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Maintaining Ukraine's Grid Reliability under Rapid Growth of Renewable Electricity Share: Challenges in the Pre-War, War-Time, and Post-War Periods

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ABSTRACT

The paper deals with the problems of maintaining Ukraine's grid reliability under high renewable electricity penetration and improving state policy measures to accelerate sustainable energy transition in the post-war period. Promoting renewable energy in Ukraine increased renewable electricity share in the country's electricity mix to 13.8% in 2021. However, such growth became critical for Ukraine's electric power system. Due to its inflexibility, the lack of balancing and energy storage capacities, adding significant amounts of renewable electricity to the grid created severe problems. Further renewable energy development required serious reforming policy measures, but the Russian invasion prevented introducing relevant legislative changes. At the same time, the war had an unprecedented impact on the Ukrainian energy sector, resulting in the damage of more than 50% of the energy infrastructure. Considering global trends towards decarbonisation and achieving climate neutrality, reconstructing Ukraine's electric power sector will be based on the large-scale involvement of renewable energy technologies. Given this, based on the study of the trends in renewable energy development in the pre-war and war-time periods and the analysis of the shortcomings of the state energy policy, the paper examines the required measures for fostering resilient reconstruction of Ukraine's electric power sector.

Keywords

Renewable energy;
Energy policy;
Power sector;
Post-war recovery;
Ukraine

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1. Introduction

The development of renewable energy (RE) is one of the priority tasks of Ukraine's state policy, a tool for decarbonising the energy sector and strengthening energy security [1]. For the successful RE development, the government set goals for increasing RE share in the country's energy consumption to 12% and 25% in 2025 and 2035, respectively [2] and implemented appropriate legal, organisational, and economic incentives [3,4]. The emphasis of state policy is mainly aimed at the electric power sector; therefore, most of the support mechanisms relate to promoting electricity generation from renewable energy sources (RES). Their implementation resulted in the rapid development of RE facilities and the growth of renewable electricity share in the country's electricity mix to 13.8% in 2021 [5].

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However, despite the progress towards the achievement of RE indicative goals, the growth of renewable electricity share caused some challenges in terms of its effective integration into the electric power system. Due to its inflexibility, the shortage of balancing and energy storage capacities, adding large amounts of electricity generated by solar (SPPs) and wind power plants (WPPs), which account for 90.7% in renewable electricity structure [5], has become practically impossible. Further RE development required significant reforming energy policy in Ukraine, but the war prevented it.

In addition to the impact on implementing plans to improve energy policy in the RE field, the war had an unprecedented effect on Ukraine's energy sector, resulting in the destruction, damage, and occupation of more than 50% of Ukraine's energy infrastructure [6]. Although the energy infrastructure was exposed to missile attacks throughout Ukraine, the scale of its losses was influenced by the large concentration of conventional and RE power plants in the southeastern regions, where active hostilities are taking place, and part of which is currently occupied [7,8].

Despite the war's continuation, issues of the post-war reconstruction of Ukraine's electric power sector are being actively discussed. Taking into account the global trends regarding the abandonment of fossil fuels, decarbonisation and achieving climate neutrality [9], most experts consider the reconstruction of the damaged conventional energy infrastructure to be impractical. The vision of restoring electric power sector in the post-war period is based on large-scale RE development. Achieving this goal will be challenging and require setting ambitious goals, improving energy legislation, attracting large amounts of investment, establishing cooperation with international partners, etc.

Given the above, the main goal of this paper is to study the problems of maintaining Ukraine's grid reliability under the rapid growth of renewable electricity share and the necessary steps for the resilient reconstruction of the electric power sector in the post-war period. The recommendations will be given based on the research of trends in RE deployment in the pre-war period, the impact of the war on Ukraine's energy sector and the shortcomings of the state policy in the RE field.

Therefore, the novelty of the research is the set of recommendations for RE development in Ukraine's electric power sector in the post-war period, which includes the key policy, market, investment, and social measures needed for RE transition. Even though the paper is focused on analysing the Ukrainian electric power sector, the outcomes of this case study can be interesting for other countries. In particular, the multi-component strategy for RE advancement in Ukraine can be used by the states that experienced energy infrastructure destruction due to military conflicts (like Siria, Afghanistan, etc.) and are looking for effective RE policy solutions for its renewal. In addition, developing countries suffering from deep economic crises, with high levels of energy poverty, energy inefficiency, or insufficient electricity infrastructure development in peacetime but willing to build RE future for their national economies can benefit from this research.

2. Operating Ukraine's electric power system under the rapid growth of renewable electricity share in the pre-war period

State support policy for RE promotion in Ukraine was introduced in 2009. Its foundation was establishing long-term goals for increasing renewable electricity share and implementing economic mechanisms to encourage electricity generation from RES. The main driver of RE development is the feed-in tariff (FIT), the high rates of which contributed to rapid deployment of RE capacities and increasing renewable electricity share in the country's electricity mix (Table 1).

