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INCREASING THE EFFICIENCY AND SECURITY OF INTEGRATED POWER SYSTEM OPERATION THROUGH HEAT SUPPLY ELECTRIFICATION IN UKRAINE

Introduction. *The paradigm of global energy development is the priority of renewable energy sources (RES), namely, wind (WPP) and solar (SPP) power plants. This process has been evolving despite the fact that these renewable energy sources, by their physical nature, are unable to provide either a stable frequency of generated energy or a guaranteed power.*

Problem Statement. *The current threatening situation in the Integrated Power System (IPS) and in the energy market of Ukraine is caused by the hypertrophied development of SPP and WPP in the structure of Ukraine's IPS and excessive preferences given to RES by the "green" laws.*

Purpose. *The purpose of this research is to create a fundamentally new structure and basis of the electric-heat system operation, which unite the IPS of Ukraine and the system of centralized heat supply (CHS), by electrifying the CHS through the use of autonomous RES energy and the capacities of nuclear power plants (NPP), in order to ensure the profitability ofUkraine's energy market and the guaranteed profitability of RES.*

Material and Methods. *Information of NEC Ukrenergo for 2021 and periodic energy publications; system analysis for established electrical, hydraulic, and temperature modes of joint operation of IPS, CHS, WPP, and SPP for a fundamentally new organization of their interaction.*

Results. *Management based on the "green" tariff laws has led to a significant unprofitability of the Ukraine's energy market. The greenhouse gas emissions during the use of RES in the IPS have increased several times, as compared with such emissions, in the case of the structure of the IPS without RES. The new principle of interrelationships between IPS, CHS, WPP, and SPP ensures high manufacturability, cost-effectiveness, reliability, and environmental friendliness of each component.*

Conclusions. *The combination of IPS and CHS structures solves several problems of the national importance: the problem of frequency and power stabilization in the IPS automatically solves; the energy market of Ukraine gets rid of USD 15 billion loss anually; it allows saving 7.28 billion m^3 natural gas and reducing the carbon dioxide emissions by 98 million tons in CO_2 equivalent.*

Keywords: pover system, energy market, traditional technologies, renewable energy sources, electric heat generator, and centralized heat supply system.

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Even in the absence of convincing evidence of the decisive influence of the anthropogenic factor on climate change, the development and use of renewable energy sources, mainly wind and solar power plants, in the structure of generating capacities of energy systems, continues to be a pripityin the world energy sector. This process has been developing for quite a long time, practically without taking into account extremely important factors: WPP and SPP are energy sources with zero guaranteed capacity; due to their technological nature, WPP and SPP cannot ensure the normalized stability of the frequency and power of the electricity they supply to the power system. Withal, the relative capacities of WPP and SPP in the initial period of their use in energy systems were insignificant, and the necessary volumes of regulating capacities were forcibly drawn from the reserves of primary and secondary regulation, which are provided in each power system in accordance with regulatory requirements for stabilizing normal and emergency modes of energy system functioning. That is, in order to ensure the stable operation of WPP and SPP as part of the integrated energy systems, fast-acting reserve capacities intended for absolutely another purposes were involved. This approach did not form problems in energy systems as long as the capacity of WPP and SPP was insignificant. Over time, when their power increased significantly thanks to the laws on “green” tariffs in many countries, heavy system accidents began, up to blackouts (South Australia) and disconnection from the electricity supply of large regions with a total capacity of several thousand megawatts (Germany and other countries). At the same time, all over the world, the rapid growth of the use of WPP and SPP in integrated energy systems was and is currently being carried out practically without proper scientific support, by trial and error. The IPS of Ukraine was no exception. As of October 2019, about 4,000 MW of SPP capacity and about 750 MW of WPP capacity were introduced into its structure. Two years later, the capacity of SPP and WPP reached about 6,500 MW and 1,500 MW, respectively. This means that the total capacity of renewable energy sources in the IPS of Ukraine has almost doubled. Additional high-speed capacities to stabilize the operation modes of Ukraine’s IPS when using in its structure large capacities of WPP and SPP, since the acceptance of the laws on Alternative Energy Sources, on the Electric Energy Market (laws on the “green” tariff) was practically not introduced.

It is expedient to analyze the evolution of the energy policy of industrialized countries regarding the use of WPP and SPP in the structure of their own energy systems. Already at the level of 2000—2010, it became clear to a wide range of professionals that the mentioned technologies are, of course, competitive only in energy systems that include powerful hydropower plants (Norway, Austria, etc.). The number of countries with such opportunities is very limited. The vast majority of others should take into account the specifics of their own economies to prevent loss of competitiveness when intending to use these renewable energy sources. It is indicative that the European Union, by its decisions already in 2016, prohibited the granting of any preferences to energy technologies and energy industrial installations. However, later, under the pressure of environmental lobby organizations, EU was forced to change this decision and gave the right to each EU member state to solve the issue of preferences at its own discretion. Currently, Germany, in particular, has already fulfilled its environmental obligations it legally assumed 20 years ago, paying at the same time with a decrease of 2—3% of its gross domestic product. Even before 2016, Poland was able to legally renounce the preferences it had granted to the owners of WPP and SPP. Other EU members and most of the other countries of the world adhere in their actions to positions that are closer to Poland’s energy strategy. Due to limitations on the scope of the article, the authors are unable to provide a more detailed analysis of foreign sources. If necessary, we recommend readers to refer to the publication [14], where such an analysis was made.

