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Lessons of War: Ukraine's Energy Infrastructure Damage, Resilience and Future Opportunities

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Summary:

- Since 2022, the military actions in Ukraine have caused losses to the country's energy infrastructure running into millions; its restoration requires more than USD 47 billion.
- Russia has systematically destroyed the energy infrastructure in order to demoralise the population, obstruct the effective functioning of the Ukrainian military and disrupt the country's economy.
- Despite huge challenges in the winter of 2022/2023, Ukraine managed to maintain its electricity supply in the winter of 2023/2024 thanks to strengthened air defence, international support and efforts to decentralise the power grid.
- Support from the EU, the USA and other countries has included providing technical assistance and supplying repair parts and generators to enable emergency repairs or to maintain power.
- Looking to the future, Ukraine aims not only to restore but also to modernise its energy sector based on the Build Back Better principle, i.e. restoration of the energy system to a better position than it was before.
- In the future, Ukraine also plans to expand the use of renewable energy sources and nuclear energy and integrate into the European energy market.
- Ukraine must continue to modernise the energy sector, seek decentralisation and expand its production volumes of renewable resources such as biomethane and green

hydrogen. At the same time, it is important to use its existing competencies in the development of nuclear energy.

- The European Union and the international community must continue to support Ukraine in order to ensure its energy stability, primarily through the provision of air defence systems but also by investing in and promoting energy sector reforms in Ukraine.
- Other countries should rely on Ukraine's lessons in safeguarding their infrastructure - ensuring adequate reserves of critical repair components, passive defense measures for equipment in case of war, proper training of specialists, and potentially further expanding the electricity grid to ensure its reliability in case of losing some infrastructure.

After the start of the Russian invasion of Ukraine in 2022, energy security became a particularly sensitive issue for Europe and seeking ways to abandon Russian energy resources became a priority. Events such as the bombing of the Nord Stream gas pipeline in September 2022 continued to increase attention to this topic in Europe. Such actions in times of war especially attract the attention of Western governments and associations. On the one hand, this is due to the direct impact on the security and economy of European countries, such as the abandonment of Russian natural resources or the aforementioned Nord Stream attack. On the other hand, the importance of energy in the war has also been heightened by Russia's reckless and systematic destruction of

Ukraine's energy infrastructure in order to intimidate and break the will of Ukrainians to oppose Russian forces. In addition, Russia's behaviour towards the nuclear infrastructure is "reckless" to say the least, such as not complying with safety requirements at the entrances to the Chernobyl nuclear power plant at the beginning of the invasion, and later, by deploying military equipment in the territory of the Zaporizhzhia Nuclear Power Plant and posing a threat to the cooling of the reactors and the general operation of the power plant.

During this war, Ukrainians have suffered a lot of damage and losses in energy while Russia continues its threats to intensify its attacks. In this situation, the population of Ukraine has experienced multiple blackouts and Russia's attacks on Ukraine's generation (i.e. electricity production) capacity and electricity transmission network resulted in blackouts reported even in neighbouring Moldova. However, Ukrainians have managed to withstand all Russian missile attacks – their air defence has strengthened significantly, a large amount of support was received from EU countries (including Lithuania) and the USA, and the decentralisation of the power grid also begun. The decrease in total electricity consumption in the country, as a result of the war, has also helped to balance the energy system.

However, the damage to the energy infrastructure, due to Russia's aggression, is estimated at billions of euros. It will take several years to fully repair the energy system from the losses and will require considerable resources. Ukraine sets itself the goal not only to repair the destroyed energy infrastructure but to restore it according to the Build Back Better principle. That is why it is relevant to analyse the damage suffered by Ukraine's energy system, how it managed to restore the damaged infrastructure, what are the main further challenges and opportunities for the development of the energy sector, and how else can the EU and Lithuania help Ukraine. To perform this analysis, in addition to the publicly available information, anonymised interviews were conducted with Ukrainian and Lithuanian experts who helped to assess the most important current and future challenges of Ukraine.

Damage to the Ukrainian energy system

Although attacks on Ukraine's infrastructure have been ongoing since the beginning of the war, the day that marks perhaps the most fundamental shift in Russian strategy can be considered to be 10 October 2022. On that day, Russia launched its first massive aerial missile attack against Ukraine's electricity transmission grid and generation capacity. It can be speculated that at the start of the war, at the end of February 2022, Russia had other goals and did not expect this war to last this long. In the early stages of the war, there was no need for Russia to destroy the energy system of Ukraine, hoping to quickly take over wider territories of this country or at least imposing its own political control. At the same time, the aftermath of a destroyed transmission system or other facilities in the approaching summer would not have given the desired effect. Whereas, during the winter, this infrastructure plays a more important role, and the lack of necessary resources, such as water, gas, heat and electricity, significantly demoralises and complicates the functioning of the country in the cold period of the year.

The 2022/2023 winter was the most sensitive for Ukraine's energy system during this war. Attacks were regular, using typical Russian cruise and ballistic missiles, and drones (including the notorious Iranian Shahed drones), and artillery were deployed along the borders and front lines. The biggest weakness of Ukraine at that time was the lack of air defence systems and ammunition. President V. Zelensky repeatedly appealed to Western allies to provide support with air defence systems – not only modern radars or medium-range NASAMS, IRIS-T or SAMP/T Mamba platforms and long-range American Patriot but also surviving air defence systems like MIM 23 Hawk (1960 technology) or Soviet-made S-125, S-200 or S-300. Although these systems are old and do not have the capabilities of modern air defence systems, their biggest advantage is the availability of ammunition reserves.

“

Colleagues told how the Russians launched eight air attack waves against one energy infrastructure facility. Our forces defended and repulsed seven attacks, but when the eighth began, they ran out of ammunition. At the same time, no highly sophisticated air defence system was used for defence. Therefore, ammunition and defence systems are what our energy infrastructure needs the most” –

Interview with a Ukrainian
energy expert

Since the end of winter 2022/2023, attacks on Ukrainian energy infrastructure have decreased significantly. The summers of 2022 and 2023 were less favourable for such attacks, and would not produce the same effect. The most important event of summer 2023 involved the destruction of the Nova Kachovka dam near the city of Kherson, presumably carried out to reduce the Ukrainians' ability to launch a counterattack on the left bank of the Dnieper. The dam was an important object not only for its generative capacity but also for shaping the landscape and ecosystem in the region. The increased current discharged a large amount of dirty water and various garbage into the Black Sea, disrupted not only electricity but also the water supply to a large part of southern Ukraine (including Crimea, which was supplied with water from the Kachovka reservoir). The resulting flood after the explosion of the dam inundated a number of settlements in the Kherson administrative region, both in the Ukrainian and Russian-controlled parts. The reservoir formed by the dam was also important in ensuring the cooling of the Zaporizhzhia Nuclear Power Plant. Its destruction can be considered the most damaging single event since the beginning of the invasion in February 2022.