A feature of RE development in Ukraine was the considerable predominance in the structure of RE capacities of SPPs and WPPs. The data in Table 1 show that as of the end of 2021, 78.5% and 17.4% of the installed capacity of RE facilities were SPPs and WPPs, respectively. Of the total renewable electricity generated in 2021, 60.4% was generated by SPPs and 30.3% by WPPs.

It should be noted that electricity generation based on SPPs and WPPs is unstable and difficult to predict. Until 2018, adding such electricity to the grid did not negatively impact electric power system operation due to its relatively small share. However, its further growth in the following years against the background of the inflexibility of Ukraine's electric power system (since nuclear power plants (NPPs) cover more than 50% of electricity demand) led to the need for additional balancing capacities, where among other power facilities, the coal-fired thermal power plants were used [10]. This situation led to the emergence of the so-called 'green-coal paradox' – the need to increase coal generation while increasing the capacities of SPPs and WPPs. Therefore, the further

Table 1: Trends in RE development in Ukraine in 2015-2021 [5]

Type of RE plants	2015	2016	2017	2018	2019	2020	2021
	Number of RE power plants, units						
SPPs	356	1239	3203	7848	22820	31044	46102
WPPs	13	16	20	30	69	77	88
Bioenergy plants	16	18	27	43	64	71	82
Small hydropower plants	114	125	137	149	157	159	163
Total	385	1398	3387	8070	23110	31351	46453
	The installed capacity of RE power plants, MW						
SPPs	434	548	793	1545	5505	6893	7568
WPPs	426	438	465	533	1170	1314	1673
Bioenergy plants	52	59	73	97	181	212	276
Small hydropower plants	87	90	95	99	104	117	122
Total	999	1135	1417	2274	6960	8536	9639
	Amount of generated electricity, GWh						
SPPs	475	496	737	1193	3235	6725	7581
WPPs	974	925	974	1181	2022	3252	3804
Bioenergy plants	141	169	194	279	436	750	941
Small hydropower plants	172	189	195	242	242	209	216
Total	1762	1779	2100	2895	5935	10936	12542
	The share of electricity from RES in the total electricity mix, %						
Total	4.3	5.6	7.0	8.0	8.6	11.3	13.8

expansion of RE capacities began to lead to increasing emissions by coal-fired power plants.

It is evident that RE development in such a way has become questionable regarding the electric power sector decarbonisation and its use as the primary tool for achieving climate goals. It contributed to revising RE energy policy measures, however, their implementation was hindered by the uncertainty caused by the COVID-19 pandemic and later by the war.

During 2019–2020, RE continued to demonstrate rapid growth against the lack of reforms regarding the effective integration of renewable electricity into the grid and quarantine restrictions under the COVID-19 pandemic. The last ones significantly reduced the demand for electricity in Ukraine, which became an additional challenge for the effective operation of the electric power system. Thus, in 2020, a decrease in electricity consumption was related to almost all groups of consumers [11]. To the problem of the decrease in electricity demand was added a reduction in its exports since quarantine measures caused a decline in electricity demand in the importing countries [12].

To solve the problem of balancing the electric power system and maintaining the course to further RE development, the government decided to shut down 4 power units of Ukrainian NPPs and transfer the 8 to work at reduced capacity [13]. Since NPPs generate the cheapest electricity in the country, and electricity from RES is purchased at the high FIT, it negatively impacted the growth of the weighted average cost of electricity. As a result, in 2020, a "Memorandum of understanding on the settlement of problematic issues in the RE sector" was signed between the government and renewable electricity producers, according to which the producers accepted the terms of voluntary FIT reduction. Thus, for SPPs it was reduced by 15%, and for wind – by 7.5% [14]. Such forced measures harmed the investors' confidence, who are not the first to face a change in legislative norms in the RE market.