The IPS of Ukraine is close to the Polish power system in terms of its capacity structure, in particular, it also does not have powerful hydroelectric power stations. However, unlike Poland, Ukraine's strategy in the area of using WPP and SPP in the energy system is strictly opposite. Ukrainian energy legislation exempts RES owners from installing special expensive equipment that ensures the standard frequency on the output buses of the power plant, at their power plants. A very valuable benefit is also the fact that RES owners are freed from the installation of expensive reserve generating capacities necessary for the stable operation of the power system in the absence of wind or solar radiation. Reimbursement of expenses for these benefits the "green" laws entrust to the energy system represented by NEC Ukrenergo, i.e., to the energy market of Ukraine. In addition, due to the effect of the mentioned laws, extremely unsuccessful management is functioning on the Ukrainian energy market, when WPP and SPP in a complex with reserve TPP displace the most efficient nuclear plants from the base zone of the daily schedule of electric loads and, as a result, from the energy market. Such powerful preferences and factors probably are currently hard to find in any country in the world. The result of this attitude of the state to its own energy system was that already in pre-war times, the revenues of the Ukrainian energy market did not cover its expenses both in 2020 and in 2021. In order to correct the situation and cover the resulting deficit, the Government introduced the issuance of Eurobonds and the provision of loans by Ukrainian banks to the Energy Market of Ukraine under government guarantees to liquidate debts owed to RES owners. In addition, the state guaranteed the owners of WPP and SPP that the installed capacity of these RES will be brought to the level of 15 GW in 2030, which is almost twice the actual value of 2021, while maintaining the existing management of IPS and of the energy market. Thus, during the last two pre-war years, the energy system and the energy market of Ukraine worked in conditions of hidden bankruptcy.

Poland's experience could be a way out of the threatening economic situation in Ukraine's energy complex. However, the Government has already granted (in 2020) and legally confirmed for the period until 2030 all owners of WPP and SPP, whose power plants operate as part of IPS of Ukraine, unjustified and destructive preferences that, in the current conditions, have already led the energy market to a situation of hidden bankruptcy and, in the future, will threaten catastrophic consequences for the entire economy of the country.

That is why an urgent problem in the electric power complex of Ukraine in the post-war period is the development of a conceptually different approach to the principles using of WPP and SPP energy, which would promote to solving the national problem of ensuring the reliability of IPS and energy security of Ukraine.

The purpose of this work is to create a fundamentally new structure and basics of operation of an ultra-large electro-thermal system for the production of electric and thermal energy (mega-system), which integrates the IPS of Ukraine and centralized heat supply systems by electrification of heat supply through the use in the primary state of the energy of autonomous renewable energy sources and the capacities of nuclear power plants, which ensures reliable manufacturability, high energy-economic indicators of IPS, RES and CHS, increases energy security and significantly improves the condition of the environment in the country.

The issues and legal support of "green" energy in Ukraine began to develop in 2008 [1]. In the period until 2020, tariffs for RES energy in Ukraine were many times higher than the market prices for electricity obtained using traditional technologies [1—5]. This factor was one of the main ones that determined the extremely high profitability of RES and the deep unprofitability of the Ukrainian electricity market. The said situation led to a significant increase of RES capacities in the IPS structure of Ukraine [6, 7]. In view of the fact of the sharp growth of RES capacities in the period after 2014, the regulatory authorities began to introduce reductions of energy tariffs for

RES [8], which were later canceled in court. The regulator's new attempt to reduce "green" tariffs [9] also did not change the situation for the better. Due to the payment crisis, already in the first months of the new electricity market operation in 2020, payments for energy produced under the "green" tariff were almost completely stopped. Electricity market actually stopped fulfilling its obligations and went into a state of hidden bankruptcy.

In order to resolve the threatening situation Cabinet of Ministers, European-Ukrainian Energy Agency and Ukrainian Wind Energy Association accepted the Memorandum of Understanding on the Resolution of Problematic Issues in the Renewable Energy Sector (the Memorandum) in 2020, where the producers agreed to a voluntary reduction "green" tariff for operating SPP and WPP. The state undertook to ensure the operation of the newly introduced auction model of RES support. The main provisions of the Memorandum were legislated [10] by taking into account the features of establishing a "green" tariff in the Law on Alternative Energy Sources [11]. As a result of the implementation of Memorandum provisions, the fixed tariffs established by law for WPP as of 2021 were close to the prices of the Ukrainian electricity market. Current SPP electricity tariffs were even lower than market prices [13].

The publication [12] provides forecast estimates of the installed capacity of WPP and SPP as part of Ukraine's IPS for the period until 2030. In combination with the data on the tariffs determined by the Memorandum, this provides an opportunity to analyze the energy economic situation projected in the IPS of Ukraine and its energy market at the level of 2030. This task is relevant both today and in the distant future, since the extremely negative forecasts made by the authors are already confirmed in the current state of the electric energy complex of Ukraine as a whole, its energy system and the energy market in particular. This was already appeared in 2021 in the irrational use of available generating capacities, first of all, highly economical nuclear generation, unreasonably high prices for electricity on the domestic market, in due to this significant import of electricity with large surplus capacities of own generation and in a number of other negative phenomena. Therefore, there is currently an urgent need and opportunity to develop the main directions and measures to increase of the operation efficiency of Ukraine's IPS under the conditions of deployment large volumes of RES in its structure. This problem is relevant not only for the electric power industry of Ukraine, it is no less important for the energy complexes of most industrialized countries that are moving to the principles of low-carbon development.

The main difficulties in solving such problems are as follows. The presence of zero guaranteed power in RES makes it necessary to use additional specific equipment in the IPS structure, which ensures the stability of the frequency and power supplied by the RES to the system. In order to formulate the technological requirements for this equipment, it is necessary to have a toolkit for analyzing its functioning as part of the IPS. At the same time, it was necessary to develop specific mathematical models of frequency and power regulation in IPS, and composition of models had to include mathematical blocks reflecting not only the characteristics (primarily frequency) of RES and traditional technologies, but also the characteristics of the specified additional technological equipment and interconnections between all IPS equipment, including RES, additional technological and traditional equipments. An additional complication in such models is the synthesis of mathematical blocks that reflect the behavior of the wind and the Sun radiation as a working body.

In the vast specialized literature devoted to RES usually issues of interrelationships and behavior between individual renewable energy sources and additional equipment of the specified purpose are investigated. A quite detailed analysis of these publications is given in [14]. Analysis of RES functioning as part of the IPS was not found among the publications known to the authors.

In the current state, a large number of studies on the RES operation as part of the IPS are carried out by the Institute of General Energy of the National Academy of Sciences of Ukraine. Wherein a set of several mathematical models with different functionalities is used. A model and software complex was developed for the study of the joint operation of WPP, SPP, hydroelectric power station (HPP) and storage batteries (SB) as part of the IPS of Ukraine [14, 15]. They underwent various tests and applications on real data.