The winter of 2023/2024 was not as difficult for Ukraine's energy infrastructure as the previous one, as Russian forces did not carry out systematic attacks against energy facilities. One of the interviewed Ukrainian energy experts said, comparing the two winters: “*This year we have*

experienced fewer attacks on energy infrastructure. They (the Russians – the author) continue to attack civil infrastructure, but there are certainly fewer attacks on the energy infrastructure than last year”. This has been confirmed by another Lithuanian energy expert, who stated that in Ukraine “*we managed to avoid mass disconnection of electricity consumers this year*”. This can also be seen from the frequency of attacks – in the winter of 2023/2024, only three mass air attacks were recorded: one in September, one in December, and the last one this winter in January. On the other hand, the December attack was seen by the Ukrainians as the biggest attack since the beginning of the Russian invasion of Ukraine. According to the information provided by the Ukrainian Air Force, by the end of 2023, Russia had launched 7,400 missiles and 3,700 Shahed drones against various targets in Ukraine. However, the situation was remedied by Western support to Ukraine – before this winter, Ukraine acquired and integrated more air defence systems allowing it to protect the most important objects. Therefore, the improved situation in the energy sector has been determined by: 1) Russia's change of tactics; 2) strengthened Ukrainian air defence after receiving more air defence support from the West; 3) lessons learned by the Ukrainians and the strengthening of grid resilience, which allowed the country to prevent massive power outages.

Several international organisations, including the World Bank, have calculated the monetary damages Ukrainians have incurred. The objects that suffered the most damage are electricity generation capacities, transmission and distribution networks and oil storage facilities. The gas infrastructure also suffered a lot of damage, but it is more difficult to measure because Ukraine does not provide information about the condition of its gas production facilities. However, according to the Energy Charter International assessment, Russian forces control 15% of Ukraine's natural gas reserves and at least 150 gas production facilities. Most of them did not operate in the Kharkiv region due to the ongoing hostilities in this region. A Ukrainian energy expert said during the interview that one of the Ukrainian gas sector companies has already suffered USD 1 billion in property damages. At the same time, the expert said that Ukraine managed to avoid more damage to its natural gas production facilities: “*They (the Russians – the author) attacked gas production, but they did not know which objects to destroy, and they may have been*

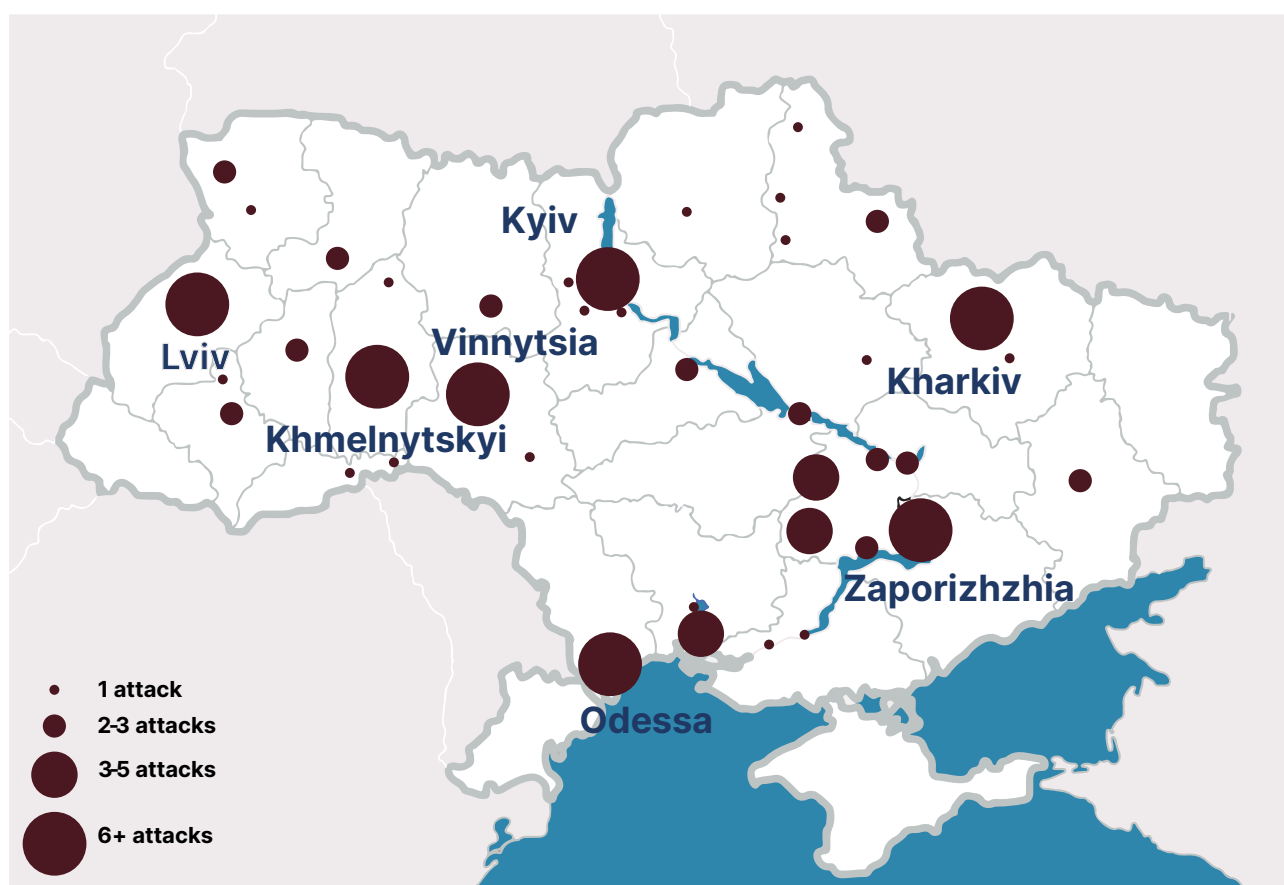


Figure 1 Frequency (days) of Russian Attacks Targeting Ukraine's Electrical Energy Infrastructure from 10 October 2022 to 1 January 2024.

