Risk of unprecedented nuclear disaster if Russia’s attacks on Ukraine’s electricity system continue

Analysis by Greenpeace Central and Eastern Europe

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Introduction

The nuclear safety and security crisis in Ukraine is entering a uniquely dangerous phase. Russia has targeted Ukraine’s energy infrastructure with military strikes, including its generation capacity and electricity substations. As a direct consequence, Ukraine’s national grid is damaged and weakened to an unprecedented level. Two and half years since Russia’s full-scale invasion, the occupation of Chornobyl in February 2022 and as well as the attack and continuing occupation of the six reactors at the Zaporizhzhia nuclear plant (ZNPP) in March 2022 – it is hard to imagine the energy crisis becoming even more severe. However, as a result of Russia’s war on Ukraine, the entire safety program of Ukraine’s nuclear reactor fleet – a total of 15 reactors - and electricity supply across the nation is at a heightened risk of potentially catastrophic failure. Most at risk are the people and the environment of Ukraine, but there is the potential for much of Europe and beyond to be severely impacted.

The current analysis attempts to explain what risks a war can pose on operational nuclear safety, and shows the possible dire consequences if Russian attacks continue on Ukraine’s remaining electric system.

Recent developments that heightened nuclear risks in Ukraine

While the six Zaporizhzhia reactors under Russian military occupation remain on a cliff edge in terms of safety, they are at least in cold shutdown. As such, even with the loss of electrical power and cooling function, it would be several weeks before the release of radioactive material would be envisaged. The same cannot be said of Ukraine’s nine reactors which continue to operate at Rivne, Khmelnytskyi and South Ukraine. These reactors are currently the primary source of electricity in Ukraine, since the Russian military attacks have incapacitated most of Ukraine's non-nuclear generating capacity, which traditionally helps maintain stability in the power grid.[1]

Recent reports from the President and Foreign Minister of Ukraine have raised the spectre of plans by Russia to further target Ukraine's electricity infrastructure, and in particular the electrical sub stations and nuclear reactor switchyards.[2] Sub stations, which serve for the transmission of electricity, are also vital to maintain the functioning of Ukraine's energy network and to maintain the operation of Ukraine's nuclear reactors.

Since Russia's full-scale invasion in February 2022, Ukraine's energy infrastructure has been under repeated attacks, which on occasions have led to nuclear power plants (NPP) suffering Loss Of Offsite Power (LOOP), including on 22 November 2022.[3] During the period 2022-23, about half of Ukraine's power generation capacity was lost either due to occupation by Russian forces, or because they were destroyed or damaged, and approximately half of the large network substations were damaged by missiles and drones.[4] Remarkably, Ukraine's electricity grid remained functional and still sufficiently robust to withstand severe consequences. This means that the rapid restoration of grid connections to nuclear power plants suffering loss of grid connection was possible, and there was sufficient electricity generation capacity in the grid to allow the restart of shutdown reactors. However, the escalation of Russian attacks from March 2024 meant that by the end of summer 2024, 95 percent of Ukraine's thermal power plants had been destroyed or severely damaged.[5] The attack by Russia on Ukraine's grid on 26

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[1] UKRINFORM, Ukraine in talks with IAEA to have monitoring mission expanded to power substations, 22 September 2024, see https://www.ukrinform.net/rubric-economy/3908359-no-blackout-schedules-to-be-applied-in-ukraine-on-monday-energy-ministry.html

[2] Office of the President of Ukraine, There Can Be No Just Peace Without Ukraine - Speech of the President at the UN General Assembly, 25 September 2024, see https://www.president.gov.ua/en/news/ne-mozhe-buti-spravedlivogo-miru-bez-ukrayini-vistup-prezide-93493l; and, UKRINFORM, Russia preparing strikes on Ukraine's critical nuclear energy facilities – MFA, 23 September 2024, see https://www.ukrinform.net/rubric-ato/3908093-russia-preparing-strikes-on-ukraines-critical-nuclear-energy-facilities-mfa.html

[3] The Russian attack on 23 November led to a decrease in the frequency in the grid, which automatically disconnected from the grid the Rivne, South Ukraine and Khmelnitskyi nuclear power plant reactors, see Statement by Ms. Marta Žiaková, Chairperson of ENSREG, following the Group's 51st meeting of 24 November 2022, see www.ensreg.eu/sites/default/files/attachments/chairs_statement_ensreg_51.pdf. The reactors at Rivne, South Ukraine and Khmelnitskyy remained in project mode or house load, not generating electricity for the grid, but sufficient to power the site. The power supply for Zaporizhzhia reactors was also stopped and the plant operated with emergency diesel generators, see SNRIU, The situation at Ukrainian nuclear power plants 23 November, 2022, 22:20hrs, see https://snriu.gov.ua/news/sytuatsiia-na-ukrainskykh-aes

[4] International Energy Agency, Ukraine's Energy Security and the Coming Winter
An energy action plan for Ukraine and its partners, September 2024, see https://www.iea.org/reports/ukraines-energy-security-and-the-coming-winter

[5] Iryna Doronina, Marie-Louise, Marcelo Galleguillos, Vasyl Doronin, Adrienne Grêt-Regamey, Tobias S. Schmidt, and Florian Egli, Why renewables should be at the center of rebuilding the Ukrainian electricity system, Technical University of Munich, 20 September 2024, see

August 2024 forced four reactors to be disconnected from the grid and therefore relied solely on onsite power. If Russian attacks continue to target Ukraine's electric system, the future scenario for this winter is for more severe consequences in terms of energy supply across Ukraine.

Current State of Electric System of Ukraine

Ukraine is currently generating electricity at a total of nine nuclear reactors - four at Rivne, near Varash, Rivne Oblast; two at Khmelnytskyi, Khmelnytskyi Oblast; and three at South Ukraine Nuclear Plant in Mykolaiv Oblast. They have a total capacity of 7.8 GW.[6] Ukraine's six reactors at Zaporizhzhia Nuclear Power Plant (ZNPP), with a total capacity of 6GW, have been shut-down for two years, following the attack and occupation of the plant by Russian armed forces and Russian State Nuclear Corporation, Rosatom, in March 2022. By 2024, Russia had destroyed 90 percent of thermal power plants and 40 percent of hydroelectric power plants.[7] Ukraine's three operating nuclear power plants currently generate the largest share of the electricity of Ukraine.[8]