A modification of the model and software complex for forecasting the long-term development of power systems with wind and solar power plants using statistical information to increase the flexibility of the power system was worked out [16].

In order to evaluate the economic efficiency of the joint operation of RES, SB and a traditional reserve power plant under the conditions of ensuring a stable level of power, an appropriate model of the life cycle of such a system has been developed [17].

To forecast the long-term development of the generating capacities structure of the electric power system, taking into account the dynamics of input and output of capacities and changes in their technical and economic indicators during the forecast period, a partial-integer mathematical model has been developed [18].

Research and modernization of energy objects, power-consuming technologies and introduction of new energy-efficient materials are based, first of all, on measurement, control and diagnosis of physical characteristics and regulation of physical processes parameters. The use of mathematical models of physical signals and fields of energy facilities operation, algorithms and programs for determining and statistical evaluation of their characteristics are the basis of information support for the operation of monitoring and diagnostic systems [19, 20].

Due to the results given, in particular, in publications [14—20], the researchers received a well-founded opportunity to choose the types and power of regulators that ensure the necessary stability of the IPS frequency in the structure of which RES of one nature or another is operating. If, for example, large-capacity WPP is part of the IPS, then only SB or large-capacity HPS can provide frequency stabilization in it. Even lowland HPP can ensure the stable operation of IPS that mainly consists of SPP. However, neither in the first nor in the second case can thermal power plants of any physical nature be used for frequency stabilization in such IPS due to their insufficient speed.

When determining of the volume and structure of the RES use as IPS part of any country, it is necessary to take into account not only the technological capabilities and indicators of frequency regulators, which can potentially be used in this case, but also the energy-economic characteristics of both RES and IPS as a whole in the system-wide measurement.

THE ENERGY-ECONOMIC INDICATORS OF SOLAR AND WIND POWER PLANTS FUNCTIONING IN THE IPS COMPOSITION OF UKRAINE ACCORDING TO ACTUAL DATA OF 2021

Energy-economic calculations were carried out by means of a system analysis of established modes of joint operation of integrated energy systems, wind and solar power plants (Table 1). At the same time, the processing of significant volumes of source information was carried out according to a large number of various dependencies and algorithms. The results of the calculations are given in the form of appropriate tables, since in this form heterogeneous and numerous indicators are perceived most accessible. Modernized coal-fired thermal power plants as reserve so and alternative power plants were used to evaluate the effectiveness of both SPP and WPP. This decision is due to the fact that in the existing structure of IPS of Ukraine these capacities were redundant as of the end of 2021, have the lowest specific capital investments and use fuel that is not included in the list of critical import goods. There are no another manoeuvrable sources of the necessary power in the IPS of Ukraine. The methodology of the calculations consists in comparing the economic efficiency indicators of two structures of Ukraine's IPS generating capacities, namely, its structure that was formed in accordance with the laws of Ukraine on the "green" tariff, and another, alternative structure, without any RES.

Initial data for calculating the SPP indicators: installed capacity of SPP is 6283 MW; the term of operation is 25 years; the specific capital investments are USD 1,000/kW; the coefficient of use of the installed capacity (CUIC) is 0.17; the tariff for SPP electricity is 4.35 euro cents/kWh. **Reserve power plants**: the installed capacity is 6283 MW; the specific capital investment is USD 400/kW; the CUIC (calculated) is 0.63; the specific fuel consumption is 0.345 kg.c.e. (coal equivalent); the service life is 35 years; the price for coal is UAH 3,274 /t; charge for CO_2 emissions is USD 3/t. **Initial data for calculating the WPP indicators**: the installed capacity of WPP is 1529 MW; the service life is 25 years; the specific capital investment is USD 1,400/kW; the CUIC is 0.35; the tariff for WPP electricity is 8.82 euro cents/kWh. **Reserve power plants**: the installed capacity of TPP is 1529 MW; the specific capital investment is USD 400/kW; the CUIC is 0.65; the specific fuel consumption is 0.345 kg.c.e.; the service life is 35 years; the charge for carbon dioxide emissions in the amount of USD 3/t is currently the average for the countries of the European Union; the CUIC for the reserve thermal power plant (TPP) when it works together with the SPP should be taken as 0.63, since the SPP works on average 11 hours a day; USD 1 = UAH 28.8; 1 € = UAH 32.5; UAH is the designation for the hryvnia. Tariffs for the energy of WPP and SPP are used in accordance with the Memorandum.

The main energy-economic indicators of the operation of SPP and WPP as part of the IPS of Ukraine in 2021 are given in the Table 1.

Table 1. **Energy-Economic Indicators of Solar and Wind Power Plants Operating as Part of Ukraine's Energy System According to the Actual Data of 2021**

No.	Size	Unit measurement	Value
	I Solar power plants		
1	Installed capacity of SPP	MW	6283
2	Production of electricity at SPP	kWh	$7.485 \cdot 10^9$
3	Production of electricity at a reserve TPP	kWh	$27.737 \cdot 10^9$
4	The cost of SPP electricity	USD	$325.6 \cdot 10^6$
5	The cost of electricity of the reserve TPP	USD	$2.617 \cdot 10^9$
6	Gross costs of the SPP owner	USD	$289.6 \cdot 10^6$
7	Gross income of the SPP owner	USD	$325.6 \cdot 10^6$
8	Gross profit of the SPP owner	USD	$36 \cdot 10^6$
9	Net profit of the SPP owner	USD	$28.8 \cdot 10^6$
10	The payback period of the SPP owner's capital	year	10
11	Emissions of CO_2 by reserve TPP	ton	$35.1 \cdot 10^6$
12	**Consumer costs for energy produced by SPP + TPP**		
12.1	The cost of electricity produced by the SPP	USD	$325.6 \cdot 10^6$
12.2	The cost of electricity for SPP reservation	USD	$1.617 \cdot 10^9$
12.3	The cost of electricity for frequency stabilization	USD	$3.368 \cdot 10^9$
12.4	General expenses of the consumer	USD	$5.311 \cdot 10^9$

