstream/123456789/11308/1/7_Kalinchyk_V_Assessment.

11. *Levelling the electrical load curves of the power system* (n.d.). Retrieved from http://www.energetika.by/arch/~page__m21=10~news.

12. Khatskevych, Yu.V., Lutsenko, I.M., & Rukhlov, A.V. (2017). Perspectives of load management in energy system with the help of electric vehicles. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 86-93.

13. Pivnyak, G., Azukovskiy, O., Papaika, Yu., Careres Cabana, E., Olczak, P., & Dyczko, A. (2021). Assessment of power supply energy efficiency by voltage quality criterion. *Rynek Energii*, (4), 75-84.

14. Papaika, Yu.A., Lysenko, O.H., Koshelenko, Ye.V., & Olishevskyi, I.H. (2021). Mathematical modeling of power supply reliability at low voltage quality. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 97-103. https://doi.org/10.33271/nvngu/2021-2/097.

15. Robinson, A.P., Blythe, P.T., Bell, M.C., Hübner, Y., & Hill, G.A. (2013). Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips. *Energy Policy, 61*, 337-348.

16. Bondarchuk, A.S. (2015). Predicted energy, economic, and ecological efficiency of the implementation of network solar power stations under market conditions. *Electrotechnical and computer systems, 20*(96), 51-55.

17. Godina, R., Rodrigues, E., Matias, J., & Catalão, J. (2015). Effect of Loads and Other Key Factors on Oil-Transformer Ageing: Sustainability Benefits and Challenges. *Energies, 8,* 12147-12186.

18. Lutsenko, I.M., & Tsygan, P.S. (2017). Technical and economic aspects of the use of electric vehicles in the electric networks of Ukraine. *Visnyk of KrNU, 6/2017*, 21-30.

19. Vinnichuk, Yu. (2018). *How did VAT abolishment influence the electric vehicle import in Ukraine*. Retrieved from https://biz.censor.net.ua/resonance/3099495/yak_skasuvannya_pdv_vplinulo_na_mport_elektromoblv_v_ukranu.

20. *Registered and predicted fleet of trucks and LCV electric vehicles (electric vehicles and hybrids) in Ukraine* (2019). Retrieved from http://irsgroup.com.ua/.

21. Lutsenko, I.M., Fedoryachenko, S.O., Maliienko, A.V., Rukhlova, N.Yu., Koshelenko, Ye.V., & Tsygan, P.S. (2021). Assessing the potential of increase in energy efficiency in SmartGrid-systems with prosumers on the basis of electric vehicles. *Visnyk of KhNADU*, (95), 241-251.

22. Balakhontsev, A., Beshta, O., Boroday, V., Khudolii, S., & Pirienko, S. (2021). A Review of Topologies of Quick Charging Stations for Electric Vehicles. *International Conference on Modern Electrical and Energy Systems (MEES), 1-4.* Retrieved from https://ieeexplore.ieee.org/abstract/.

23. Pivnyak, G.G., & Beshta, O.O. (2020) A complex source of electrical energy for three-phase current based on a stand-alone voltage inverter. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (1), 89-93. https://doi.org/10.33271/nvngu/2020-1/089.

24. *The geopolitics of the European Green Deal* (2021). Retrieved from https://ecfr.eu/publication/the-geopolitics-of-the-european-green-deal/.

25. Verkhovna Rada of Ukraine (n.d.). *National security strategy of Ukraine*. Retrieved from https://zakon.rada.gov.ua/laws/show/392/2020#n12.

26. *State and prospects for the development of technologies of "smart" power grids, demand management, and mode control systems in terms of development of renewable energy sources in the foreign energy sector* (2018). Retrieved from https://ua.energy/wp-content/uploads/2018/04/1.-Stan-rozvytku-smart-grid.pdf.

27. *SE NEC "Ukrenego". IT-PROJECTS* (n.d.). Retrieved from https://ua.energy/diyalnist/projects/spilni-proekty-z-mfi/#1538032249035-96c4bd2a-d9fc1cf7-ff2a.

28. Verkhovna Rada of Ukraine (2016). *Cabinet of Ministers of Ukraine. Decree of 13 July 2016 No. 552-p on approval of the Programme of the development of hydroenergetics for the period up to 2026.* Retrieved from https://zakon.rada.gov.ua/laws/show/552-2016-%D1%80.

29. *Minutes of a working meeting on the formation of prospective scenarios of hydroenergetics development in terms of preparation of the draft of the Report on compliance (sufficiency) assessment of generating units* (2019). Retrieved from https://ua.energy/wp-content/uploads/2019/11/Protokol-vid-02.10.2019.pdf.

30. *Concept of "green" energy transition of Ukraine up to 2050* (2020). Retrieved from http://mpe.kmu.gov.ua/minugol/control/uk/publish/article;jsessionid=12D73B364595AE9BC3059133CE27EA7A.app1?art_id=245434883&cat_id=35109.

31. *European Commission: A European Green Deal* (2022). Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en/.

Проблеми розвитку новітніх систем електрозабезпечення України в контексті європейської інтеграції

Г. Г. Півняк[1], *О. О. Азюковський*[1], *Ю. А. Папаїка*[1], *І. М. Луценко*[1], *Н. А. Нойбергер*[2]

1 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна, e-mail: Lutsenko.I.M@nmu.one

2 – Есслінгенський університет прикладних наук, м. Геппінген, Федеративна Республіка Німеччина

Мета. Аналіз проблематики та особливостей формування перспективних концепцій і сценаріїв розвитку новітніх структур систем енергозабезпечення для України в контексті енергетичного переходу та євроінтеграції.

Методика. Теоретичні дослідження, аналіз та узагальнення наукових і практичних результатів, порівняльний аналіз.

Результати. Європейська Green Deal сприяє широкому розвитку відповідних систем на базі ВДЕ у країнах ЄС. Україна також задекларувала свою активну позицію стосовно питань низьковуглецевого розвитку й «зеленого» переходу з формуванням відповідних сценаріїв реалізації до 2035, 2050 та 2070 років. У роботі проведено аналіз сучасного стану та структури системи електрозабезпечення у ФРН та Україні на шляху низьковуглецевого розвитку енергетики та економіки. У результаті проведеного дослідження можна визначити подальші раціональні кроки щодо ефективної трансформації електроенергетичної галузі за стратегією прагматичного або низьковуглецевого розвитку з подальшими заходами з модернізації атомного й теплового секторів енергетики й помірним розвитком ВДЕ. Розвиток раціональних структур електроенергетичних систем нового технологічного укладу – це постійно актуальний, наукоємний напрям, що несе серйозні зміни для традиційної сировинно-ресурсної економіки та енергетики.

Наукова новизна. Проведений комплексний аналіз сучасного стану й перспектив розвитку структури електроенергетичного комплексу України та ФРН дозволяє формувати першочергові раціональні кроки в досягненні енергонезалежності та енергобезпеки з урахуванням екологічності та низьковуглецевого розвитку національної економіки.

Практична значимість. Наведена аналітика може бути використана з метою забезпечення сталого розвитку енергетики України, формування світогляду щодо проблем, перспектив та аспектів оптимістичних і песимістичних сценаріїв розвитку системи електрозабезпечення.

Ключові слова: *електроенергетика, енергетичний перехід, низьковуглецевий розвиток, сценарії розвитку енергетики*

The manuscript was submitted 16.05.22.