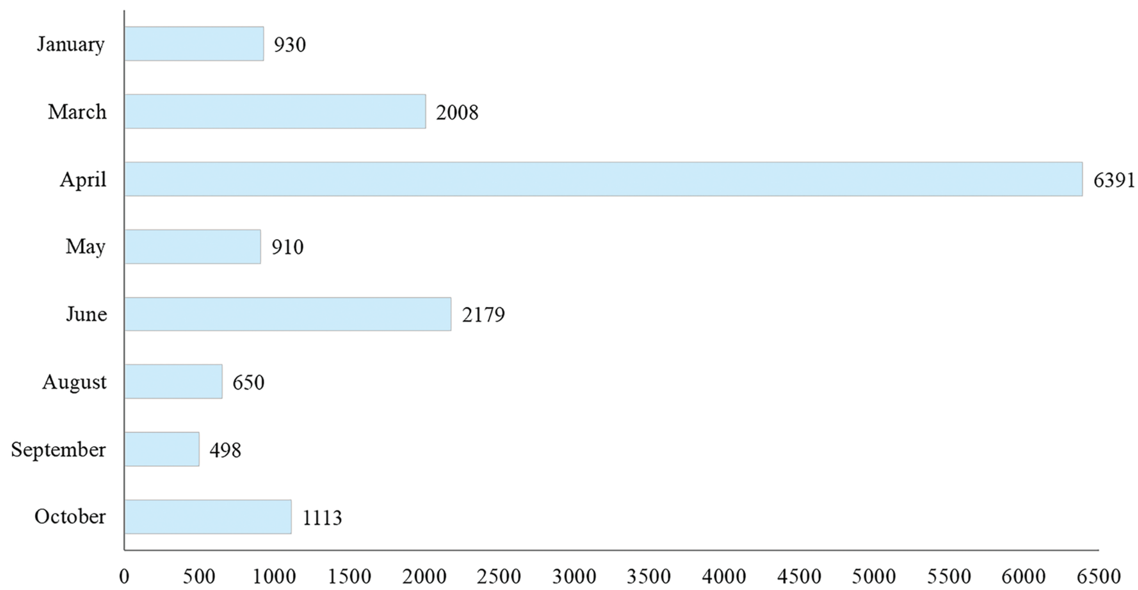

Figure 1: Limitation of electricity generation by SPPs and WPPs in 2020, MW [15]

However, more than the applied measures to limit generation by NPPs were needed to operate the electric power system efficiently. As a result, the system operator NEC "Ukrenergo" was forced to significantly limit electricity generation by SPPs and WPPs during the year (Fig. 1).

As quarantine restrictions eased, the number of cases of limitation of electricity generation by SPPs and WPPs in 2021 decreased but still occurred [15].

Therefore, in the pre-war period, the declared long-term goals for RE development and implemented support mechanisms caused the rapid deployment of RE facilities. However, the lack of energy policy measures to increase the electric power system's flexibility caused some challenges to its effective operation under high renewable electricity penetration. So, it can be argued that in the pre-war period, RE development in Ukraine's electric power sector reached a plateau effect, and the subsequent significant increase in RE capacities required severe changes in energy policy.

3. Operating Ukraine's electric power system during the war-time: challenges for RE development

The Russian military intervention became especially noticeable for Ukraine's electric power sector since one of its features was the full-scale destruction and occupation of energy facilities. However, although the shelling of the energy infrastructure started from the beginning of the war, its intensity from February 22 to October 10, 2022, did not have a critical impact on the electricity shortage in the electric power system. During the first 7 months of the war, the main challenge was electricity surplus due to the decrease in demand, as about 2.6 million Ukrainians left the country and many industrial enterprises stopped their activities [16].

One of the measures to stabilise the electric power system was the limitation of electricity generation by SPPs and WPPs. Thus, the limitation of only SPPs for March-May 2022 was 573 GWh (30% of potential generation); in financial terms, it amounted to EUR 80 million [17]. Although the state undertook to compensate electricity producers for such limitations, they were paid with a significant delay and not in the total amount [18].

In addition to limitations of renewable electricity generation, the RE sector suffered from state policy measures implemented in response to financial challenges caused by the war. After the beginning of the war, the level of payments for consumed electricity decreased by about a third compared to the pre-war period. It led to a decrease in revenues, at the expense of which payments to electricity producers from RES under the FIT are made. In this regard, the Order "On calculations in the electricity market" for the duration of martial law in Ukraine, established a new procedure for payments for electricity generated by industrial RE power plants [19]. Thus, for solar and wind electricity producers, the level of payments was set at 15% of the weighted average FIT rate for 2021, for hydropower – 35%, biogas – 40%, and biomass – 60%. The indicated payments level was insufficient even to ensure operational activity and maintain the financial liquidity of generating companies [20].

The legislative changes also affected the RE power plants installed in the residential sector. In April 2022, the Resolution "On the peculiarities of determining the amount and carrying out calculations for the electricity generated by RE power plants of households during the martial law in Ukraine", provided for only partial payment at the FIT, was adopted [21]. It was assumed that households would start receiving the remaining funds 2 months after the end of martial law. Since the government was forced to extend martial law repeatedly, it led to the accumulation of substantial debts to the owners of RE power plants.

While the situation with arrears of payments under the FIT remained unchanged, the problem with the electricity surplus in the electric power system radically changed. Starting from October 10, 2022, massive damaging energy facilities has become one of the main goals of Russia. Shelling took place in all regions of Ukraine, which proves the deliberate destruction of the energy infrastructure throughout the country.

Thus, due to targeted strikes on energy facilities and territories occupation, as of April 2023, more than 50% of energy infrastructure was destroyed, damaged, or occupied (Fig. 2).

In the conventional energy sector, one of the most notable losses was the occupation of the Zaporizhia NPP (6000 MW), which is the largest in Europe and the sixth in the world by installed capacity [22]. It provided about 20% of electricity generation in Ukraine [23]. The big catastrophe was caused by the Russian military's detonation of the Kakhovka hydropower plant (334.8 MW) on June 6, 2023. As a result of the explosion, Ukraine lost 1500-2000 GWh of annual electricity generation and the Kakhovka Reservoir, with a volume of 18.2 thousand m^3, which supplied water to 4 regions of Ukraine and the annexed Crimean Peninsula. In addition, several thermal power plants with a total installed capacity of about 6300 MW remain in the occupied territories.