End of Table 1

No.	Size	Unit measurement	Value
13	The total electricity generated by the SPP + TPP complex	kWh	$35.22 \cdot 10^9$
13.1	The cost of electricity produced by the SPP	USD	$325.6 \cdot 10^6$
13.2	The cost of electricity for SPP reservation	USD	$1.617 \cdot 10^9$
13.3	The cost of electricity for frequency stabilization	USD	$3.368 \cdot 10^9$
13.4	General expenses of the consumer	USD	$5.416 \cdot 10^9$
14	The cost price of electricity produced at the SPP + TPP complex	USD/kWh	0.153
15	**An alternative TPP to the SPP + TPP complex**		
15.1	The installed capacity of the alt. TPP	kW	$1.068 \cdot 10^6$
15.2	Fuel consumption	ton	$2.582 \cdot 10^6$
15.3	CO_2 emissions alt. TPP	ton	$9.5 \cdot 10^6$
15.4	Total costs per alt. TPP	USD	$338.1 \cdot 10^6$
15.5	The cost price of energy produced on alt. TPP	USD/ kWh	0.0452
	II Wind power plants		
16	The installed capacity of the WPP	MW	1529
17	Production of electricity at WPP	kWh	$3.75 \cdot 10^9$
18	Production of electricity at a reserve TPP	kWh	$6.965 \cdot 10^9$
19	The cost of WPP electricity	USD	$330.8 \cdot 10^6$
20	The cost of electricity of the reserve TPP	USD	$657.1 \cdot 10^6$
21	Gross costs of the WPP owner for 1 year of operation	USD	$99.34 \cdot 10^6$
22	Owner's gross income	USD	$330.8 \cdot 10^6$
23	Owner's gross profit	USD	$231.46 \cdot 10^6$
24	Owner's net profit	USD	$185.7 \cdot 10^6$
25	The payback period for the owner's expenses	year	0.536
26	Emissions of CO_2 by reserve TPP	ton	$8.81 \cdot 10^6$
27	**Consumer costs for electricity WPP + TPP**		
27.1	The cost of electricity produced at WPP	USD	$330.8 \cdot 10^6$
27.2	The cost of electricity for the reservation of WPP	USD	$463.6 \cdot 10^6$
27.3	The cost of electricity for frequency stabilization	USD	$1.6876 \cdot 10^9$
27.4	General expenses of the consumer	USD	$2.483 \cdot 10^9$
28	Total electricity produced by the WPP + TPP complex	kWh	$10.72 \cdot 10^9$
29	The cost price of electricity produced at the WPP + TES complex	USD/kWh	0.234
30	**An alternative TPP to the WPP + TPP complex**		
30.1	Production of electricity at alt. TPP	kWh	$3.75 \cdot 10^9$
30.2	The installed capacity of the alternative TPP	kW	$0.535 \cdot 10^6$
30.3	Coal consumption	ton	$1.294 \cdot 10^6$
30.4	CO_2 emissions alt. TPP	ton	$4.744 \cdot 10^6$
30.5	Total costs per alt. TPP for 1 year of operation	USD	$170.5 \cdot 10^6$
30.6	The cost price of electricity alt. TPP	USD/kWh	$43.47 \cdot 10^{-3}$

In the Table 1 the volumes of electricity production at the SPP (line 2) coincide with the volumes of its generation at the corresponding alternative TPP for the validity of comparisons of their energy-economic characteristics. A similar condition is also provided for TPP that is an alternative to WPP.

According to the Memorandum, tariffs for SPP and WPP electricity in Ukraine are legally set at the 2030 level of 3.9 and 7.72 euro cents per 1 kWh respectively. These tariffs are lower than the current prices on the Ukrainian energy market [13]. This gives grounds to assert that starting from 2023 solar and wind energy will no longer have such a destructive effect on the condition of the country's energy complex, the demonstrations of which took place already in 2021, as can be seen from Table1. This study proved that such assessments and statements have no basis. At the same time, the forecast of installed capacities at the level of 2030 [12] was used for SPP with a volume of 9947 MW and for WPP with a volume of 5033 MW.

The methodology and algorithms for calculating the energy-economic indicators of this period are similar to those used in calculating the indicators in Table 1. It is important to compare the relevant values to recognize trends and the speed of their change.

ANALYSIS AND COMMENTS OF ENERGY-ECONOMIC INDICATORS OF SPP AND WPP FUNCTIONING AS PART OF UKRAINE'S IPS ACCORDING TO REPORTS (2021) AND FORECAST DATA FOR THE PERIOD UNTIL 2030

The main political argument used to justify the need for the use of SPP and WPP technologies is the need to reduce greenhouse gas emissions. However, as shown by the obtained results (Table 1), in reality the situation is completely opposite. Indeed, in the conditions of the IPS of Ukraine that does not include powerful hydroelectric power plants, to ensure the reliable operation of renewable energy sources and the entire energy system, it is necessary to use additional reserve energy sources, among which coal-fired thermal power plants, the installed capacity of which coincides with the total installed capacity of SPP and WPP, are uncontested. Due to the fact that the CUIC of WPP is almost twice less than this indicator for reserve TPP, and for SPP — almost four times, CO_2 emissions by the SPP + TPP complex at the level of 2030 amount to $55.6 \cdot 10^6$ tons in equivalent CO_2, while these emissions by an alternative coal-fired thermal power station are only $15 \cdot 10^6$ tons. For the WPP + TPP complex and the alternative TPP, these indicators are $29 \cdot 10^6$ tons and 15.6×10^6 tons, respectively. The ratios of these indicators in 2021 are similar (Table 1). Thus, due to the presence of SPP and WPP in the IPS of Ukraine, CO_2 emissions will increase by 54 million tons in 2030, and the ratio of these emissions in reserve and alternative TPP is 2.8. That is, the comparative analysis of greenhouse gas emissions presented in this work completely refutes the stated political rationale for the feasibility of using SPP and WPP as part of the IPS of countries that, according to conditions of nature (lack of opportunities to build powerful hydroelectric power stations), are similar to the conditions of Ukraine. The use of RES in the IPS of Ukraine not only does not improve the environmental situation, but even significantly worsens it.