Sources – media news, social media posts, LiveMapUA and ACLED maps. Remark – artillery shelling along the front line and at the borders was also frequent, but it is not included here due to their large number and difficulty in distinguishing the exact target.

using strange or outdated maps. They attacked a property that was no longer in use.” According to the World Bank’s assessment, damage to the gas sector (excluding gas extraction) amounted to USD 1.3 billion. Meanwhile, the electricity sector suffered the most damage – USD 7.5 billion. The Russian forces targeted power generation and transmission capacities the most, so the distribution network suffered the least. Coal and gas power plants were affected, transmission grid substations were destroyed and renewable resource generation was also targeted (i.e. wind and solar, and also including the destruction of the Nova Kachovka dam).

Attacks on oil infrastructure are discussed somewhat less in the public domain. Mainstream reports about attacks on oil production and storage facilities and transmission plants emphasise successful attacks by Ukrainians on Russian territory rather than Russian actions in Ukraine. However, such infrastructure and resources in both countries have a greater impact on the capabilities

of the military. It is oil and fuel reserves that determine whether units can manoeuvre and carry out actions with military equipment. Therefore, the destruction of such objects can often be a painful blow to both Russian and Ukrainian forces, complicating the logistics of the most important energy resources to the front. According to the assessment of the previously mentioned World Bank report, damages in the oil sector amounted to USD 1.7 billion. Russian forces have mainly targeted Ukrainian fuel depots, oil refineries and other similar infrastructure.

According to the general assessment of the World Bank study, Ukraine suffered damage to the energy infrastructure (excluding heat supply networks) amounting to USD 10.6 billion. It is additionally estimated that due to the war and its consequences, the electricity, gas extraction, gas transmission, coal mining, fuel and oil sectors in Ukraine have lost revenues in the amount of USD 54 billion. USD 47 billion will be required in the next 10 years for the reconstruction of the energy infrastructure in

Damage to the energy infrastructure of the Ukrainian regions in USD billions (from 24/02/2022 to 31/12/2023)

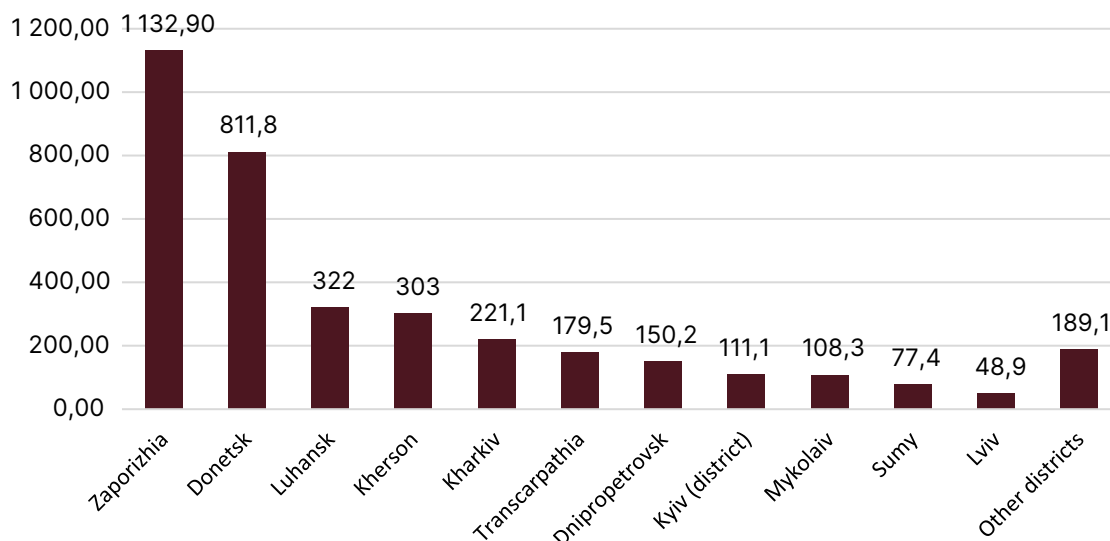


Figure 2 Source – [World Bank's damage assessment report](#). Remark - **the total damage is estimated at USD 10.6 billion, but only damage that is clearly attributable to specific regions (USD 3.7 billion) is shown.** The remaining damage, not shown in the chart, amounts to USD 6.9 billion.

Funds required by Ukraine for the restoration of the energy sector until 2033, in billions of USD

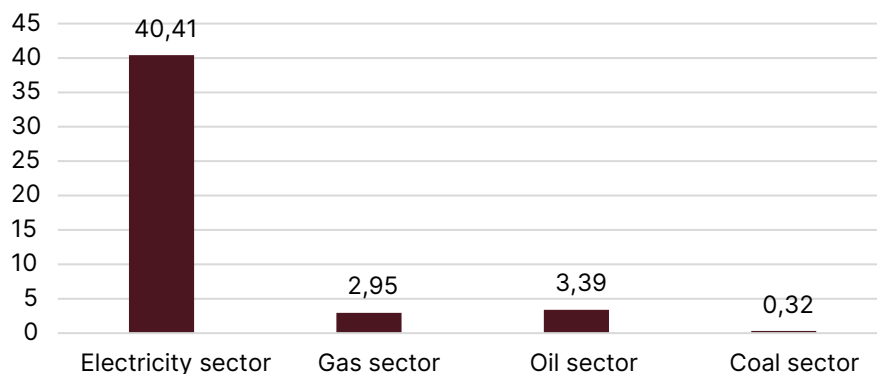


Figure 3 Source – [World Bank's damage assessment report](#).

accordance with the Build Back Better principle, of which USD 40 billion will be needed to restore generating capacity. However, while damage to infrastructure and even lost revenue can be calculated, it is difficult or even impossible to estimate the lives of Ukrainian energy workers and soldiers who defended the infrastructure, and

various other professionals whose lives were lost in attacks or extreme situations while trying to keep the infrastructure running. An [example](#) of energy workers affected by the conflict happened on 3 May 2023, when three electricians were killed by a Russian rocket artillery attack while carrying out repair work in the vicinity of Kherson.