At the same time, severe damage was done to the RE sector. As a result of the war, Ukraine lost about 90% of WPPs due to their high concentration in the southeastern regions, where active hostilities are taking

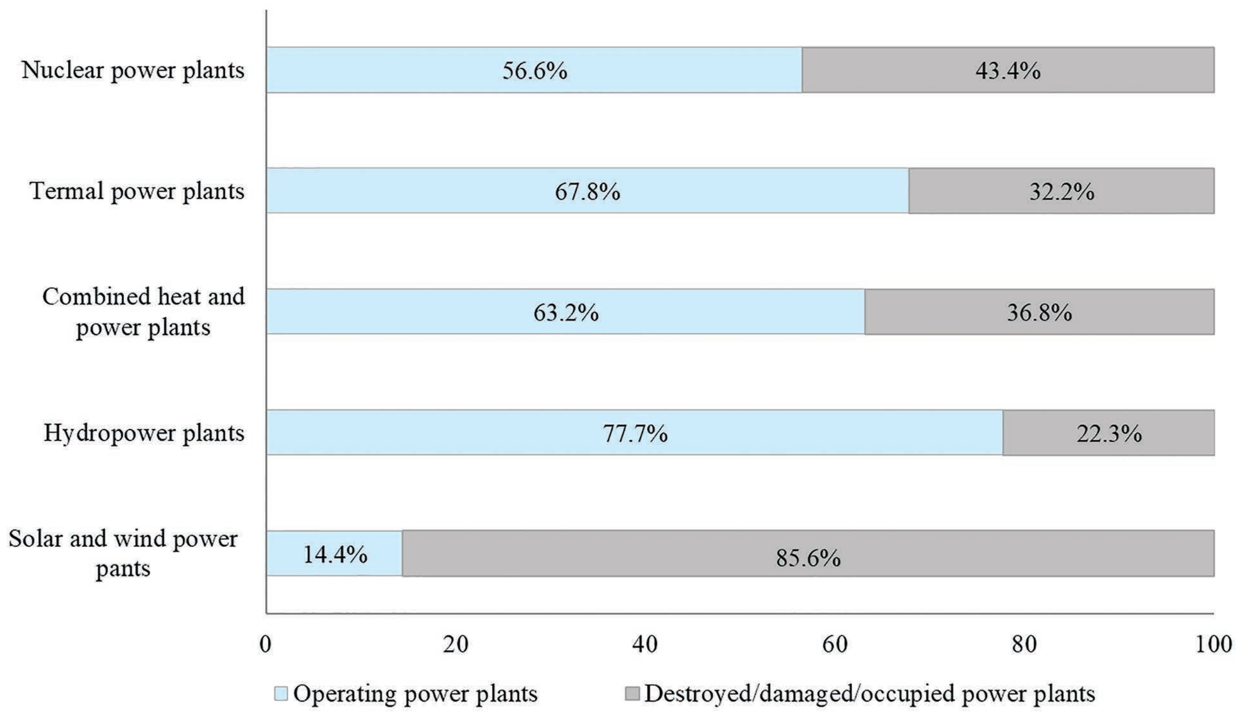

Figure 2: Destroyed, damaged, occupied, and operating power plants in Ukraine as of April 2023 [6]

place [24]. The placement of SPPs in Ukraine is more geographically decentralised, which minimised their losses and amounted to 30% of all SPPs as of August 2023.

Thus, the Russian military aggression has caused significant damage to the Ukrainian power sector, which cannot be fully assessed today, as the military actions are still ongoing. Restoring the destroyed outdated conventional power plants in the post-war period will not make sense. Given this, Ukraine's electric power sector reconstruction will be based mainly on RE, rapid and effective development of which will require the implementation of appropriate measures.

4. Towards sustainable reconstruction of Ukraine's electric power sector in the post-war period: necessary steps

Large-scale RE development in the post-war period will only be possible with significant improvement of policy, market, investment, and social measures described in the following sections.

4.1 Required policy measures for rebuilding Ukraine's electric power sector based on RE

One of the key approaches to accelerating RE transition in the post-war period will be the implementation of appropriate policy measures aimed at the effective deployment of RE facilities. The main measures include implementing green auctions and net billing, developing balancing and energy storage capacities, regulating the structure of RE technologies and their geographical location, and fostering domestic equipment production for the RE industry. A more detailed justification for the necessity of implementing the specified measures is described in the subsections below.

4.1.1. Implementation of green auctions to promote RE development in the industrial sector

Implementing the green auctions mechanism is one of the key measures required to be implemented for the effective deployment of RE facilities in the industrial sector. One of the critical advantages of auctions compared to the FIT is the creation of competition between participants in the RE market. Competition makes it possible to determine the market price for renewable electricity, which will be more profitable for final consumers and the state. In addition, green auctions are a flexible mechanism that can be adapted depending on the needs of the electricity market in a specific period. It is worth noting that the necessary legislative changes for implementing this mechanism have already been prepared in Ukraine [25], however, was not implemented.