In addition, in terms of energy economy, the supporters of the widespread introduction of SPP and WPP into the structure of the IPS argue their position by the fact that these energy sources do not require fuel. But at the same time, it is not taken into account that to ensure their working, it is necessary to additionally use reserve TPP. Thus, for the reservation of a SPP with a capacity of 9,947 MW (2030), it is necessary to have a TPP of the same capacity, which produces $43{,}916 \times 10^9$ kWh and consume $15.15 \cdot 10^6$ t of thermal coal, while the alternative TPP requires only 5.11×10^6 t of the same coal and will produce the same amount of electricity as provided by the SPP. That is, the SPP + TPP complex requires almost three times much coal for its operation than the alternative TPP consumes. The fact that the SPP itself does not use fuel not only does not give it any advantages, but even complicates the situation significantly.

The main strategic miscalculation in the formation of directions for the use of SPP and WPP as part of the generating capacity of the IPS of Ukraine was the simultaneous use of IPS network for the transmission of energy like from both traditional energy sources so from RES. Such an approach makes it necessary, in the conditions of a unified energy system, to ensure the introduction of additional expensive equipment into its structure (reserve energy sources and fast-acting frequency regulators), which could compensate for the unevenness of power generation and the instability of the RES frequency, which are technologically inherent in these energy sources. This equipment (or the import of its energy) causes the majority of the hypertrophied costs of the consumer, who uses the energy of the IPS with large capacities of SPP and WPP. In particular, at the level of 2030, in the total costs of the consumer for the production of electricity from SPP + TPP in the amount of USD 8,777 $\cdot$ 10^9, the costs of SPP reservation are USD 2,893 $\cdot$ 10^9, and the costs of frequency stabilization are USD 5,332 $\cdot$ 10^9, totally USD 8,225 $\cdot$ 10^9 that is 93.7% of total consumer spending. The energy market of Ukraine is the consumer of the indicated energy worth USD 8,777 $\cdot$ 10^9. His expenses for this segment will be compensated according to "green" laws only by the cost of SPP energy in the amount of USD 522.2 $\cdot$ 10^6. The difference between these indicators (USD 8,255 $\cdot$ 10^9) is the loss of the energy market. A similar situation occurs in the wind power plant sector at the level of 2030, as well as in the SPP and WPP sectors at the level of 2021 (Table 1).

A very important strategic mistake during the development of laws on the "green" tariff was the introduction of a provision that in the practice of legal and economic relations between economic entities is called the "take or pay" principle, in the Law of Ukraine on the Electricity Market. This principle obliges the operator (dispatcher) of the energy system to give priority in the use of energy to wind and solar power plants. In case of violation of this principle, the owner of the SPP or WPP receives compensation from the energy market of Ukraine in the amount of the lost benefit (the cost of the energy not released). The research results show that the specified principle leads to unacceptable systemic losses. Indeed, it is planned that at the level of 2030, the SPP + TPP and WPP + TPP complexes will produce a total of 91 $\cdot$ 10^9 kWh. In the current state of energy legislation in Ukraine, all this energy must be sold to consumers without alternatives. It is generated around the clock, so it covers part of the base zone of the electric load schedule (ELS), competing only with nuclear plants (NPP). At present, the maximum amount of energy production at NPP according to their working capacity is 97 $\cdot$ 10^9 kWh, therefore RES together with reserve TPP have been almost completely displacing NPP units that are the most economical among all conventional technologies, from ELS. This leads to large systemic losses and a significant increase in the unprofitability of the Ukrainian energy market. The Government attempts to equalize the situation by monetary means were not successful during 2020—2021, especially their use in the period up to 2030 does not make sense due to the projected doubling of the installed RES capacity. The forecast of the energy economic situation in the IPS of Ukraine at the level of 2030 shows that with the existing structure of management in the IPS of Ukraine, the IPS will not be able to function. If the installed capacity of SPP and WPP is doubled from the current one to almost 15 million kW and the existing approaches to their use are preserved, the losses will increase to a fantastic index of over UAH 460 billion. It will be impossible to correct such a situation only with the specified monetary measures. The country's economy simply will not be able to provide compensation for the IPS losses of above USD 15 billion annually, especially in the post-war period and especially without a reasonable answer to the question of why this should be done. On the other hand, the state has already provided guarantees by the Memorandum to the owners of SPP and WPP to use all the energy produced by them at economically acceptable, fixed prices in hard currency for the period until 2030. It seems that due to a number of negative factors, a closed circle has formed, the rational exit from which is unreal. However, in addition to the extremely negative phenomena that are currently occurring in the IPS of Ukraine as a result of imperfect management caused by the laws on the "green" tariff and other regulatory documents that grant unjustified preferences to the owners of SPP and WPP, in the energy sector of Ukraine (in contrast to the situation in the vast majority industrialized countries) there is an opportunity to reorganize the existing management in the IPS in such a way that the guarantees provided by the state to the owners of RES are fully implemented, and the economic activity of the IPS becomes highly profitable. This can be ensured by organizing a new electro thermal energy system that includes IPS of Ukraine and centralized heat supply systems (CHSS) of large cities with specific connections between them. In countries where there are no CHSS, it will be impossible to implement such an approach.

COMPREHENSIVE INCREASE OF FUNCTIONING EFFICIENCY IPS OF UKRAINE IN THE CONDITIONS OF GROWING RES CAPACITIES IN ITS STRUCTURE THROUGH THE ORGANIZATION OF ITS COMMUNICATIONS WITH SYSTEMS OF CENTRALIZED HEAT SUPPLY

The research on the possibilities of using the interaction of the IPS of Ukraine and the CHSS of large cities to increase the energy-economic indicators of both systems are carried out in Institute of General Energy of the NAS of Ukraine. At the same time, the tasks of synthesis mathematical models for the construction of effective systems of frequency and power automatic regulation (AFPR) in emergency modes, development of new structures of AFPR, based on consumers-regulators, new peak means of electric power regulation, which are more effective than hydro accumulating power plants, etc., were solved. At the same time, the problems of the synthesis of mathematical models for the construction of effective systems of automatic frequency and power regulation (AFPR) in emergency modes, the development of new structures of AFPR based on consumers-regulators, new means of peak electric power regulation, more effective than hydro accumulating power plants and others. In all these developments, the basic element is an electric heat generator (electric boiler or heat pump). The accumulated experience in the development of such systems has allowed the researchers of the Institute of General Energy of the National Academy of Sciences of Ukraine to synthesize an ultra-large electrothermal energy system (mega-system) that generates both electric and thermal energy in volumes that are not less than those that would be generated by IPS and CHSS in isolated modes. At the same time, SPP and WPP, formally (legally) being part of the IPS, are physically and functionally removed from its structure and form their own autonomous subsystem of the IPS (Electrical Heat Supply System (EHSS)).