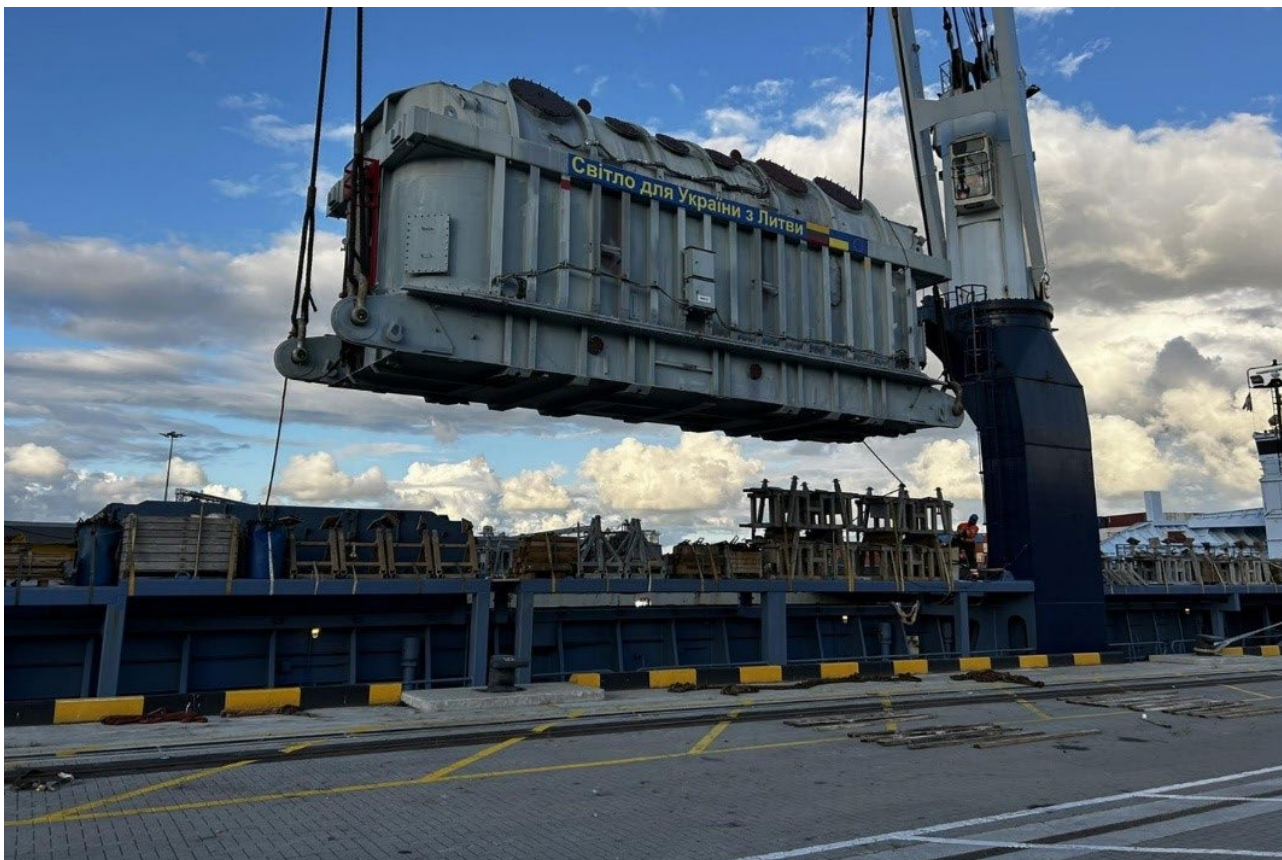


Figure 4 One of the autotransformers provided by Lithuania to Ukraine, photo [source](#) – Ministry of Energy of the Republic of Lithuania

Urgent repairs and assistance provided to Ukraine

With the start of the first mass attacks against Ukraine's energy infrastructure in winter 2022/2023, many cities and districts of the country experienced complete power outages. This was caused mainly by the damage to the electricity transmission network, as it limited the ability for electricity to flow even from more distant, unaffected Ukrainian energy generation facilities. The Ukrainians have turned to their allies for help and support to keep the critical infrastructure system operating, mostly through the supply of rechargeable generators. However, parts were also provided for network repair works, with Lithuania also offering significant assistance in this regard.

The main goal of Ukrainian energy specialists was to carry out emergency repairs in order to restore at least minimal grid operation. Since the transmission system equipment was often the target, Ukraine mostly needed the elements necessary to support

the operation of this equipment, such as medium and high-voltage transformers. Lithuania had just the right opportunity to help Ukraine, because in preparation for synchronisation with the synchronous zone of Continental Europe Networks (CEN) and updating the infrastructure of the transmission system, existing autotransformers – large and expensive devices that allow for voltage regulation like reducing high voltage to a lower voltage, suitable for the transmission of electricity to the distribution network – were being replaced. As a result, Lithuania [provided](#) Ukraine with as many as two powerful 200 megavolt-ampere (MVA) autotransformers for the restoration of the transmission network, along with other types of assistance, which in the middle of 2023 was estimated at EUR 11 million.

When the Russian attacks began, the European Union was the main supplier of the variety of previously mentioned generators. According to EU [data](#), at the end of 2023, more than 5,500 generators were handed over to Ukraine. The last aid package of 500 generators was worth EUR 16.5 million, and the power of the generators ranged from a smaller capacity of 12.5 kVA to 1000 kVA, able to provide a full supply of electricity to hospitals

in the event of a power outage. In total, the EU provided support from the Energy Community Fund amounting to EUR 332 million to cover Ukraine's most essential energy needs, such as emergency repairs. Another very important element that helped ensure overall greater security of the Ukrainian energy system was the urgent synchronisation with CEN synchronous zone at the beginning of the war. When the war started, Ukraine was in the process of testing synchronisation with CEN, but this test quickly turned into real action. Both Ukrainian energy experts who were interviewed emphasised the importance of this event. One of them describing the process said that *"integration with ENTSO-E (European Network of Transmission System Operators – author) /.../ was a big event, the most important one for security"*. Synchronisation helped Ukraine to manage its transmission network more freely and autonomously and, most importantly, to desynchronise from the Russian-controlled IPS/UPS synchronous zone, no longer providing this country with critical information about the electricity system.