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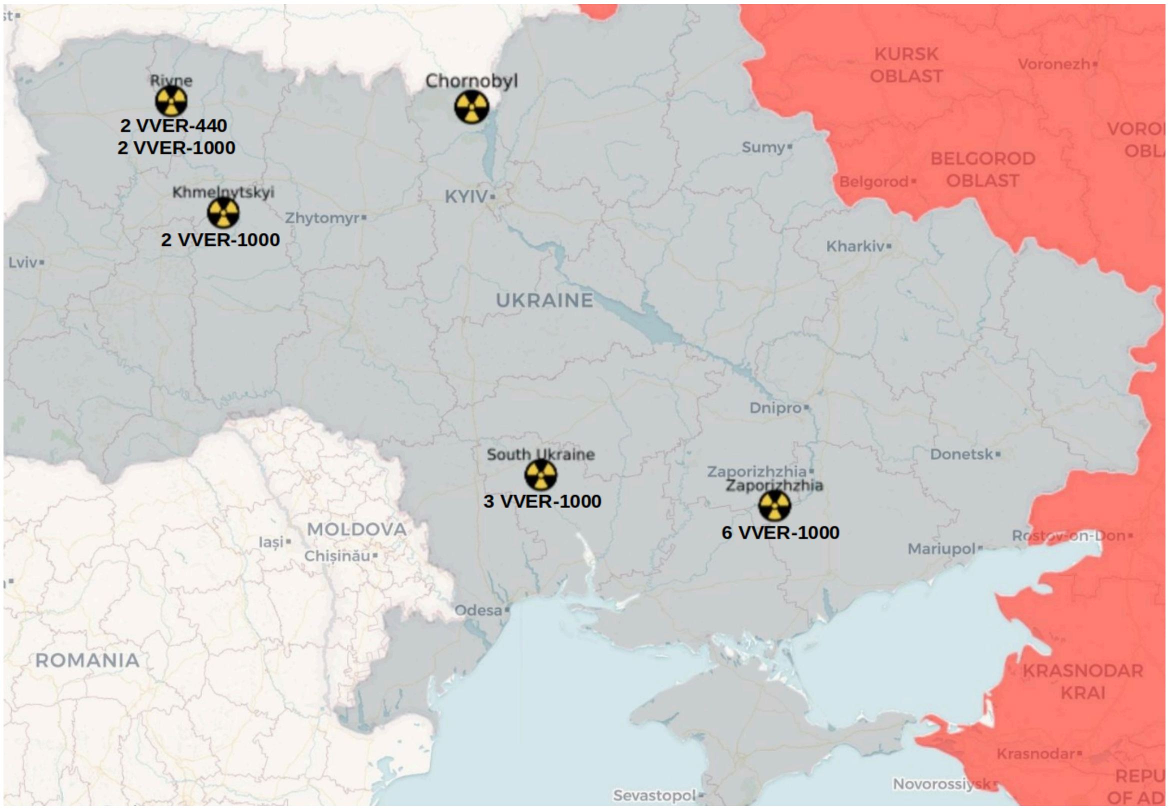
https://www.tum.de/en/news-and-events/all-news/press-releases/details/how-ukraine-can-rebuild-its-energy-system

[6] WNISR, World Nuclear Status Report 2024, Mycle Schneider, et al, September 2024, see https://www.worldnuclearreport.org/IMG/pdf/wnisr2024-v1.pdf

[7] Forbes Ukraine, The IAEA will monitor key Ukrainian substations for the first time, Anastasia Dayna, 13 September 2024, see https://forbes.ua/company/magate-vpershe-bude-monitoriti-ukrainski-klyuchovi-pidstantsii-chi-zakhistit-tse-ikh-vid-obstriliv-rf-a-krainu-vid-totalnogo-blekautu-13092024-23608

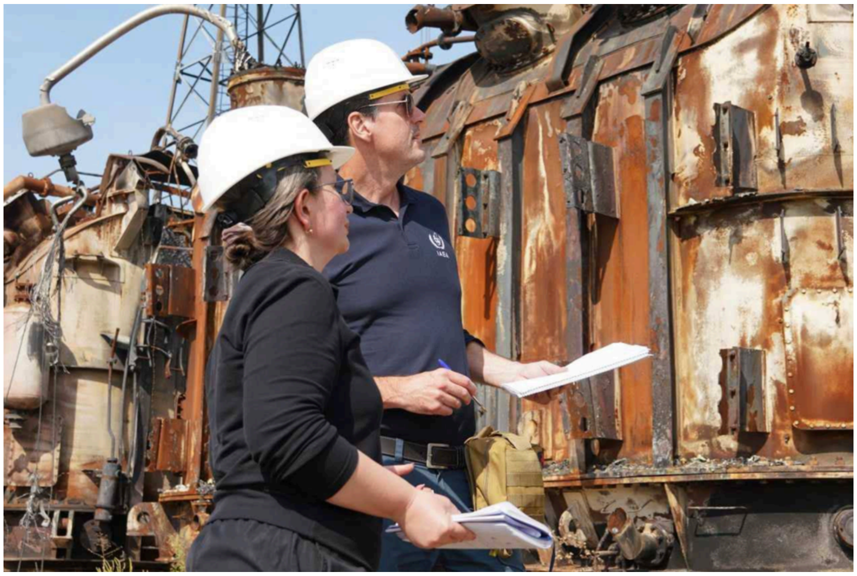
[8] Kateryna Hodunova, Russia has destroyed all thermal power plants, nearly all hydroelectric capacity in Ukraine ahead of winter, Zelensky says, Kyiv Independen, 25 September 2024, see https://kyivindependent.com/russia-destroys-all-thermal-power-plants-nearly-all-hydroelectric-capacity-in-ukraine-ahead-of-winter-zelensky-says/#:~:text=According%20to%20the%20Energy%20Ministry%2C%20nuclear%20generation%20currently%20accounts%20for,Russian%20occupation%20since%20March%202022



[Interactive map](#) reveals severe hazards at Ukraine's nuclear plants caused by Russian invasion, Greenpeace International 2022-2024

Ukraine experienced a major electrical power deficit during the summer of 2024, when generation capacity fell 2.3 GW below its peak demand of 12 GW, this despite electricity imports from Ukraine's western neighbours.[9] The deficit has been managed by Ukrenergo, Ukraine's state-owned electricity transmission system operator (TSO), through various emergency measures - rolling cuts to supply, limitation of electricity provision in the worst-affected regions to a few hours per day.

[9] International Energy Agency, Ukraine's Energy Security and the Coming Winter An energy action plan for Ukraine and its partners, September 2024, see https://iea.blob.core.windows.net/assets/cec49dc2-7d04-442f-92aa-54c18e6f51d6/UkrainesEnergySecurityandtheComingWinter.pdf



The first IAEA Ukraine mission to electrical substations took place on September 12. *Photo: NAEK Energoatom*

Russian attacks on Ukraine's electric substations are not new. In October 2022, Russian missile strikes on substations led to scheduled load-shedding (rolling blackouts) by Ukraine's national transmission system operator (TSO), Ukrenergo.[10] The destruction and damage to substations prevented the distribution and transmission of energy to users. The work of Ukrenergo and foreign assistance led to the reconstruction of many substations. This permitted Ukraine to operate through the winter of 2023/24 without significant disruptions to the power system [2]. Additionally, Ukrenergo secured more than 100 substations with physical reinforcements protecting against drones or shrapnel.