The primary energy that comes to the consumer from generator bus of SPP or WPP has a wide range of harmonics in its composition. Currently, in the IPS of almost all countries of the world, using a set of converters, they achieve the fact that only one harmonic with a standard frequency of 50 Hz remains in this spectrum, and the converted energy with this frequency is delivered to the consumer through the IPS electrical network. An alternative principle is to attract a consumer who would be insensitive to the change in frequency, that is, would be able to use electricity with the frequency spectrum that it has in its original form. Such a consumer is an electric boiler. It can work with energy that has one standard 50 Hz harmonic in the spectrum, or accept energy with a wide spectrum, then it generates heat based on the principle of superposition, when the thermal energy of each harmonic in the spectrum is integrated. Due to such a scheme, the expensive cost item for frequency stabilization disappears. However, there is another expensive item of expenses in the totality of expenses for the use of RES energy, these are expenses for reserve energy sources. The said problem is solved in the proposed mega system by choosing the consumer of thermal energy generated by the electric boiler. Centralized heat supply systems are such an ideal consumer. A design and operational feature of CHSS systems is that in order to minimize total costs in the system, a temperature schedule with a max water temperature of 120° and a min of 70 °C is implemented in them. This makes it possible to organize the coverage of this schedule in such a way that the zone between the max and min temperatures of 120 °C and 70 °C is supplied by SPP and WPP, and the base zone up to 70 °C by NPP energy. These two operations are enough so that with such management in the IPS the incomes and profits of RES owners will remain the same as those guaranteed by the Memorandum. In addition, there appear several energy-economical factors that, together with the ones already mentioned, also ensure high profitability of CHSS.

ENERGY-ECONOMIC INDICATORS OF JOINT FUNCTIONING IPS AND CHSS WITH USE OF SPP AND WPP ENERGY AT THE LEVEL OF 2030

The specified indicators were determined by applying a system analysis of the established electric, hydraulic and temperature modes of the join to peration of WPP, SPP, IPS and CHSS according to the fundamentally new, above-mentioned organization of their interaction (Table 2).

Input data for calculating the energy-economic indicators: the total length of the power transmission line of the RES is 500 km; the specific costs of the transmission line construction are 1,971 × × 10^3 UAH/m; the specific costs for the electric boiler power (connection) are $2.28 \cdot 10^3$ UAH/kW; the electric boiler resource is 25 years; the capital investment for an electric boiler is USD 35/kW; the efficiency coefficient (e.c.) of gas boiler is 0.93; the e.c. of electric boiler is 0.98; the specific emissions of CO_2 of gas boiler are 1.622 t/t.c.e.; the natural gas price is USD 700 per 1,000 m^3; the tariff for thermal energy (2021) is 2047 UAH/Gcal.

The energy-economic indicators of the functioning of IPS and CHSS in Ukraine based on electric heat generators using RES are given in Table 2.

Table 2. **Energy-Economic Indicators of the Joint Operation of IPS and CHSS in Ukraine Using Renewable Technologies at the Level of 2030**

No.	Size	Unit measurement	Value
1	Consumption of thermal energy from CHSS	Gcal	$62 \cdot 10^6$
2	including for hot water supply	Gcal	$18.5 \cdot 10^6$
3	Production of electricity at SPP	kWh	$11.85 \cdot 10^9$
4	Production of electricity at WPP	kWh	$12.34 \cdot 10^9$
5	SPP electricity tariff	€/kWh	$3.9 \cdot 10^{-2}$
6	WPP electricity tariff	€/kWh	$7.72 \cdot 10^{-2}$
7	Payments for CO_2 emissions	USD/t	3
8	Efficiency coefficient of a gas boiler	–	0.93
9	Electric boiler resource	year	25
10	Specific emissions of $CO_2$of a gas boiler	t/t.v.e	1.622

End of Table 2

No.	Size	Unit measurement	Value
11	Price on the electricity market: weighted average for the day	UAH/ kWh	2.717
12	of the base zone	UAH/ kWh	0.8
13	The natural gas price	USD/1000m^3	700
14	Tariff for thermal energy	UAH/Gcal	2047
15	Specific costs		
15.1	For the construction of power lines	UAH/m	$1.971 \cdot 10^3$
15.2	For the electric boilers power	UAH/kW	$2.28 \cdot 10^3$
16	Total length of power lines	km	500
17	NPP energy (line 1 × 1.161 × 7/12)/0.98	kWh	$41.7 \cdot 10^9$
18	The NPP electricity cost (line 17 × UAH 0.8)	USD	$1.16 \cdot 10^9$
19	The volume of natural gas substitution (lines 3 + 4 + 17) × 10^{-3} × 130.85 (kg.c.e.)/0.94	m^3	$7.28 \cdot 10^9$
20	Reduction of CO_2 emissions due to natural gas savings line 19 (line 19 × 1.15 × 1.622)	ton	$13.58 \cdot 10^6$
21	Reduction of fees for CO_2 emissions according to line 20	USD	$40.74 \cdot 10^6$
22	The replaced gas cost (line 19 × line 13)	USD	$5.1 \cdot 10^9$
23	Reduction of CO_2 emissions due to the replacement of the reserve station (line 11 Table 3 + line 26 Table 3)	ton	$84.55 \cdot 10^6$
24	Reduction of fees for CO_2 emissions according to p. 23	USD	$0.254 \cdot 10^9$
25	Overall reduction of CO_2 emissions (line 20 + line 23) in comparison with the scenario in Table 3	ton	$98.13 \cdot 10^6$
26	Costs for the construction and operation of the electric heat supply system		
26.1	New transmission lines (line 15.1 × line 16)	USD	$34.2 \cdot 10^6$
26.2	Installed capacity of electric boilers (line 1 Table 3 + line 16 Table 3 + line 17/(0.8 × 8.76 × 10^3))	MW	$20.93 \cdot 10^6$
26.3	Capital investment for 1 year, taking into account construction, voltage limiters and connection of electric boilers (line 26.1 × 1.112 + line 26.2 × 1.1 × (line 15.2 + 35))/25	USD	$106.64 \cdot 10^6$
26.4	Salary with accruals (1250 persons × 600 USD/month × 12 × 1.24)	USD	$11.16 \cdot 10^6$
26.5	Other costs (materials, etc.) (line 26.3 × 0.02)	USD	$2.13 \cdot 10^6$
26.6	The cost of SPP, WPP and NPP electricity (line 4 Table 3 + line 19 Table 3 + line 18)	USD	$2.762 \cdot 10^9$
26.7	Total EHSS costs (lines 26.3 + 26.4 + 26.5 + 26.6)	USD	$2.937 \cdot 10^9$
27	The thermal energy cost (line 1 × UAH 2047)	USD	$4.407 \cdot 10^9$
28	Gross revenues of EHSS (lines 21 + 22 + 24 + 27)	USD	$9.802 \cdot 10^9$
29	EHSS gross profits (line 28 – line 26.7)	USD	$6.868 \cdot 10^9$
30	EHSS net profit of (line 29 × 0.8)	USD	$5.22 \cdot 10^9$
31	The payback period for EHSS costs (line 26.7 / line 30)	year	0.56