The United States has also greatly helped Ukraine's energy industry. According to USAID's mid-2023 data, the USA has provided assistance to Ukraine that has amounted to more than USD 475 million. The assistance included more than 3,600 generators, 85+ kilometres of steel and pipes to repair the heat networks, 60 excavators, a 28 MW mobile power generation plant, 360 heated tents and various other forms of support that have either allowed for the repair of damaged networks or temporarily provided necessary supplies. This, along with the support provided by the EU, has allowed Ukrainians to carry out critical repairs, and the transferred generators have made it possible for smaller communities and critical facilities, such as hospitals, to secure an uninterrupted supply of electricity.

Another very important part of the assistance to Ukrainian energy was military assistance, i.e. air defence systems. As mentioned earlier, it was the air defence systems that were most requested from the West, as not only do they protect the most important infrastructure but they also ensure air defence for the Ukrainian military units at the front. In order to protect critical energy and other civilian objects, it was and still is important for Ukrainians to receive not only more expensive medium-range and long-range air defence systems, like NASAMS or Patriot, but also short-range systems and guns, which are cheaper and therefore more suitable for protection against smaller drone attacks than missile systems.

The table below lists the air defence assistance Ukraine has received from allies since October 2022 (when the airstrikes intensified. Before then, air defence support was less crucial, mainly for short-range systems called MANPADS) according to data collected by Oryx. The table does not include information about MANPADS and radars, which are equally important for ensuring integrated layered air defence.

Countries	Air defence systems provided
USA	MIM-23 HAWK; AN/TWQ-1 Avengers; Patriot; Vampire (counter UAS); NASAMS; Cheetah PRTLs
United Kingdom	ASRAAM SAM; Terrahawk Paladin AA
Germany	IRIS-T; Patriot; Gepard; Oerlikon Skynex
Poland	S-125 NEWA SC; 9K33 Osa-AK(M); Osa-AKM-P1; ZSU-23-4 Shilka; Hibneryt; ZSU-23-2CP; AZP S-60
France	Crotale NG; SAMP/T; MISTRAL
Italy	Skyguard Aspide; Spada; SAMP/T
Czech Republic	2K12M2 Kub-M2s
Slovakia	2K12M2 Kub-M2s; Zastava M55; Zastava M75
Netherlands	Patriot; Viktor mobile AA; Bofors 40L70
Spain	Spada 2000; MIM-23 Hawk Phase I/III
Norway	NASAMS; CORTEX Typhon
Lithuania	NASAMS; Bofors 40L70
Canada	NASAMS

After assessing Ukraine's capabilities and Russia's efforts to destroy critical infrastructure, it can be stated that the Ukrainians have been able to ensure the operation of their energy system well. It is important to understand that it is impossible to fully protect all available infrastructure – Ukraine is too big to protect its entire territory with air defence systems. It lacks sufficient aviation capabilities, and at the same time, along the borders and the front, the country is vulnerable not only to air attacks but also to artillery fire. The most important factors that can help promptly deal with the damage suffered are the appropriate formation of reserves of energy resources and critical parts, along with a well-trained and capable corps of specialists who are able to respond quickly. In the case of Ukraine, the country benefited most from the international assistance received, and as one of the interviewed Ukrainian energy experts said, also from the reserves of old and obsolete, not the best condition equipment. However, as summed up by a Lithuanian energy expert answering the questions: *"Given the current circumstances, the Ukrainian energy sector specialists managed to perform a unique historical*

deed – to balance the functioning of the energy sector, ensure the timely repair of necessary energy equipment and respond promptly to the continuously changing tactics of Russia in attacking the infrastructure of the energy sector.”

How can Ukrainians be supported at this time?

Although the intensity of Russian attacks on energy infrastructure decreased in the winter of 2023/2024, Ukraine still faces a number of challenges in maintaining its critical infrastructure. This is due to the fact that only mainly emergency and urgent works and repairs have been carried out, allowing Ukraine to solve the problems of the first necessity. However, long-term damage to Ukraine remains, and it will take years to resolve it. According to one of the interviewed Ukrainian energy experts: *“[...] what the engineers are telling me is that the way the network operates at the moment is not sustainable. Everything has to be modernised and fixed, often rebuilding from scratch. The network was built by the Soviets and does not function well.”*

One of the support measures is to continue to provide Ukrainians with the necessary financial and material assistance to carry out network maintenance. However, an important problem identified by one of the Ukrainian energy experts is the lack of investments in Ukraine: *“From my point of view, the most important thing is to support businesses to return and operate in the Ukrainian energy sector.”* The respondent further identified that *“guarantees of support from other national governments would help business [...] EU companies will come to Ukraine if they are insured against risks by national governments and thus will bring their expertise”*. Indeed, it is difficult to attract foreign investments to the country in the background of war when it is not clear how the conflict will end and there is a real threat that the infrastructure objects you are developing will suffer due to Russian aggression. In addition, a considerable part of the labour force is engaged – mobilised, employed in the defence industry, in supporting the most important functions of the state, or has simply fled the country. Nevertheless, Ukraine as a country has a lot to offer even against the background of war – when the invasion started in 2022, foreign investments in Ukraine fell by about 13 times; however, there is great potential for the reconstruction of Ukraine. It is estimated

that at least USD 400 billion will be needed for the reconstruction. As mentioned earlier, USD 47 billion will be required to restore the energy sector alone. Ukraine also has a lot of [mineral resources](#) needed by the EU – not only natural gas but also lithium, graphite, iron and uranium – all elements that are extremely necessary for the development of energy facilities and the transition to less polluting forms of energy production. Therefore, certain guarantees for businesses to invest at least in the safer regions of Ukraine could already help Europe to secure the satisfaction of its metal needs and would provide Ukraine with much-needed economic support.

Another area of assistance to Ukraine discussed during the interview is EU legal support. Ukraine is currently working to reform its energy sector to meet EU standards of transparency and market liberalisation. In times of war, it is difficult to balance the needs of liberalisation and security. However, this is very important for Ukraine in order to join the EU as soon as possible – the reforms must be carried out as carefully and urgently as possible in order to obtain full approval for membership in the European Union. As one of the interviewed Ukrainian energy experts stated: *“What the EU can do is encourage us to carry out market liberalisation. All of Ukraine is currently considered a vulnerable consumer, but there are different levels of vulnerability. For example, at the moment we see consumption growth in Ukraine in some real estate segments. Therefore, there is a need for a constructive dialogue with the EU about which sectors can be liberalised. It would provide liquidity to the market.”* Liberalisation of the market was one of Lithuania's main aspirations when breaking away from the Russian energy monopoly. But Ukraine's situation is different from when Lithuania sought liberalisation – it is not dependent on Russian gas or electricity supply, and no Russian-controlled energy entities operate in the country. Therefore, the liberalisation of certain segments would possibly be easier than it was for Lithuania. The European Union could help facilitate this for Ukraine, provide expert insights into which sectors are optimal for this in wartime conditions and potentially provide the necessary financial support or facilitate entry of EU energy companies to the Ukrainian market.