Chronology of Russian attacks against Ukraine's electrical system and IAEA missions

23 October 2022 – A massive Russian missile attack led to a decrease in the frequency in Ukraine's grid. The reactors at Rivne, South Ukraine and Khmelnitskyi remained in project mode or house load, not generating electricity for the grid, but sufficient to power the site. The power supply for Zaporizhzhia reactors was also stopped and the plant operated with emergency diesel generators.

22 March 2024 – Russia launches its largest attack on Ukraine's electrical system. The then CEO of Ukrenergo Vladimir Kudritsky called the attack on the energy system, "the largest since the start of the full-scale war." The attack was characterised by the use of combined weapons. The strikes were carried out on various regions of Ukraine, on thermal and hydroelectric power plants, as well as on main substations managed by Ukrenergo.

26 August 2024 – Russian fires over 200 missiles and drones at Ukraine, targeting energy infrastructure, including electric power substations in Kharkiv, Odesa, Vinnytsia, Zhytomyr, Rivne, Lviv, and Ivano-Frankivsk regions. Around 8 million households lost power without warning; the capital, Kyiv, experienced its first unscheduled blackout since November 2022.

[10] Forum Energii, Ukraine in Darkness: Preventing the Worst-Case Scenario for Its Energy System, 1 July 2024, see https://www.forum-energii.eu/en/ukraine-destroyed-system

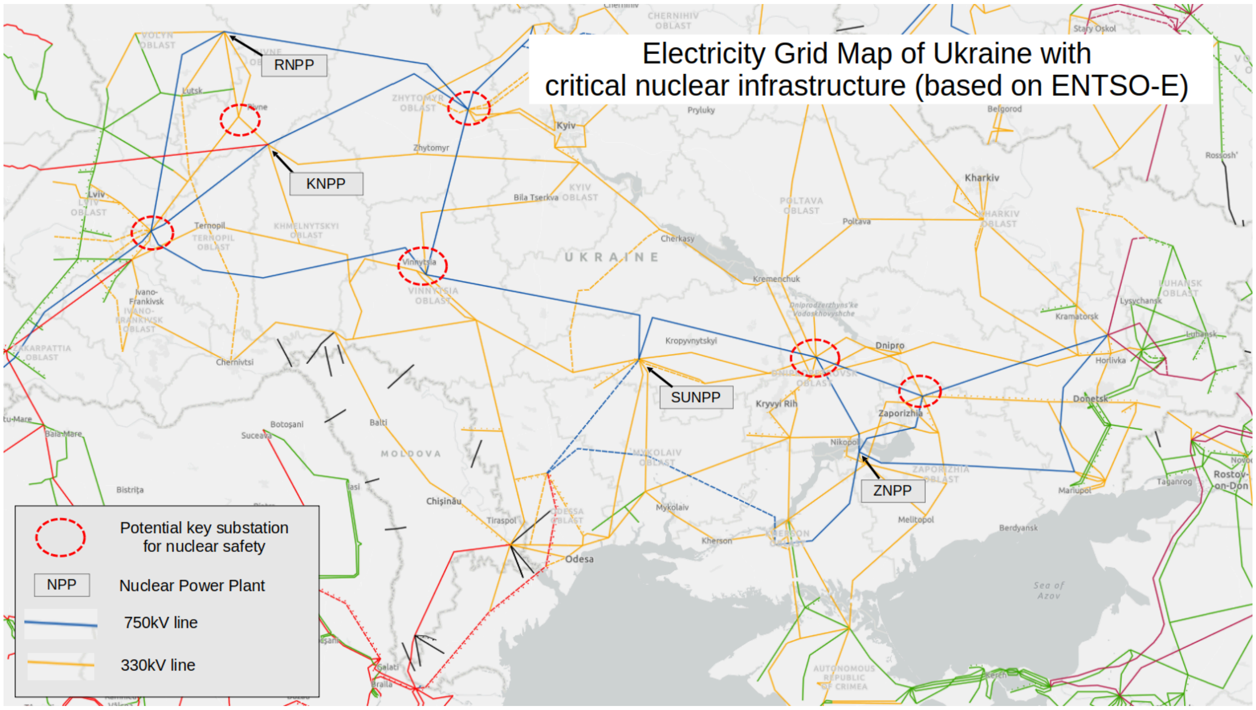
26 August 2024 - Ukrainian President Volodymyr Zelenskyy held a meeting of the Staff of the Supreme Commander-in-Chief today, August 26. "The meeting of the Staff of the Supreme Commander-in-Chief. Restoration of energy infrastructure following one of the largest Russian attacks. At least 127 missiles and 109 drones," the President wrote. During the meeting, reports were given by Air Force Commander of the Armed Forces of Ukraine Mykola Oleshchuk, Minister of Internal Affairs Ihor Klymenko, Minister of Energy Herman Halushchenko, and Chairman of the Board of NEC Ukrenergo Volodymyr Kudrytsky.

28 August 2024 – Ukraine government communication to IAEA, INFCIRC 1242: "On 26 August 2024, the Russian Federation launched a massive missile and drone attack on Ukraine's critical infrastructure and energy sector with the objective of paralysing the operation of power generation facilities of Ukraine. As a result of the attack, at 08:58 (EEST}, power units 1, 3 and 4 of the Rivne Nuclear Power Plant were disconnected from the grid. At 09:05 (EEST), the South Ukraine Nuclear Power Plant units' power was decreased to a total level of 1,800 MW. Due to fluctuations in the national power grid caused by Russia's attack, at 17:10 (EEST}, power unit 3 of the South Ukraine NPP was disconnected from the grid. The Russian Federation continues to deliberately target Ukraine's energy infrastructure, intending to disrupt the operation of the country's nuclear power plants, which provide most of Ukraine's electricity. Russian attacks pose a significant risk to the stable operation of nuclear facilities in Ukraine and the safety of millions of people."

3 September 2024 - Agreement reached during a meeting between President of Ukraine Volodymyr Zelenskyy and International Atomic Energy Agency (IAEA) Director General Rafael Mariano Grossi on 3 September 2024 on expanding IAEA mission to electric substations. The President also briefed his interlocutor on the consequences of the massive Russian attacks on Ukraine's energy infrastructure with ballistic and cruise missiles, along with kamikaze drones, which led to the temporary disconnection of NPP units from the grid and a reduction in their capacity. "The shelling of critical infrastructure by the Russian Federation is the largest threat to the safe operation of nuclear power plants in Ukraine. It primarily affects ordinary people," the Head of State emphasised.

6 September 2024 – Oleh Korikov, Chief State Inspector for Nuclear and Radiation Safety of Ukraine at the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU), reported that the IAEA will expand its presence in Ukraine to monitor also electric substations important for nuclear plant safety.

12 September 2024 - IAEA monitoring personnel visits one of the electric substations in Ukraine, which has suffered significant damage as a result of Russian missile attacks. Representatives of NNEGC «Energoatom», NPC "Ukrenergo" and SNRIU and the IAEA conducted a site visit and inspection, documented the damage sustained by the facility as a result of missile attacks, discussed the impact of these damages and losses on the safety of nuclear power plants in Ukraine and prepared a technical report to the IAEA Director General.