In the Table 2, as in Table 1, energy-economic indicators are defined in the uniform prices of 2021 for the possibility of these indicators comparison and analysis.

The main advantages of the proposed megasystem in comparison with the current structure of IPS of Ukraine is that, due to fundamentally new management, the need to use expensive equipment for frequency stabilization and power reserve in the power system has disappeared. These two factors determine the currently enormous unprofitability of the Ukrainian energy market, which threatens its destruction by 2030. In the new mega system, the sources of instability (WPP and SPP) are functionally removed from the structure of the IPS, which provides it with the opportunity to operate in the conditions of the classic market with appropriate profitability. During 2020–2021, the problem of market profitability existed as a result of its unsuccessful management, caused by the action of priorities for RES, determined by the "green" tariff laws.

The gross revenues of the electric heat supply system (p. 28 of Table 2, USD $9.8 \cdot 10^9$) far exceed its expenses (p. 26.7 of Table 2,USD $2,937 \cdot 10^9$), which guarantees the payment of the cost of WPP and SPP electricity defined by the Memorandum. Such a high profitability of EHSS (payback period — 0.56 years) is caused by several factors: high current tariffs for thermal energy (p. 14 of Table 2); replacing large volumes of natural gas (p.19 of Table 2, $7.28 \cdot 10^9$ m^3) by cheap energy of NPP, WPP and SPP; reduction of large volumes of greenhouse gas emissions (p. 25 of Table 2, $98.13 \cdot 10^6$ t). Due to the proposed structure of EHSS, NPP are actually used as reserve sources of thermal energy, and the market cost of NPP energy is almost 3.5 times lower than the cost of TPP energy [13], with TPP having reserve functions in the current IPS structures with a large share of SPP and WPP. In addition, there is no need for large volumes of TPP capacity reservations that currently partially block and will completely block the use of effective NPP energy at the level of 2030. As a result of the use of such a EHSS structure, nuclear power plants will have free access to the electricity market. If the EHSS system is implemented during the heating period, NAEC *Energoatom* will supply about 40% of its energy to this system. In the non-heating period, the use of NPP energy in EHSS will decrease to 12%, which will not affect the profitability of this company in any way, since this period is used by almost all power plants as a repair site. In addition, the surplus of the NPP energy is easily sold on the Ukrainian or European markets.

CONCLUSIONS

1. The political argument by supporters of the use of SPP and WPP that the use of these renewable energy sources leads to a decrease of greenhouse gas emissions for the conditions of Ukraine is false. The analysis demonstrates the opposite phenomenon, namely, the specified emissions in the absence of RES in the power structure of the IPS of Ukraine are reduced several times as compared with the options when these RES are present in it. CO_2 emissions by SPP + TPP and WPP + TPP complexes during their operation as part of the IPS of Ukraine at the level of 2030 total $84.5 \cdot 10^6$ t in CO_2 equivalent. At the same time, the total emissions of these gases from alternative TPP producing electricity of the same volume as that generated by SPP and WPP together, amount to only $30.6 \cdot 10^6$ tons. In this particular case, alternative TPP emit 2.76 times greenhouse gases less than RES + TPP complexes. The very common statement that the use of RES does not require fossil fuels is not true. At the same time, it is not taken into account that the functioning of RES in the current conditions of the IPS of Ukraine is impossible without the use of reserve TPP. This is a gross mistake. At the level of 2030, coal consumption by reserve TPP is predicted to be 28.83 · 106 t c.e., while alternative TPP will need only $10.43 \cdot 10^6$ t c.e. The ratio of these indicators (2.76) strictly coincides with the corresponding ratio of greenhouse gas emissions, as it should be. The use of RES as part of the IPS of Ukraine with the cur-

rent structure not only does not improve the environmental situation, but even worsens it multiple times. This condition is typical for most countries, the only exception being those that are rich in hydro resources.

2. Immediately before the war, in 2020—2021, the state carried out a series of monetary and organizational measures to settle the current threatening energy-economic situation on the country's energy market (establishing more or less acceptable tariffs for RES energy; issuing Eurobonds and providing loans to repay losses in the energy market caused by the action "green" laws; reducing the rate of growth of new construction of SPP and WPP by holding auctions for permits for such construction, etc.). However, despite these measures, the total losses of Ukraine's energy market in 2021 amounted to about USD 7 billion (Table 1), which is estimated as its hidden bankruptcy. The energy-economic forecast of the IPS functioning and the energy market of Ukraine at the level of 2030 shows that if the management of the energy market, defined by the current laws on the "green" tariff, is preserved, annual losses of the energy market will increase to USD 15 billion. This will lead to the destruction of the energy market and shocks for the entire economy of the country up to and including the threat of its default.