On the other hand, one of the Ukrainian energy experts said that certain pressure from the EU poses challenges for Ukraine in a state of war and is related to the implementation of green technologies: *“When Ukraine is asked to implement green technologies in its current situation, when we do not even know how much territory we will*

control – it is not good /.../ self-sufficiency is the most important thing for Ukraine right now, while the EU tells us that it will not support our companies that invest in natural gas. This is a dogmatic and wrong approach, and the context of the war should be taken into account.” The European Union aims to implement the Green Deal and not promote any polluting technologies to combat climate change. Naturally, this policy also applies to Ukraine, which is seeking EU membership. However, it is important to consider the fact that predictable generators, like gas power plants, could really help Ukraine at this time when a large part of the energy infrastructure is damaged. Much of the generation capacity is damaged, destroyed or occupied and inoperable, like the largest nuclear power plant in Europe – Zaporizhzhia Nuclear Power Plant. Flexibility and the application of concessions to the Ukrainian natural gas sector would be a significant help from the EU, for example, by setting clear deadlines for the application of such concessions. Moreover, it should be considered that according to the updated EU [taxonomy](#), natural gas power plants (together with nuclear) are considered transitional green technologies and can be considered green investments.

Finally, Ukraine still faces challenges on the issue of physical security. Naturally, it remains important for the country to obtain the necessary amount of air defence systems and ammunition to protect its critical infrastructure and its soldiers at the front as widely as possible. However, as a interviewed Lithuanian energy expert stated, the Ukrainians are currently asking for specialised transport and demining works in the recaptured territories. The Ukrainian demining coalition, [organised](#) in the Lithuanian NATO format, can partially meet these needs of Ukraine. As more territories are reclaimed in the future, demining needs will only grow.

The future of Ukraine's energy sector

Despite the losses, Ukraine has great potential to play an important role in the future of Europe. This country has always been important for the transit of natural gas from Russia to many countries. By abandoning Russia's energy resources, Ukraine can partially take over the role of natural gas supplier. Natural gas and oil deposits in the country can be [found](#) in the northeast (mostly in the Kharkiv and Poltava regions) and in the Black Sea to the south

and west of Crimea. Known Ukrainian natural gas reserves [amounted to](#) over 1 trillion cubic meters, the largest in Europe after Norway and Russia. Since the infrastructure for the supply of natural gas to the EU countries already exists, it would be possible to speed up the extraction of these resources in peacetime and easily supply them to Europe. Ukraine also has a significant amount of natural gas storage – all EU storage facilities can [hold](#) around 1,100 TWh of natural gas, while Ukraine has storage with a capacity of more than 300 TWh. Ukraine's large storage capacity allows neighbouring countries to use it as well, and EU countries [used](#) this opportunity last winter.

However, as the EU and other countries around the world seek to decarbonise, there are questions about the need for long-term demand for natural gas. Natural gas is less polluting for the production of electricity and heat than coal, but it will still have to be abandoned in the long run if we want to reduce methane and CO₂ emissions into the atmosphere. One of the measures that can help at the moment is the reorientation to biomethane production, i.e. methane, which is produced from the decomposition processes of renewable resources (such as various agricultural waste). The advantage of biomethane is that it can be supplied to the natural gas network right now, without the need for any transformations of pipelines, compressors and other infrastructure. The main limiting factor is the availability of sufficient waste amount to produce green gas. [According](#) to Ukrainian experts, in 2030 they could already produce 1 billion cubic meters of biomethane, which would be about 5% of Ukraine's current natural gas consumption.

The Ukrainian government also seems to appreciate its country's potential to supply biomethane to the EU. In March 2024, the Verkhovna Rada (Supreme Council) of Ukraine [adopted](#) a law allowing the export of this gas to Europe. The law was drafted as part of a memorandum on strategic partnership in the development of biomethane, hydrogen and other synthetic gases.

Another area where Ukraine can develop its capabilities is electrification through the development of renewable resources and nuclear power plants. Ukraine has not been a leading country in the development of renewable energy resources (RES) for a long time, but in recent years, before the war, a significant increase in the installed capacity of RES has been observed. In 2018, in

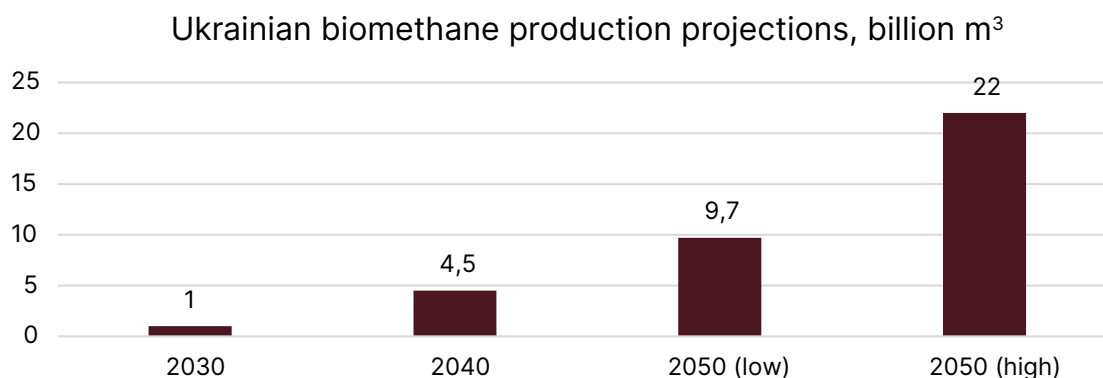


Figure 5 Ukrainian biomethane production projections, sources [1](#), [2](#)

Ukraine, [there were](#) 1.7 GW of installed power RES resources (not counting hydropower), and in 2021, the installed capacity had already reached 8.1 GW, with the majority of this capacity (78%) being solar power plants. However, part of the solar and the absolute majority of wind farms were occupied by Russian forces or are currently in the zone of military operations, so the production of RES electricity has been limited due to the war.