This is a screen capture of a detailed [map](https://www.entsoe.eu/data/map/) of the Ukrainian grid which is available from the European network of grid operators, ENTSO-E[11]. To this map, we have added the location of the four nuclear power plants: Rivne plant (RNPP, 2 VVER-440, 2 VVER-1000 reactors), Khmelnytskyi plant (KNPP, 2 VVER-1000 reactors) and the South Ukraine plant near Youzhnoukrainsk - SUNPP, 3 VVER-1000 reactors), which are still generating electricity, and the Zaporizhzhia plant (ZNPP, 6 VVER-1000 reactors), which were occupied by Russian armed forces on 4 March 2022 and has been shutdown since September 2022. The six key substations indicated on the map are the most critical ones according to Greenpeace CEE's nuclear experts assessment based on their central connection to the 750kV network.

The potential for an unprecedented nuclear disaster in Ukraine

The risks of a Station Black-Out (SBO)

When a nuclear power plant loses its offsite power from the grid, a so-called Loss of Offsite Power (LOOP) event occurs and the power plant falls back to three main power sources for its critical safety systems: on site batteries, back-up diesel generators, and the possibility to trip one reactor at the plant to house load. Batteries can supply electricity immediately, but only for a short period of time. The diesel generators have a stock of fuel onsite sufficient to operate for about ten days, but their continued operation over such a long period of time might be challenging, even if there is some redundancy in the number of generators. The trip to house

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[11] ENTSO-E Transmission System Map, see https://www.entsoe.eu/data/map/

load is a procedure to reduce the power of one reactor at the plant to about 10%, with sufficient electricity output to secure the electricity needs of the safety systems at the entire plant. However, experience has shown that this is a delicate procedure which does not always succeed[12]. If all power supply fails, both offsite (LOOP) and onsite, then the plant enters a Station Blackout (SBO). For an operational nuclear power plant this can lead to the boiling out of the cooling water in the reactor vessel in a matter of hours, leading to core damage and releases of radiation within the reactor containment building, and further into the environment due to overpressure within the containment.

Even if nuclear power plants are designed to cope with a LOOP through their onsite power generation, a LOOP is a serious incident and is considered as a precursor to a SBO[13]. Under normal power operating conditions, the risk of an SBO is a main contributor to reactor core damage at a nuclear power plant[14]. The 2011 Fukushima-Daiichi nuclear disaster and the following nuclear power plant stress-tests around the world have also highlighted the central importance of the reliable electricity supply to the nuclear plant. And even faults on the grid system at a significant distance from a nuclear power plant can be the cause of reactor trips or the loss of offsite power.[15]

Table 3.2 Summary of core damage frequency results: Surry.*

	5%	Median	Mean	95%
Internal Events	6.8E-6	2.3E-5	4.0E-5	1.3E-4
Station Blackout				
Short Term	1.1E-7	1.7E-6	5.4E-6	2.3E-5
Long Term	6.1E-7	8.2E-6	2.2E-5	9.5E-5
ATWS	3.2E-8	4.2E-7	1.6E-6	5.9E-6
Transient	7.2E-8	6.9E-7	2.0E-6	6.0E-6
LOCA	1.2E-6	3.8E-6	6.0E-6	1.6E-5
Interfacing LOCA	3.8E-11	4.9E-8	1.6E-6	5.3E-6
SGTR	1.2E-7	7.4E-7	1.8E-6	6.0E-6
External Events**				
Seismic (LLNL)	3.9E-7	1.5E-5	1.2E-4	4.4E-4
Seismic (EPRI)	3.0E-7	6.1E-6	2.5E-5	1.0E-4
Fire	5.4E-7	8.3E-6	1.1E-5	3.8E-5

*As discussed in Reference 3.4, core damage frequencies below 1E-5 per reactor year should be viewed with caution because of the remaining uncertainties in PRA (e.g., events not considered).

**See "Externally Initiated Accident Sequences" in Section 3.2.1.2 for discussion.

An operational nuclear power plant requires significant amounts of power to maintain the cooling of the heat of the fuel in the spent fuel pools and the residual heat in the reactor cores after the shutdown of the reactor. Without the water circulation pumps functioning, the cooling water in the reactor core will boil out in a matter of hours and core damage will occur including fuel melt. Immediately after the shutdown of the reactor its thermal power is still around 6.5

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[12] For example see the Forsmark nuclear plant 2006 incident: IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012, see https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf

[13] IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012, see https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf

[14] NRC, NUREG-1150 part 3 for internal events:

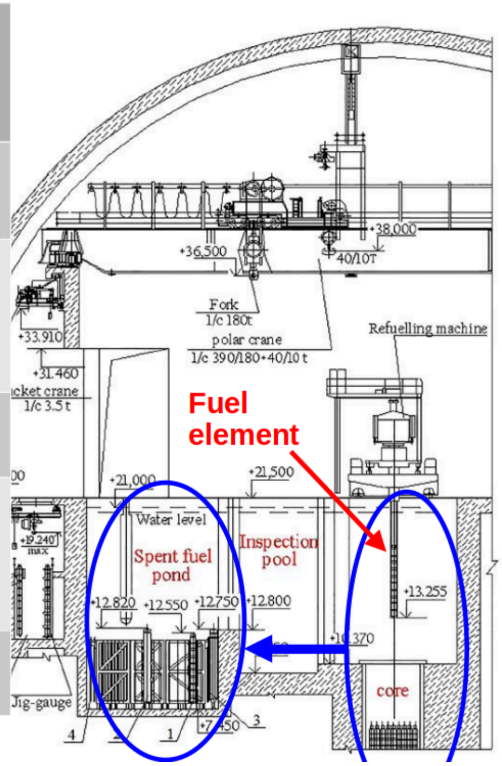
[15] IAEA, 2012.

percent and after one hour around 1.5 percent.[16] Although this seems low, the thermal power of a VVER-1000 reactor is around 3000 MWth, so 1.5 percent is still a massive 45 000kWth, or about 22 000 typical electric water kettles used in a domestic kitchen. Seven of Ukraine's reactors that are generating electricity are VVER 1000 design, while two are VVER 440 design. The full electrical load of the auxiliaries of a nuclear power plant is typically 5-8 percent of the nuclear plant rated load.[17] For a VVER-1000 we can thus estimate the needs around 50MWe.