Under the green auctions, on a competitive basis, investors who get state support for renewable electricity generation within set annual quotas (MW of installed capacity) established by the government for developing specific RE technologies, are determined. Support based on the results of the green auctions is carried out by guaranteeing the purchase of the entire amount of generated electricity at the auction price. The auction price is the price of 1 kWh offered by the business entity that is the auction winner. It is worth noting that the government has formed indicative forecast indicators of annual quotas for supporting RE development until 2025 [26]. However, in the post-war period, they will require a radical revision due to the significant destruction of RE plants and energy infrastructure due to the war.

The law [25] provides for mandatory participation in green auctions for investors who plan to construct WPPs with an installed capacity of more than 5 MW and SPPs with a more than 1 MW capacity. Other business entities that intend to generate electricity from RES can use the FIT or participate in auctions voluntarily.

The main disadvantage of auctions is the risk of investors refusing to implement RE projects due to a low auction price. It should be noted that the law [25] provides certain sanctions, namely the deprivation of the right to participate in further auctions for one year for the business entity that won the auction but refused to implement the investment project. However, the specified legal norm is not strict enough to reduce potential risks. In addition, there is a risk of the market monopolisation.

Thus, in addition to accelerating this mechanism implementation, the government's actions should be aimed at revising the forecast indicators of annual quotas to support RE development in the post-war period and improving the legislation regarding the elimination of shortcomings mentioned above.

4.1.2 Implementation of net billing to promote RE development in the household sector

Effective RE development in the post-war period will also require a revision of the mechanisms of its promotion in the residential sector. Nowadays, state support for RE development in households is based on the FIT. Using the high FITs guaranteed a quick payback of investment projects, contributing to the rapid deployment of SPPs in households. The economically unjustified approach for its formation focused energy policy not on prosumerism but on obtaining profits by the owners of SPPs from the sale of surplus electricity not consumed for their own needs [27].

This approach to forming the FIT policy led to some abuses by households and technical and financial challenges related to financing payments under the FIT. To increase revenue from the sale of surplus electricity, increasing the capacity of SPPs beyond the amount allowed by law, setting the equipment to maximum output, absent or low amounts of electricity consumption were observed [28]. The most significant abuses were related to electricity consumption amount, which in about 40% of households that installed SPPs are at the level of less than 10 kWh/month, while the average monthly electricity consumption of one household in Ukraine is about 168 kWh [29]. Therefore, further implementation of such FIT policy model in households will not be able to ensure prosumerism development, strengthening energy independence and stability of the electric power system. Therefore, it should be revised.

As evidenced by world experience, applying high FITs only at the initial stages of the RE technologies development is advisable to give them an appropriate impetus for growth. Reducing and replacing them with other mechanisms that do not require state support is reasonable in the future [30]. Applying the FIT for wind and hybrid solar-wind plants in Ukraine's residential sector is expedient since their development has not reached the desired scale. However, the FITs for such generating facilities should be economically justified.

For further development of SPPs, which have already become widespread in Ukrainian households, it is advisable to use such support schemes as net billing. It aims to cover households' electricity consumption and not require additional financial costs from the state budget and electricity consumers. Effective implementation this mechanism will require revision of electricity prices in terms of their maximum approximation to the market level. It is worth noting that today, the state subsidises electricity prices for Ukraine's households. As of June 2023, the household electricity tariff is 0.65 EUR/kWh. The low electricity tariffs can become a significant barrier to further RE development in households, as they can negatively affect the profitability of investment projects under net billing. Therefore, the transition to a new support scheme requires a creating favourable economic conditions for its effective implementation.

4.1.3 Development of balancing and energy storage capacities

Large-scale RE development in the post-war period will require the effective integration of renewable electricity into the grid. As noted above, the Ukrainian RE sector is based on SPPs and WPPs, the peak of electricity generation based on which does not coincide with consumption peak. Accordingly, in specific periods, there is surplus electricity. Given this, the further growth of electricity share from RES will require the commissioning of balancing and energy storage capacities, which allow to eliminate the daily imbalance between electricity supply and demand.

It is worth noting that even before the war, due to the electric power system's inflexibility, adding a significant amount of electricity generated by SPPs and WPPs was problematic. In the post-war period, the situation will only worsen without the necessary regulatory changes, as shelling of the energy infrastructure led to the destruction of a significant share of balancing facilities.

The pumped storage, gas turbine, and gas-piston power plants are the most promising types of balancing capacities that should be developed. At the same time, considering further European integration processes, which require the electricity sectors to come as close as possible to climate neutrality, it is advisable to abandon coal-fired thermal power plants, which are also used to balance Ukraine's electric power system.