In the future, the development of renewable energy in Ukraine is almost inevitable, as is the case in other countries that are striving for decarbonisation. In addition, electricity produced by solar and wind farms is cheaper than if produced from coal or natural gas plants. With some of Ukraine's coal or natural gas power plants destroyed or severely damaged, switching to RES

makes even more sense. On the other hand, it would also help to ensure a more decentralised electricity grid. [According](#) to the International Energy Charter, Ukraine has one of the largest technical potentials of renewable energy capacity in South-Eastern Europe – up to 438 GW of onshore wind, 250 GW of offshore wind and 83 GW of installed capacity of solar power plants can be developed. The Ukrainian government has plans to take advantage of this by announcing the [goal](#) that 50% of Ukraine's electricity production will come from RES resources by 2035.

The rapid development of wind and electricity generation would also help another EU-supported initiative – the production of green hydrogen – to gain impetus. Green hydrogen is hydrogen that is produced using electricity from renewable

Installed capacity of electricity generation
of Ukraine by source, GW

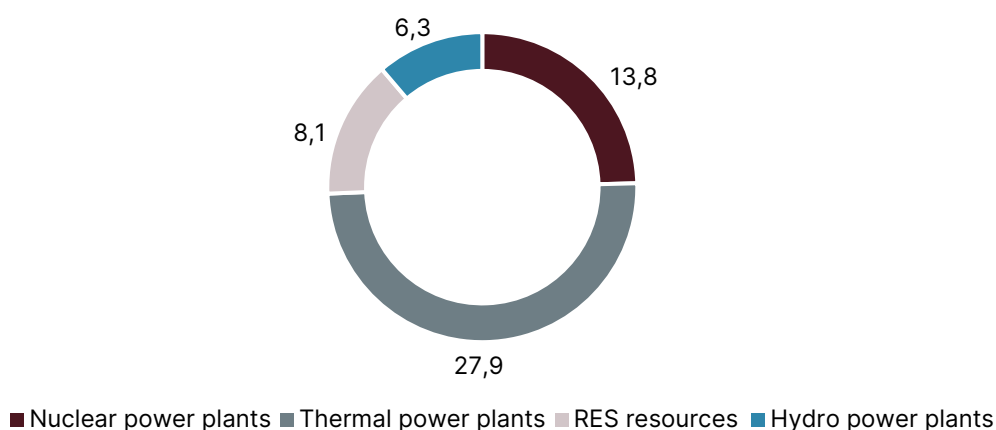


Figure 6 Installed capacity of electricity generation of Ukraine by source. [BDO data](#).

resources (such as wind, solar and hydropower) through electrolysis. For Europe, which is seeking to decarbonise, hydrogen would play one of the main roles in this process, as it can be produced from the surplus of RES electricity generation and then used for the production of various synthetic fuels (such as methanol), in industries and for electricity generation. Current forecasts [show](#) that Germany alone will require between 100 and 300 TWh of hydrogen per year by 2040, and by 2050 – between 400 and 800 TWh. Germany will have to import a large part of its hydrogen. Ukraine could become one of the suppliers of green hydrogen to those European countries that lack it. According to the 40×40 initiative plans [outlined](#) by the German agency DENA for mid-2021, Ukraine could have 9.8 GW of green hydrogen electrolysis facilities by 2030, of which 8 GW would produce hydrogen for the EU market. This would allow the production of 21 TWh of hydrogen per year and cover 12% of the EU's demand by 2030. Electrolysis facilities would also help Ukraine balance the power grid, ensuring system stability. However, the potential of hydrogen in this country is likely to depend on the outcome of the war. The greatest potential for RES development is in the south and east of the country, i.e. in the territories currently occupied by Russia. Their recovery and repair would allow for the construction of a greater number and more efficient solar and wind power plants.

Finally, Ukraine has traditionally sought to exploit its existing nuclear power competencies and further develop nuclear power plants. At the end of 2023, the Ukrainian state-owned company Energoatom signed an [agreement](#) with the American company Westinghouse on the construction of the AP1000 model reactor. Energoatom plans to have nine of these reactors, which would essentially allow them to replace most of the existing Soviet nuclear infrastructure with a newer Western one. Ukraine has ambitions to [develop](#) an entire chain of nuclear fuel production, which would allow the country not only to supply fuel for its own needs but also to export it to other countries. However, it is small modular reactors (SMR) that might play the biggest role in future of nuclear energy. At least three companies are interested in or have already signed agreements for potential SMR development in Ukraine – [Holtec](#), [Rolls Royce](#) and [Westinghouse](#). Ukraine has a large number of nuclear energy specialists; therefore, the development of SMR is favourable in this country. In the future, the country may be one of the most important countries for the

production of SMR, since the economic efficiency of these reactors depends on the possibility of mass production. Ukraine could develop an infrastructure that produces SMR reactors or their parts, not only for domestic needs but also for export.

Conclusions

It is the third year of the war, which will undoubtedly bring new problems for Ukraine, including its energy infrastructure. The first winter of the war was particularly difficult for the energy sector. The lack of air defence systems, and at the same time a certain surprise and the intensity of the campaign, meant that the Ukrainian electrical system was very vulnerable. Power outages have become almost the norm in big cities like Kyiv. This was the way Russia sought to influence the fighting spirit of Ukrainians during the cold period, to encourage the flow of refugees from Ukraine, but it was equally important to disrupt the general functioning of the state and its economy. There are also active defence industry companies in Ukraine, for which it is critical to ensure the uninterrupted supply of energy resources for the production of ammunition or equipment. Air defence weapons that were gradually provided and trained to operate by the West were perhaps the key factor in protecting critical infrastructure. The effects of its absorption can be seen from the second winter of the war – Ukraine managed to avoid massive power outages, and more electricity was exported than imported to neighbouring countries. The changing tactics of Russia, which focused more on the destruction of military (command posts and logistics) and some civilian infrastructure, conduct of local (regional) attacks and the decreased consumption of energy resources in Ukraine also contributed to this effect.

An important part of this energy crisis is the organisation of critical repair works and the provision of support to Ukraine. The support provided by the European Union, the United States and other countries with generators and other tools made it possible to maintain the electricity supply to at least the most important facilities, such as hospitals, public institutions and schools, even when part of the grid was not functioning. By providing two autotransformers, Lithuania has also made a significant contribution to the restoration of the grid. Meanwhile, Ukraine also seems to be learning from the lessons of the war: at the end of 2023, it [announced](#) that it would purchase as many as 100 high-voltage transformers and store them in Poland

and Romania for use as needed after Russian attacks. However, in the management of the crisis, the most praise can be given to Ukrainian energy, infrastructure and other specialists, who performed urgent repair work even near the front line, with some of them injured or even killed during double-tap attacks.