Due to the further decay of radioactivity in the fuel of the reactor, the heat declines exponentially. Hence, the consequences of an SBO are very different for the Zaporizhzhia NPP, where the last reactor was shut down in September 2022, than for the three other NPPs in Ukraine, where a total of seven reactors continue to operate. These differences are summarised in the illustration below:

Operational VVER-1000 reactor vs reactor 2 years in shutdown: time without cooling before meltdown of the fuel

2 years shut down (Zaporizhzhia NPP since Sept. 2022)	**Operational** (e.g. South Ukraine NPP or re-start of ZNPP)
Several **weeks** before meltdown	**hours** before meldown
Russian occupation (restart possible)	Many steps where UA operator can intervene to stop nuclear disaster
Not enough staff	Normal operation
Risk of **deliberate sabotage** to release radioactivity	Risk of Russian **attack** e.g. on electricity supply of NPP
No iodine-131 unless restart by Rosatom	Iodine-131 and other short-living isotopes



In the case of Zaporizhzhia and over a longer timescale, closer to several weeks, and depending on the burnup of the fuel and its time since unloading from the reactor, the spent fuel in the cooling pond will heat up and evaporate its cooling water. Spent fuel recently discharged from a reactor on the other hand is much hotter and in the event of loss of cooling will begin to heat

[16] IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012: see https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf

[17] IAEA, 2012.

up to pool water rapidly. After the water level has dropped below the top of the fuel it becomes exposed to air, which is followed by ignition into a so-called zirconium-fire, releasing even larger amounts of radiation than the reactor core. These risks were explained more extensively in a briefing by Greenpeace International in March 2022.[18]

Major difficulties to recover from a black-out (black start)

A black start (or black-out recovery) is the complex process to restart the electric power system from a black-out. This process will be coordinated by the TSO (Ukrenergo) and requires a sufficient number of power plants with black start capability, such as diesel generators, Battery Energy Storage Systems (BESS), hydro-electric and thermal plants and hydro plants. BESS can be combined with variable renewable sources such as wind and solar.

Nuclear power plants are not capable of a black start and are thus dependent on those other sources[19]. This is particularly problematic in the Ukrainian context of today, because most of the hydro and fossil generation capacity has been incapacitated by the Russian aggression, and Ukraine does not have (yet) a significant BESS capacity.

Potential radiological consequences of a station blackout

Nuclear safety is complex and multi-faceted. It not only requires a stable nation-wide offsite electricity system, but also the availability of sufficient competent staff onsite and nation-wide logistics of supplies, such as fuel for diesel generators or heavy equipment in the case of an emergency. The 2011 Fukushima Daiichi nuclear crisis showed a massive logistical operation in Japan, in the midst of power cuts and the consequences of the 11 March magnitude 9.0 earthquake and resultant tsunami.

In Ukraine there would be multiple related challenges in a nation-wide grid blackout. There would be difficulty in securing sufficient supplies to the three operational nuclear plants under Ukrainian control. The challenge to maintain onsite electricity production at the power plants after a LOOP, and a wider societal disruption of such a situation would also impact the staff. It is clear that this is far, far beyond the design basis of a nuclear power plant, and thus largely unknown territory in terms of how these different components interact systemically.

A nation-wide grid blackout could affect all four nuclear power plants which further complicates the emergency response management.

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[18] Greenpeace International, The vulnerability of nuclear plants during military conflict Lessons from Fukushima Daiichi Focus on Zaporizhzhia, Ukraine, 2 March 2022, see https://www.greenpeace.de/publikationen/vulnerability-nuclear-plants-during-military-conflict

[19] IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf

It is necessary to restate that the current situation in Ukraine is on the edge of a nuclear crisis of unprecedented proportions in the history of nuclear power.

Greenpeace analysed the potential radiological risks for both shutdown and operational reactors in previous briefings.[20] A distinction needs to be made between reactors that have been shut down for at least two years as at the ZNPP, and the seven operational reactors. We also need to distinguish between the spent fuel pools and the reactor cores. Below a summary of the main points:

- Each reactor building has both a reactor core and an at-reactor spent fuel pool (see illustration above for a VVER-1000). This means that for a total of 15 reactors apart from other installations), there are 30 large sources of highly radioactive nuclear fuel.
- Each spent fuel pool can contain an amount of radioactivity (in addition to short-living isotopes) that is multiple times the amount of radioactivity in the reactor core. This is especially relevant for the radioactive cesium isotopes.
- A release of radioactive cesium from a single spent fuel pool can be in the order of 100 times more than the 2011 Fukushima-Daiichi nuclear power plant releases, and up to 10 times greater than the 1986 Chornobyl disaster. There are nine spent fuel pools at immediate risk at three operational nuclear plants, plus six at risk over a period of weeks.
- Because the Ukrainian nuclear plants are land-locked, most of the radioactive contamination would be deposited on land (and into river systems such as the Dnipro or Bug), whereas at Fukushima Daiichi, about 80 percent was released into or deposited onto the Pacific Ocean.
- In the case of one nuclear reactor event, atmospheric modelling simulations show that the highest risk for high level of contamination (>1000kBq/m2 of Cs-137, requiring relocation) would be within a radius of a few hundred kms, thus mostly in Ukraine itself but also its neighbouring countries. At a lower level of contamination, still requiring protective measures (between 128-1000 kBq/m2 of Cs-137), it would cover the entire European territory. These are models for single reactor events.
- There are no public models that show the radiological releases and dispersal from multiple nuclear reactor units at multiple nuclear power plants.

It is hard to imagine a worst-case scenario than the situation in Ukraine. There are 30 large sources of radioactivity, each one of which could lead to radiological consequences beyond the total release from Fukushima Daiichi and its radiological impact, with consequences on a European continental scale and beyond. With a long-duration grid blackout, there would be a risk of core damage at multiple power plants. At each power plant, there could be cascading

[20] Greenpeace International, March 2022; and The vulnerability of nuclear plants during military conflict Yuzhnoukrainsk (South Ukraine) Nuclear Power Plant, Greenpeace International, 9 March 2022, see https://www.greenpeace.org/static/planet4-international-stateless/2022/03/559dfc6b-nuclear-power-plants-in-military-conflict-yuzhnoukrainsk-south-ukraine-briefing.pdf

consequences, when one large-scale release of one reactor could lead to loss of control at adjacent reactors leading to further release of radioactivty.

Risks resulting from the key characteristics of the offsite electricity grid

Because the offsite grid is so important for the safety of the NPP, they are connected through several electricity lines. For instance, the ZNPP has 10 connections, both 330 and 750kV. In a war context, this redundancy has proven not to be sufficient, with the ZNPP suffering a LOOP eight times since the full-scale invasion. This is called a “common cause failure”, where one cause (in this case the devastating aggression by Russia) is causing all grid connections to fail. Such a common cause is well beyond the design base of the nuclear power plant.

Not only is the physical connection important, also the stability of the electricity generation is required. This is particularly a problem in Ukraine, where alone in 2024, 9GW of production capacity has been lost due to Russian aggression. It is the responsibility of the grid operator (Ukrenergo) to balance generation and demand and to keep the voltage and frequency within narrow margins. When there is an imbalance between generation and load, grid frequency tends to lower, caused by the trip of a major generator or a fault on a substation. When the frequency is too low, the grid operator will first call for more generation to start up, which is highly challenging in the current Ukrainian context. Next is load-shedding where parts of the grids are switched off in order to lower the demand.