The development of pumped storage power plants is considered the most reasonable. Today, 3 such power plants with a total installed capacity of 4.31 GW operate in Ukraine. In pre-war times, it was planned to complete the construction of some pumped storage power plants; however, implementing such projects faced many barriers, including the complexity of technical expertise, environmental challenges, lack of access to high-tech equipment and investment [3]. To effectively implement such projects in the post-war period, the government should make efforts to minimise these barriers.

The operation of gas turbine and gas-piston power plants, which can quickly change the generation amount depending on the need for electricity, is a practical approach to balancing the electric power system. Despite the dependence on the import of natural gas, Ukraine can provide such power plants with gas by increasing its own production. At the same time, in the future, gas power plants can be switched to biomethane, the production potential of which in Ukraine, as an agricultural country, is significant (21.8 billion m^3/year) [32, 33].

Along with constructing balancing capacities, special attention should be paid to energy storage systems. It should be noted that today, this segment is practically undeveloped in Ukraine. As of 2023, only one energy storage system with a capacity of 1 MW was commissioned, which now is located on the occupied territory. The lack of legislation in this field was the main reason that restrained energy storage systems development. Only in 2022, the Law "On Amendments to Certain Laws of Ukraine Regarding the Development of Energy Storage Systems" [34], which regulates the rights and obligations of business entities in the energy storage market, was adopted.

To accelerate energy storage systems development, it is advisable to implement motivational levers for their construction to the current mechanisms for RE support. In particular, the green auctions can be adapted to achieve this goal. It is expedient to provide support quotas to new producers of renewable electricity, provided they ensure the parallel construction of energy storage systems of the required capacity.

Therefore, the development of balancing and energy storage capacities is an integral condition for effective RE development in the post-war period. Improving the legislation in this field, setting clear goals and requirements not only growth of renewable electricity share but also providing additional capacities for balancing the electric power system, will contribute to its flexibility, sustainable and safe electricity supply.

4.1.4 Regulation of the structure of RE technologies and their geographical location

One of the shortcomings of the RE policy in Ukraine is the lack of regulation of the structure of RE technologies and the geographical location of RE power capacities. On the one hand, this makes it possible to achieve the indicative goals for the growth of renewable electricity share more quickly; on the other hand, it leads to severe issues in the electric power sector.

Thus, in the absence of state regulation of the structure of RE technologies, investment flows in the RE sector were directed to the most mature technologies with the highest profitability. It led to the predominance in the RE structure of SPPs and WPPs. On the one hand, the instability of electricity generation based on them significantly aggravated the problem of balancing the electric power system; on the other hand, the high cost of electricity generation led to an increase in the financial burden on the state budget and final electricity consumers.

In turn, the consequences of focusing SPPs and WPPs installation based on the criterion of only economic feasibility in regions with the most attractive climatic potential led not only to such problems as a surplus of installed capacity in particular territories, increased load on local power grids, but also to significant losses RE facilities in due to the Russian intervention. Thus, on the Crimean Peninsula, which has the best climatic conditions for solar and wind generation, as of the end of 2013, 75% of SPPs and 70% of WPPs of their total installed capacity in Ukraine were located. As a result, after the Crimea annexation in 2014, Ukraine lost a considerable share of RE facilities. After the peninsula's annexation, SPPs and WPPs were primarily located in the southeastern regions of continental Ukraine, where now hostilities are taking place. As a result, due to the war, in 2022, about 90% of WPPs and 30% of SPPs were destroyed or occupied [35].

It is possible to solve the abovementioned problems by adapting the green auctions mechanism. Thus, to regulate the structure of RE technologies under this mechanism, it is advisable to allocate quotas according to the priority of specific RE technologies development, considering their impact on the electric power system operation. To regulate the geographical placement of RE power plants, it is advisable to distribute quotas by region, considering the potential of various RE technologies development, the degree of satisfaction of the energy needs, etc.

4.1.5 Fostering the production of domestic equipment for the RE industry

An important direction for RE development in the post-war period is to promote domestic production of equipment for the RE sector. It is worth noting that Ukraine has a significant potential for localisation of such manufacture. Nowadays, two factories "Kvazar" and "Prolog

Semicor", which are able to provide a full cycle of solar panel production operate in Ukraine. However, due to constant changes in legislation, political, and economic instability, they face difficulties in doing their business. The most significant challenge is fierce competition with foreign-made solar panels, which intensified in 2019 after introducing tax incentives for their import. Due to the introduction of tax benefits, the prices of imported panels became 20% lower than domestic ones. As a result, companies were forced to reorient their activities mainly to the assembly of solar panels in Ukraine from imported components.

In addition, some companies in Ukraine specialise in producing equipment for WPPs, namely "Wind Parks" and "Fuhrlander Wind technology". However, although the production of small wind turbines with a capacity of 1 to 25 kW has been established in Ukraine, there is practically no demand for them within the country due to the underdevelopment of this segment in the residential sector. As a result, Ukrainian manufacturers mainly export them to other countries [36].