Although the situation in the winter of 2023/2024 was more favourable, while the war continues, it cannot be resolved and can change quickly. There is currently a resurgence in Russian attacks on energy infrastructure, linked to a potential new Russian offensive. The need for air defence has not disappeared. Ukraine still needs help in securing its infrastructure. At the same time, Ukraine will need millions in new investments to fully restore its damaged infrastructure, demining works await the country in the recaptured territories, and at the same time, the threat of air attacks has not disappeared. This country has the potential to become an important part of the EU energy system in the future due to its available energy sources and other resources. Ukraine already provides gas storage services to Europe. Ukraine has the potential to develop both renewable resources and nuclear energy and potentially contribute to the production or storage of green hydrogen on its territory, as well as export biomethane to the EU. Therefore, support from the EU is very important at the moment – it can help to ensure the future energy stability of Ukraine, and at the same time, the proper implementation of reforms and the development of the energy sector in accordance with the Green Deal supported by Europe.

An important issue that has not been discussed in detail in this article is cyber security – Russian electronic warfare systems also affect the energy infrastructure. However, the extent of damage in this area is not as publicised as extensively as physical damage.

Recommendations

Russia's war in Ukraine and its consequences for energy infrastructure teaches a lesson not only to Ukraine but also to energy sectors of all countries on how to deal with crises like this. Therefore, the following recommendations are grouped into three categories – recommendations for Ukraine; recommendations for the European Union; and general recommendations for infrastructure protection.

1. Recommendations for Ukraine:

1. As is the case in a number of countries, the Ukrainian network is quite centralised, and therefore, vulnerable to attacks. The damage caused by Russia forces Ukraine to rebuild its infrastructure and at the same time provides an opportunity to do it better – by means of decentralisation. Decentralisation would be beneficial in two ways – firstly, it would help to ensure greater security against possible future attacks, and secondly, it would help Ukraine to better integrate renewable resources, since it is likely that their development will be completed in this country as well.
2. Promoting the development of renewable resources is important not only in thinking about the future of Ukraine but also in the current situation, and this must be supported by the Ukrainian government. RES resources can help the aforesaid decentralisation of the grid, but at the same time, as noted by the United States NREL laboratory, solar power plants can significantly contribute to the longer operation of diesel generators (which are important for Ukraine at the moment, when there is still a real threat of power outages).
3. Ukraine has considerable experience and potential in the field of nuclear energy. The country has uranium and is developing nuclear fuel production capacity. This makes it possible to become a supplier of nuclear fuel to other countries, and, while using its competencies, to become one of the most important developers of this energy in Europe. If the development of small modular reactors is successful, Ukraine would be a good location for their development and potential production, thus becoming an important part of the nuclear energy value chain.
4. Ukraine has a lot of potential to expand its energy sector and become one of the energy centres of Europe in the future. However, Ukraine needs to provide a clear vision of how it wants to move and develop its energy sector. An energy strategy up until 2050 is not public: if it is expected to attract foreign investments, the plans need to be communicated at least at a high level. It is understandable that during the war, extremely high detailing is not desirable,

but it is difficult to talk about attracting foreign investors if there are no clear and easily accessible guidelines on how Ukraine itself sees its energy future.

2. Recommendations for the European Union:

1. The EU must provide more air defence support to Ukraine – all levels of air defence systems and ammunition, which is still lacking. The threat of Russian attacks has not gone away, and protecting critical infrastructure is an important factor in ensuring that Ukraine can operate, defend itself and continue to fight. Joint purchases of EU ammunition and air defence systems would also allow the member states to obtain more supplies of these measures at a lower price.
2. It is not necessary to wait for the end of the war in order to use the potential of Ukraine and allow it to get back on its feet faster. A large number of companies are afraid to invest in Ukraine and develop their business there. However, the EU can provide businesses, willing to invest, with financial guarantees against the risks posed by the war and thus support investments in Ukraine. Undoubtedly, this would help to rebuild the economy of this country more quickly after the end of the war, and at the same time, it would stimulate reforms. However, foreign businesses operating in the country and the experience it brings can often influence the reformation of the legal framework into a more harmonised one with the place where the activity was typically developed until then (i.e. in the territory of the EU).

3. General recommendations for infrastructure protection:

1. Other countries must learn from Ukraine how to protect their critical infrastructure. For example, in Lithuania, due to the small size of the country, it would not be very difficult to damage the most important energy facilities using conventional means, such as artillery. Therefore, it is necessary to ensure an adequate reserve of generators and the most important parts that could be used to carry out network restoration work.

2. The war in Ukraine shows that the electricity transmission network equipment is highly vulnerable, and if one or several key substations are destroyed, it becomes difficult to avoid power supply interruptions. The reason for this is a centralized network in several main substations with few backup lines. States, especially those with critical electricity transmission infrastructure easily accessible to artillery, such as the Baltic countries, should evaluate and potentially support network expansion not only based on production/consumption needs. The network can additionally be expanded to ensure that even if one critical part is destroyed, the stability of the power system can be maintained. Simultaneously, such additional network expansion should involve military representatives to assess where the threat is lowest and where it is most realistic to protect critical infrastructure in case of crisis, considering limited air defense capabilities.
3. In Ukraine, concrete blocks helped protect its network infrastructure equipment. Preparing for the winter of 2023/2024, Ukrainians covered their existing facilities with concrete blocks or even bags of sand. Arranging this permanently during peacetime would not be useful and would likely cause difficulties in maintaining the equipment; however, having a ready supply of covering materials available and knowing how to deploy them properly would be useful. This would make it possible to protect the equipment at least from the simplest shrapnel, which can also cause a lot of damage to the infrastructure.
4. It is very important to have the right number of trained electricians and other specialists ready to act in extreme war situations. This requires coordination of practices and procedures with the military, such as how emergency repairs would be carried out in the event of a military crisis. It is likely that they would be carried out close to enemy forces; therefore, it is important to maintain a high level of preparation of specialists for such situations, conduct exercises and, at the same time, ensure the greatest possible protection of specialists from enemy actions.