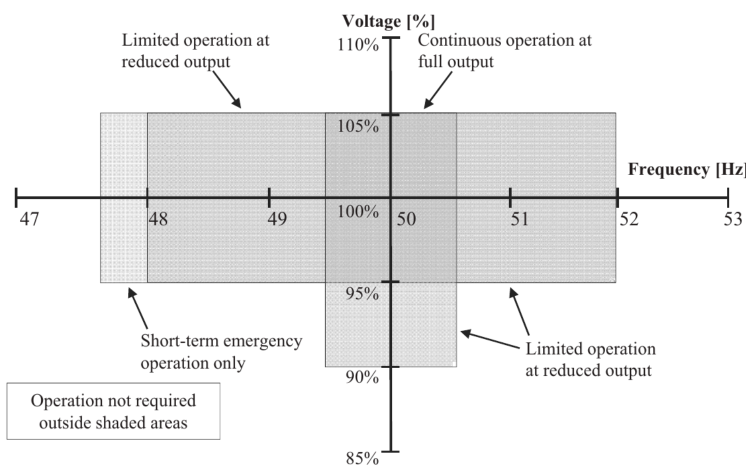

FIG. 1. Illustration of required frequency and voltage ranges for operation.

A first problem with a degraded grid, even without a LOOP is that the pumps that circulate the cooling water in a nuclear reactor rely on stable electric power. If the grid voltage and frequency are not sufficient, the operating motors will not maintain sufficient torque, and the electrical system will shut them down.[21]

A second problem is the risk of a cascading system-wide blackout in a large part of the country.

When one or several NPPs trip, and/or key substations have been damaged or destroyed by Russian military strikes, this could push voltage and frequency beyond the margins, with no additional generation capacity available. This can then lead to other generation capacity to trip, leading to a cascade and a system-wide blackout. This could put all four nuclear plants in Ukraine in a LOOP situation.

Possible sequence of events leading to core damage

Phase 1: collapse of the grid

- Damage to one or several main substations
- Critical disturbance in the grid, beyond the criteria for frequency or voltage
- Loss of Offsite Power (LOOP) for one or several NPPs
- Reactor scram; electricity at the plant required for safety systems is provided by onsite diesel generators, batteries and/or trip to house load by 1 reactor at minimal power
- Due to loss of generation capacity of one or several nuclear power plants, the limited remaining generation capacity in the grid cannot compensate causing a general black-out

Phase 2: not possible to re-start the grid (black start)

- It is impossible to black start the grid, because most hydro and fossil plants are damaged and nuclear power plants do not have a black-start capability. This leads to a prolonged black-out
- Diesel generators run out of fuel or disfunction, houseload production at the NPP fails
- Nuclear power plant Station Black-Out (SBO), all safety functions at the NPP stop
- Reactor core damage and large-scale release of radioactivity

The state of nuclear safety in Ukraine

Not a single national nuclear power program in the world has been designed to cope with the scale of disruption the full-scale Russian war has inflicted on the territory of Ukraine. There is currently no existing safety analysis available for nuclear regulators worldwide that considers such a scale of a crisis in a national electricity grid and its consequences for nuclear power plant safety.

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[21] Grid Stability and Safety Issues Associated with Nuclear Power Plants Dr. John H. Bickel Evergreen Safety and Reliability Technologies, LLC , 2026, see http://large.stanford.edu/courses/2016/ph241/yang2/docs/bickel.pdf

The radiological implications for Ukraine, Europe and beyond are profound. Ukraine's three nuclear power plants at Rivne, Khmelnytskyi and in South Ukraine are each loaded with hundreds of tons of highly radioactive core fuel. In addition to the nuclear fuel in the nine reactors at these sites, there is one spent fuel pool by each reactor, which in total are loaded with several thousand tons of spent fuel, including many tens of tons of recently unloaded fuel assemblies.[22] The level of risk and the potential consequences of possible multiple and cascading reactor unit failures due to a collapsed electrical grid due to Russian military strikes can only be described as cataclysmic. The consequences of a radiological disaster would spread far beyond Ukraine's borders.

The entire nuclear safety analysis for Ukraine (and all nations) is designed and planned with some redundancy in the electric grid taken into account the so called 'N-1 standard', which ensures that the system is secure against any one single event.[23]

The IAEA 2012 assessment on electric grid reliability and nuclear plant describes the following examples:

- Trip of a single generating unit (which could be a unit at an NPP);
- Short-circuit fault or earth fault on an overhead line;
- Short-circuit fault or earth fault on an underground cable;
- Fault on a section of bus bar;
- Failure of any one grid transformer.

The system is considered secure against the events listed above if such events do not lead to consequences such as:

- Frequency outside normal range;
- Voltage outside normal range;
- Overloading of other transmission circuits or generators;
- Cascade tripping of other transmission circuits;
- Loss of synchronism (grid separation) between parts of the network.

However, by 2024, Russia had destroyed 90 percent of thermal power plants and 40 percent of hydroelectric power plants and incapacitated 40 percent of Ukraine's nuclear capacity at

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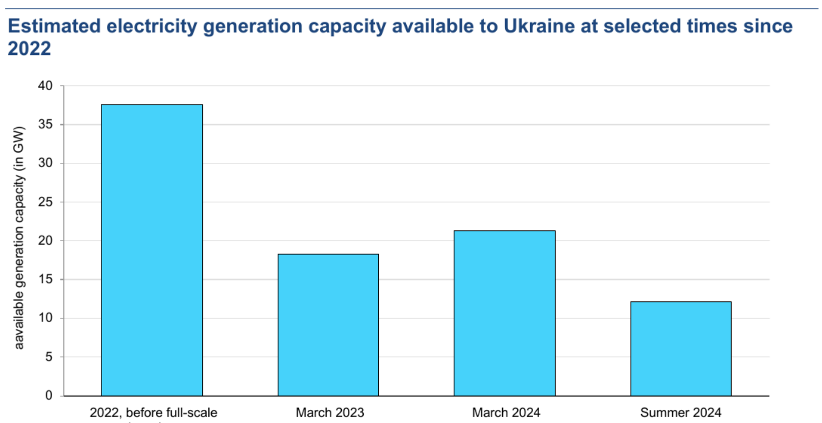
[22] Nuclear reactors undergo regular refuelling outages where a percentage of the fuel in the reactor pressure vessel is unloaded into a spent fuel pond or water pool where it is stored for several years while it cools. Ukraine's spent fuel inventory in reactor pools, not including Chornobyl nuclear power plant spent fuel, was 2,339.39 tons heavy metal as of July 2020. Spent fuel in wet pool storage at Chornobyl ISF-1 was 2396.11 tons heavy metal as of July 2020; see Ukraine, National Report, On Compliance with Obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 2020, see https://www.iaea.org/sites/default/files/ukraine-7rm.pdf

[23] IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf

Zaporizhzhia NPP.[24] The IEA estimated an overall decrease in generation capacity by the Summer of 2024 (see illustration below)[25]. Furthermore, there is a risk of the destruction of one or several critical substations, essential for the operation of the three remaining nuclear power plants in Ukraine.