It should be noted that the impetus for developing domestic production of equipment for the RE sector was the introduction of an allowance to the FIT for compliance with the level of use of Ukrainian-made equipment in RE projects implementation. Thus, according to [3], when using Ukrainian-made equipment at 30% and 50%, the allowance to the FIT is 5% and 10%, respectively. Today, this norm applies to industrial RE power plants but does not apply to RE capacities in households. Therefore, an additional incentive for developing Ukrainian equipment for the RE industry can be using this norm for RE facilities in the residential sector. Regarding the growth of demand for small wind turbines, it is essential to review the FITs for electricity generated by wind and solar-wind power plants of households to ensure an acceptable payback period for such projects. For the segment of domestic equipment for solar energy, the abolition or reduction of tax incentives for importing foreign solar panels is of utmost importance.

Thus, Ukraine has a significant potential for producing equipment for the RE sector, and with needed investments, can occupy a worthy place in the world market of components for the RE industry. Improving the state policy to support such equipment production along with the creation of a stable business environment, will not only accelerate RE development in Ukraine but will also contribute to creating new jobs, which is extremely important in the post-war country's recovery.

4.2 Market and investment measures for accelerating RE development in the post-war period

The post-war reconstruction of the electricity sector and implementing the above measures will require adopting new decisions to liberalise the electricity market, attract investments, technical assistance from international organisations and donor countries, etc.

Market liberalisation is vital to the recovery of Ukraine's electric power sector. It envisages introducing competitive market mechanisms, reducing state intervention, and increasing the participation of the private sector. It is worth noting that Ukraine has already progressed in this direction. In particular, the law "On the Electricity Market" was adopted [3], which, marked the transition to the bilateral contract market. In addition, an independent regulator – the National Commission for State Regulation of Energy and Public Utilities was created to separate the functions of electricity generation, supply, and transmission. In addition, in 2023, the law "On Amendments to Certain Laws of Ukraine as to Prevention of Abuse in the Wholesale Energy Markets" was adopted [37], which envisages implementing the Regulation on Wholesale Energy Market Integrity and Transparency.

One of the essential steps towards increasing Ukraine's electricity market liberalisation is introducing the Fourth EU Energy Package. Among other things, it will increase the level of generation and consumption of electricity from RES and raise the role of various associations such as RE cooperatives, joint electricity producers, etc. Another measure aimed at further liberalisation of the electricity market is the need to increase price caps during peak hours, which will increase liquidity in the market and allow electricity to be imported from the EU, where prices are traditionally higher.

The reconstruction of Ukraine's energy sector will require attracting significant amounts of investment [38]. However, today, access to investments is complicated by the military conflict. In the post-war period, risk could persist due to the neighbourhood with Russia. In 2022, Ukraine has prioritised several directions for energy sector recovery, with the necessary investments of EUR 114 billion (Table 2).

The indicated directions provide for the renewal of the energy sector in the context of modern low-carbon

Table 2: Priority areas for investments under the low-carbon energy transition of Ukraine [38]

Item	Investments needed, EUR billion
Building 5-10 GW RES and ~3.5 GW hydro and hydro pumped capacities	15
Increasing nuclear capacity (prolongation, safety, higher utilisation of existing capacities, and 2 GW new units at Khmelnytskyi NPP)	14
Biofuels market development (liquid, gaseous)	4.2
Localising nuclear value chain (sustainable uranium mining, plant for fuel production, waste storage)	1.3
Increasing gas production from existing fields, developing tight gas fields	18
Build 1.5–2 GW peaker and 0.7–1 GW of storage	2.8
Localizing RE equipment production	2
Building 15 GW electrolyser capacities	7
Developing hydrogen transport infrastructure (including export infrastructure)	2
Building 30+ GW RES for hydrogen production	38
Building smart grids	5-10

technologies. However, the investments indicated in Table 2 may not be sufficient since the war is ongoing that can lead to greater losses of energy facilities.

It is worth noting that during the war, Ukraine actively seeks opportunities to attract investments from international and domestic sources to overcome the financing deficit. A significant contribution in attracting grants from international organisations and initiatives to support energy infrastructure projects was made by the Energy Community, which launched the Ukraine Energy Support Fund. As of June 2023, the Fund purchased equipment worth EUR 220 million [39]. At this stage, the funds are directed to solve urgent energy problems, particularly purchasing critical energy equipment. In the post-war period, it will be essential to continue accumulating financial resources under this Fund and direct them to sustainable energy transition measures. In addition, attracting funds that the EU has pledged to allocate in the form of grants and loans for reconstructing crucial Ukraine's economy sectors for 4 years, starting in 2024, will significantly help rebuild the electric power sector. The total amount of promised assistance is EUR 50 billion. The Ukraine Facility mechanism must be created to apply funds [40], designed to provide short- and medium-term financing Ukraine's needs for reconstruction during 2024-2027.

One of the approaches to attract more financial resources, the electricity tariff for households was increased to 0.65 EUR/kWh in 2023. However, it is still lower than the prices for electricity generation in the country. It is worth noting that electricity tariffs in Ukraine remain extremely low compared to other European countries [41]. Therefore, their gradual increase to the market level is necessary for more efficient operating the electricity sector.