3. The main strategic mistake in the formation of directions for the use of SES and WPP as part of the generating capacity of Ukraine's IPS was the simultaneous use of IPS network for the transmission of energy from both traditional energy sources and RES. This approach makes it necessary in the conditions of a unified power system to ensure the introduction of additional expensive equipment (reserve energy sources and fast-acting frequency regulators) into its structure, which should compensate for the unevenness of power generation and frequency instability, which are technologically inherent in RES. In this work it was established that this equipment causes the hypertrophied losses of the energy market of Ukraine in the amount of USD $15 \cdot 10^9$ at the level of 2030.

4. The main advantages of the proposed mega-system in comparison with the current structure of Ukraine's IPS is that, due to a fundamentally new management, the need to use equipment for frequency stabilization and power reserve in the power system has disappeared. It is these two factors that determine the currently flagrant unprofitability of the Ukrainian energy market, which threatens its destruction at the level of 2030. In the structure of the mega system, the sources of instability (WPP and SPP) are functionally removed from the composition of the IPS, which provides itthe opportunity to work in the conditions of the classic market with acceptable profitability. During 2020—2021, the problem of its profitability existed as a result of its unsuccessful management, caused by the action of priorities for RES, determined by the laws on the "green" tariff.

5. The gross revenues of the electric heat supply system (USD $9.8 \cdot 10^9$) far exceed (Table 2) its expenses (USD $2.937 \cdot 10^9$), which guarantees payment of the cost of electricity from WPP and SPP, determined by the Memorandum. Such high profitability of EHSS is caused by several factors: high current tariffs for thermal energy; replacing large volumes of natural gas by cheap energy from NPP, WPP and SPP; reduction of large volumes of greenhouse gas emissions.

6. The proposed approach of transferring CHSS to the use of electric boilers with the combined use of electricity from both traditional and renewable sources instead of natural gas heat generators provides for the new system of centralized heat supply high economic efficiency with a capital payback period of about half a year (Table 2). This indicates that the tariff for thermal energy in the new EHSS system can be reduced at least 4 times, as compared with the tariff, in particular, that was in effect at the CHSS *Ukrteploenergo,* in October 2021 (before the rapid increase of world natural gas prices).This will ensure an increase in the demand for heat supplied through CHSS, with a further increase CHSS efficiency.

7. As a result of the implementation of the project to construct new, combined structures of the

IPS and CHSS in Ukraine, several problems of state importance are immediately solved:

- full payment of the cost of electricity produced at SPP and WPP is ensured at the expense of EHSS system revenues;
- the capacities of SPP and WPP are removed from the structure of the IPS of Ukraine, therefore the problem of frequency and power stabilization disappears in the IPS, it gets the opportunity to operate in the full extent of its capacities in market conditions, without fixed prices for RES energy and without other privileges for RES, which leads to huge losses on the energy market; thanks to this, the energy market of Ukraine automatically gets rid of losses of about USD 15 billion annually;
- 7.28 billion cubic meters of natural gas are saved, which is a significant contribution to the energy security of the country;
- emissions of carbon dioxide are reduced by more than 98 million tons in CO_2 equivalent, which accounts for about 50% of all emissions in Ukraine in 2020 in the production of thermal and electrical energy.

8. In the current state of war, almost all Ukrainian WPP and SPP have been destroyed. In the post-war period, they will be quickly restored, since they (especially WPP) are very profitable and require minimal capital investment. Therefore, in order to prevent possible economic shocks in the country, a green energy reorganization project should be implemented, the conceptual provisions of which are given in this paper. There is simply no other way out.

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТА БЕЗПЕКИ ФУНКЦІОНУВАННЯ ОБ'ЄДНАНОЇ ЕНЕРГЕТИЧНОЇ СИСТЕМИ ШЛЯХОМ ЕЛЕКТРИФІКАЦІЇ ТЕПЛОЗАБЕЗПЕЧЕННЯ В УКРАЇНІ

Вступ. Парадигмою світового розвитку енергетики є пріоритетне використання відновлюваних джерел енергії (ВДЕ), а саме вітрових (ВЕС) та сонячних (СЕС) електростанцій. Цей процес розвивається, незважаючи на те, що ці ВДЕ за своєю фізичною природою не здатні забезпечити ані стабільної частоти генерованої енергії, ані гарантованої її потужності.

Проблематика. Поточний загрозливий енергоекономічний стан Об'єднаної енергосистеми (ОЕС) України та її енергоринку зумовлено гіпертрофованим розвитком СЕС та ВЕС у структурі ОЕС України та надмірними преференціями, які надаються ВДЕ «зеленими» законами.

Мета. Створення принципово нової структури і основ функціонування електротеплової системи, що об'єднує ОЕС України та системи централізованого теплопостачання (СЦТ) шляхом електрифікації СЦТ через використання енергії автономних ВДЕ та потужностей атомних електростанцій, яка забезпечить рентабельність енергоринку України та гарантовану дохідність ВДЕ.

Матеріали й методи. Використано інформацію НЕК «Укренерго» за 2021 р. та періодичних енергетичних видань. Застосовано методи системного аналізу усталених електричних, гідравлічних і температурних режимів сумісного функціонування ОЕС, СЦТ, ВЕС і СЕС для принципово нової організації їхньої взаємодії.

Результати. Менеджмент, діючий на енергоринку України, є глибоко збитковим, що зумовлено законами про «зелений» тариф. Викиди парникових газів при використанні ВДЕ в ОЕС зростають у кілька разів порівняно зі структурою ОЕС, коли ВДЕ у ній відсутні. Новий принцип взаємовідносин між ОЕС, СЦТ, ВЕС і СЕС забезпечує високу технологічність, економічність, надійність і екологічність кожної із цих складових.

Висновки. Поєднання структур ОЕС та СЦТ вирішує кілька проблем державного значення: в ОЕС автоматично вирішується проблема стабілізації частоти і потужності; енергоринок України позбавляється збитків обсягом 15 млрд дол. США щорічно; вивільнюються 7,28 млрд куб. м природного газу; на 98 млн т в еквіваленті CO_2 скорочуються викиди вуглекислого газу.

Ключові слова: енергосистема, енергоринок, традиційні технології, відновлювані джерела енергії, електротепловий генератор, система централізованого теплопостачання.