IEA, September 2024

Although the precise vulnerabilities and status of the Ukrainian grid is for obvious strategic reasons confidential, it is known that the reliability criteria that should apply to the operation of nuclear power plants are not met, such as the N-1 criterion. A further major disturbance in an already fragile electricity system could lead to a cascading black-out of the entire system, and thus put all 4 Ukrainian nuclear power plants in a LOOP (including the ZNPP which is already shutdown but still connected to the Ukraine grid).

The social impact of Russia targeting Ukraine's energy system

The nuclear safety and security threat posed by Russia's military attacks should also be seen in the wider context of their impacts on the Ukrainian people. As the United Nations Human Rights Monitoring Mission in Ukraine (HRMMU), recently reported the "Russian attacks on Ukraine's electric power system, damaging or destroying numerous power generation, transmission, and distribution facilities have had reverberating effects causing harm to the civilian population and the country's electricity supply, water distribution, sewage and sanitation systems, heating and hot water, public health, education, and the economy."[26]

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[24] Forbes Ukraine, The IAEA will monitor key Ukrainian substations for the first time, Anastasia Dayna, 13 September 2024, see https://forbes.ua/company/magate-vpershe-bude-monitoriti-ukrainski-klyuchovi-pidstantsii-chi-zakhistit-tse-ikh-vid-obstriliv-rf-a-krainu-vid-totalnogo-blekautu-13092024-23608

[25] International Energy Agency, September 2024.

[26] OHCHR, Attacks on Ukraine's Energy Infrastructure: Harm to the Civilian Population UN Human Rights Monitoring Mission in Ukraine, September 2024, see https://ukraine.ohchr.org/sites/default/files/2024-09/ENG%20Attacks%20on%20Ukraine's%20Energy%20Infrastructure-%20%20Harm%20to%20the%20Civilian%20Population.pdf

In addition, there is the issue of the violation of the principles of international law. The United Nations Independent International Commission of Inquiry on Ukraine has already concluded that Russian attacks on electricity infrastructure in 2022-2023 were widespread, systematic, and disproportionate, constituting the war crime of excessive incidental civilian harm and potentially a crime against humanity.[27]

With millions of Ukrainian citizens already displaced from their homes due to the Russian war, "the energy infrastructure attacks have caused additional population displacement and have disproportionately impacted groups in a situation of vulnerability, such as older persons, those with disabilities, households with lower incomes, and the internally displaced, with women particularly affected," HRMMU warned. "The fragility of the electric grid during this coming winter will increase along with electricity consumption as Russian attacks continue. Ukraine will face a significant electricity deficit in the winter, with daily power cuts during the cold months leaving civilians without the electricity they need to power homes, run water pumps and allow children to study online."

Even without a nuclear disaster the conditions for the people of Ukraine this winter are potentially severe in terms of prolonged power cuts and lack of access to heating. Under war conditions, Ukrainian government authorities, energy companies, and humanitarian and recovery agencies are engaged in immense mitigation efforts to avert a humanitarian crisis this winter.[28] The full consequences of further Russian attacks, that leads to the further loss of grid capacity and nation-wide blackout, then a potential cascading crisis at multi reactor units and at multiple nuclear plants, and finally, the potential for major radiological releases is impossible to comprehend. Other than the scenarios for nuclear war and the effects of nuclear weapons use, this is a uniquely terrible reality that is facing the people of Ukraine. The worst-case scenarios can be avoided but it demands absolute priority attention by the international community to prevent the current disaster from becoming far greater and by stopping Russian attacks.

Conclusion with recommended actions

Given the fragility of the Ukrainian electricity system due to more than two years of military attacks by Russia on the civilian electricity system, there is uncertainty on how much the system can further endure before it collapses. Greenpeace Central and Eastern Europe believes that what is needed now is not only the active protection of a limited number of key substations, but an immediate end to any further attack on Ukraine's electricity system, including the remaining operational generation capacity.

[27] Report of the Independent International Commission of Inquiry on Ukraine, A/HRC/52/62 (hereinafter: A/HRC/52/62), 16 March 2023, available at: https:// www.ohchr.org/en/hr-bodies/hrc/iicihr-ukraine/index
[28] OHCHR, 2024.

The current analysis aims to send a strong wake-up call to the international community, including the International Atomic Energy Agency (IAEA), to act with much more urgency and decisiveness than so far in Ukraine. Nuclear regulators in many countries have also been briefed in detail by the Ukrainian authority SNRIU[29], and so are perfectly aware of the seriousness of the situation.

It is now on governments globally and the IAEA to put pressure on Russia to immediately stop all attacks on the fragile electricity system of Ukraine, as well as on the most critical substations to avoid the consequences of a radiological disaster that would spread far beyond Ukraine's border and would potentially affect the whole European continent.

The IAEA had agreed to a request to expand the permanent monitoring mission in Ukraine to cover electrical substations, according to the announcement of the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) on 6 September 2024.[30] An IAEA inspection took place six days later at a substation already damaged by Russian military strikes.[31] The agreed expanded mission would mean that IAEA inspectors are assigned to all Ukraine's substations specifically linked to nuclear power plants of which there are less than ten. However, if the mission is to be effective in protecting critical energy infrastructure and to prevent Russian attacks, it must be undertaken immediately and comprehensively. In a letter to the IAEA Director General, sent on 30 September 2024, Greenpeace International has urged the IAEA to act urgently.

Beyond the rapid deployment of an expanded IAEA mission, and using any means to stop Russian military strikes, which are the immediate priorities, and are essential for the coming winter, there are also other measures that Ukraine should prioritise over the next few years.

Ukraine needs the full support for large-scale investment in rebuilding its energy infrastructure and to further increase the import capacity from the European Network of Transmission System Operators (ENTSO-E) grid.[32] Equally, international support is essential on the demand side, with energy efficiency measures and smart demand management and on the generation side decentralisation, industrial-scale Battery Energy Storage Systems combined with solar PV and

[29] e.g. letter of the Head of SNRIU - Chief State Inspector for Nuclear and Radiation Safety of Ukraine Oleh Korikov - dated 21 September 2024 to the European Commission, European Nuclear Safety Regulators Group (ENSREG), the Western European Nuclear Regulators Association (WENRA), the Nuclear Energy Agency (NEA), nuclear regulators of the USA, the UK, Canada, Finland, Poland, Norway, Germany, France, Lithuania, Sweden, the Czech Republic, Slovakia:
https://snriu.gov.ua/en/news/snriu-chairman-new-russian-attacks-on-ukraines-energy-infrastructure-will-create-new-challenges-and-threats-for-nuclear-safety

[30] SNRIU, Oleh Korikov: IAEA will expand its presence in Ukraine - substations important for NPP safety will be monitored by permanent missions, 6 September 2024, see
https://snriu.gov.ua/en/news/oleh-korikov-iaea-will-expand-its-presence-in-ukraine-substations-important-for-npp-safety-will-be-monitored-by-permanent-missions

[31] Ukrainska Pravda, Russians attack energy facilities in six oblasts over past 24 hours, 24 September 2023, see https://www.pravda.com.ua/eng/news/2024/09/23/7476346/

[32] The European Network of Transmission System Operators, which represents 40 electricity transmission system operators from 36 countries across Europe, see https://www.entsoe.eu/

wind power. This would also end Ukraine's high reliance on nuclear generation capacity and this would be the best way forward to build a security, resilient power system for Ukraine.