Ukraine must strengthen its capacity to create and manage national climate and other funds to support the low-carbon transition. It is planned to create the State Fund for Decarbonisation and Energy Efficiency Transformation to finance energy efficiency, RE, and energy storage projects in Ukraine [42]. It is expected that the Fund will start working in 2024, and the source of funds will be a tax on carbon emissions from stationary sources of pollution [43].

Recovery and sustainable electricity sector transition will be accompanied by political, military, economic, and market challenges that require careful consideration and strategic planning. Market liberalisation, attracting domestic and international investments, and creating and managing national funds are critical essential in the post-war RE transition.

4.3 Social actions towards effective RE transition in the post-war period

The energy transition must focus on environmental and economic aspects and prioritise social sustainability [44, 45]. Energy transformation through the prism of social justice will ensure fair access to affordable, reliable, and clean energy. It is worth noting that the social dimension of the sustainable energy transition is complex and includes many aspects among which affordability of energy resources and energy poverty, structural unemployment, creating new jobs, etc.

One of the key aspect is addressing energy poverty, where vulnerable populations have limited access to energy services. There is no official definition of "energy poverty" in Ukrainian legislation; therefore, monitoring this phenomenon is complicated. However, it is obvious that manifestations of energy poverty will increase in Ukraine due to the war. It is worth noting that in the first quarter of 2023, the official unemployment rate was about 20%, while before the war, it was 10% [46]. At the same time, during 2022, real wages in Ukraine decreased by 11.9% [46]. Given the above, the government's actions should be directed to financial and non-financial support for vulnerable consumers.

It should be noted that state support for vulnerable consumers in Ukraine was relevant and relatively widespread in the pre-war period. Among the non-financial support measures, a ban on disconnecting vulnerable consumers from heating systems during the heating season and financial subsidies and benefits were introduced. As of the beginning of 2021, more than 3.1 million households in Ukraine received housing subsidies. Another 1.8 million consumers received discounts from 25 to 100% on the payment of utility services, depending on the recipient category [46]. It is advisable to continue to subsidise the most vulnerable and low-income consumers to reduce energy poverty manifestations.

The appearance of structural unemployment in the post-war period is inevitable. During the post-war reconstruction, Ukraine plans to localise equipment production for the RE industry. The reorientation of the electricity sector will require new qualified workers. Therefore, as a response to structural changes, the organisation of training programs for the retraining of laid-off workers and implementing new educational programs to provide students with the necessary knowledge and skills in RE, energy efficiency, smart grids fields will be highly relevant [47].

To achieve social sustainability in the post-war RE transformation, involving new stakeholders is essential. Joint decision-making and public consultations will contribute to higher involvement of the community in the post-war electricity sector recovery. It is worth noting that several competent non-governmental organisations whose activities are related to RE transition are already operating in Ukraine. With their increased activity, RE transformation will become more democratic and sensitive to society's needs.

Thus, the social dimension of sustainability is a fundamental factor in RE transition. Developing new educational programs, creating jobs, engaging new stakeholders, and implementing effective communication strategies will ensure just resilient RE transformation in the post-war period.

5. Conclusion

The Russian invasion caused colossal damage to Ukrainian energy infrastructure that became a trigger for discussing the possibilities of creating a new, sustainable Ukraine's electricity sector in the process of post-war recovery. The common vision of Ukrainian and international experts is the large-scale involvement of RE technologies in electricity generation processes in the medium- and long-term perspectives. However, analysing the trends in RE development in the pre-war period and its impact on the electric power system operation proves that achieving the specified goal can be challenging. In 2021, RE development reached a plateau effect, and further deployment of RE capacities due to the impossibility of adding renewable electricity to Ukraine's inflexible electric power system became practically impossible. The destruction and occupation of the energy facilities in the war-time period only worsened the situation, bringing additional problems in the post-war electricity sector reconstruction. Introducing new support mechanisms for RE development in the industrial and residential sectors, developing balancing and energy storage capacities, and regulating the structure and geographical placement of RE capacities, along with other market, investment, and social measures explored in this paper, will accelerate RE development, and contribute to resilient and equitable Ukraine's energy future.

The main limitation of the study and, at the same time, its advantage, is its focus on the electricity sector only. On the one hand, focusing on the electricity industry allows for conducting a deep analysis of the phenomena occurring in the field. On the other hand, the presence of close and extensive connections of the sector with other branches of the national economy somehow limits the research outcomes application. Thus, the prospects for further research in this direction are the integration of our findings with strategies developed for other sectors (heating and gas industries, transmission grids, transport, etc.), as, for example, it was done in [48–50]. Moreover, the development of energy storage technologies, as shown in [51], should not be the only way to balance the electric power system with high renewable electricity penetration. Instead, integrating the electricity sector with other energy components to form a smart energy system offers more efficient and cost-effective solutions. It should also be considered for future research.

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