In addition, Greenpeace CEE also calls on national governments in the EU to stop continuing to trade almost unrestrictedly with the Russian nuclear state corporation, Rosatom, and include the EU sanction packages also to Rosatom. This has been blocked in particular by Hungary and France so far. Furthermore, the IAEA also needs to stop actively supporting Russia's nuclear power expansion projects worldwide, for example in Türkiye and Egypt.

Key actions needed:

- Russia must stop any further attack on the electricity system of Ukraine, and not only the nuclear plants and the most critical substations;
- The international community needs to apply all possible pressure on Russia to stop the attacks;
- The IAEA, with the full support of member states, must immediately implement its planned extended mission in Ukraine to deploy inspectors to critical electricity infrastructure, specifically substations essential for nuclear power plant operation, and thus act as a deterrent to further Russian military attacks;
- Extend and apply faster international support to rebuild Ukraine's damaged energy infrastructure and to protect it;
- Increase further the import capacity through the ENTSO-E grid interconnections to Ukraine;
- On electricity demand side – expand energy efficiency measures and smart metres and extend and apply demand-side management;
- On electricity generation – further decentralisation, industrial-scale Battery Energy Storage Systems to be combined with solar PV and wind power to make Ukraine less vulnerable to attacks.

GLOSSARY

Blackout: a condition in which all electrical power has been lost in all or a large part of the grid system.

Black start of the electricity grid: restart of the electrical power system from a blackout condition. The black start process will require a coordinated effort by the grid operator, Ukrenergo in Ukraine, in cooperation with the power plants in the system. For a black start to be possible, there must be a sufficient number of black start power plants.

Black start power plant: a power plant that has the capability to start up fairly quickly from a shutdown condition with no external source of power. NPPs do not have this capability.

Common cause failure: failure of two or more structures, systems and components due to a single specific event or cause. One example is the earthquake and tsunami at Fukushima Daiichi, which led to a core meltdown of three reactors. In the Ukrainian context, a system-wide blackout could have an impact on all fifteen reactors simultaneously.

Core damage: the core or reactor vessel of the nuclear reactor is significantly damaged. This may be caused by a loss of cooling of the reactor core so that the core overheats, and parts of the core melt. This can result in a significant release of radioactivity into the reactor building and further into the environment, depending on the severity of the core damage.

Design basis accident: accident conditions against which a facility is designed and for which the damage to the fuel and the release of radioactive material are kept within authorised limits.

Distribution system: the public electricity system operated at lower voltages (below 330kV in Ukraine). The distribution system connects the transmission system to customers and generation is supplied at low voltage.

Grid system: refers to both the distribution and transmission systems and interconnections, including substations, switchyards and a grid control centre.

House load operation: operating a nuclear unit so that it is generating electricity only for the unit's own needs but not exporting power to the grid system. This is mostly for safety systems such as the control room and pumps for cooling of nuclear fuel and spent fuel. At a nuclear power plant with multiple reactor units, usually only one reactor will be put in such operation at reduced power (e.g. 10 %).

Loss Of Offsite Power (LOOP): an event in which a nuclear unit loses all electrical power supply from the grid system (but can still rely on onsite generation). This may be the result of events that disconnect all the connections between the nuclear power plant (NPP) and the local substation, or between the substation and the rest of the grid system, or because of a total blackout of the grid system in the country or region.

Loss of load: an event where the NPP is not able to export power to the grid but the power supply from the grid is still available.

Load shedding: disconnecting some electricity customers to reduce load when there is a shortage of generation and/or when system frequency is below a defined value. In Ukraine, this can be either planned (e.g. DTEK schedule for Kyiv) or unplanned. It is usually applied for a certain region.

NPP operator: The company or organisation that is the operator of the nuclear power plant. It has the primary responsibility for the safe operation of the NPP and it will have to satisfy the requirements of the nuclear regulatory body in the country. In Ukraine, Energoatom is the operator of all four NPPs. However, due to the Russian occupation of the Zaporizhzhia NPP (ZNPP), Rosatom falsely claims it is the operator of ZNPP and is not responding to Ukraine's only legal regulator, SNRIU.

Nuclear unit: a nuclear unit comprises a nuclear reactor and all the auxiliary equipment (generator, transformers, motors, pumps, electrical supplies, protection systems etc.) that are required for its operation. An NPP may have one or more nuclear units.

N-1 standard: the minimum level of security used in the planning and operation of the transmission system. 'N' refers to the total number of transmission circuits that are in service at the time after allowing for planned outages of circuits for maintenance, and the '-1' refers to an unplanned event that causes one of those circuits to be switched out of service. The 'N-1' standard requires the system to have sufficient redundancy that the unplanned loss of any one circuit in this way would not have unacceptable consequences.

Offsite grid: the offsite grid of an NPP is the transmission grid to which the NPP is connected both for injecting the generated electricity from the power plant into the transmission grid, as well as to supply the NPP with electricity through the transmission grid.

Reactor vessel: for Pressurised Water Reactors (PWR, or in Ukraine VVER) such as the VVER-440 and VVER-1000, the pressure vessel is a steel vessel where the nuclear fuel is placed in a matrix, and the criticality of the nuclear fission is regulated and its heat is transferred through the primary cooling circuit to the steam generators. In a VVER, the reactor vessel is pressurised.

Station Blackout (SBO): when a nuclear unit loses all electrical power supply from the grid system (LOOP) as well as the onsite generation.

Substation, also called switchyard: an installation on the transmission system to which transmission circuits, generating units and customer load may be connected, and which has facilities for switching. An NPP is normally connected to one or two substations located close to the NPP site.

System frequency: the frequency of the alternating voltage on the system. In an interconnected system, the frequency is the same throughout the system at any instant in time. The nominal frequency in Ukraine is from April 2022 at the ENTSO-E standard of 50 Hz.

Transmission system: the public electricity system operated at high voltages (330 and 750kV in Ukraine). The transmission system is used to interconnect large power stations, such as NPPs, with centres of load, and to transmit large amounts of power long distances.

Transmission system operator (TSO): it is responsible for the transmission system to which the NPP will connect. The Ukrainian TSO is Ukrenergo.

Trip: the unplanned disconnection or rapid shutdown of a transmission circuit, generating unit, or nuclear unit. The rapid emergency shutdown of a nuclear unit also called a 'scram.'

Trip to house load: following a LOOP, reduction of the electric generation of a nuclear unit to house load.

For a more extensive glossary on this topic, see e.g.: IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, 2012: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf