The role and importance of Kakhovska HPP to the Ukrainian power system

Source: Ukrhydroenergo

Prepared by: Energy Community Secretariat

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Abbreviations

BESS	Battery energy storage system
CHP	Combined heat and electricity production
ECS	Energy Community Secretariat
EnC	Energy Community
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EU MS	European Union Member State(s)
FCR	Frequency Containment Reserve
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
GW	Giga Watt (1000 MW, 1 000 000 kW)
HPP	Hydro Power Plant
HUPX	Hungarian Power Exchange
IAEA	International Atomic Energy Agency
kW	Kilo Watt (1000 W)
LOOP	Loss-of-offsite-power
MW	Mega Watt (1000 kW)
NPP	Nuclear Power Plant
NTC	Net Transfer Capacity
OPEX	Operational expenditures
PV	Photovoltaic
RES	Renewable Energy Source(s)
SBO	Station blackout
SFP	Spent fuel pool
SPP	Solar Power Plant
TSO	Transmission System Operator
TPP	Thermal Power Plant
TW	Tera Watt (1000 GW, 1 000 000 MW, 1 billion kW)
TWh	Tera Watt hour (1000 GWh, 1 000 000 MWh, 1 billion kWh)
UHS	Ultimate heat sink
WPP	Wind Power Plant
WENRA	Western European Nuclear Regulators Association
ZNPP	Zaporizhzhia NPP

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1 Introduction

This report aims to provide a short description of the Ukrainian power system and analyse the role of hydropower plants within it, paying special attention to the Kakhovska hydropower plant (HPP). This HPP is under particular interest since it is suspected, according to the statements of Ukrainian officials, that its dam is mined and may be purposely destroyed to cause massive damage to the surrounding area and harm the power system operation and electricity supply in Ukraine. Based on desktop research and available reports, studies, development plans and other literature (listed in the footnotes), this report gives a brief overview of the Kakhovska HPP's role and importance within the Ukrainian power system and discusses the possible consequences of the potential destruction of its dam.

The report is divided into the following chapters: the operation of the power system of Ukraine before the war and after the Russian invasion is described in the subsequent chapter. Chapter 3 provides an overview of the hydropower plants in Ukraine, analysing their role within the generation mix and the electricity market. Large hydropower plants on the Dnipro river cascade, including the Kakhovska HPP, are described in chapter 4, highlighting their role and importance within the Ukrainian power system. Discussion about the possible consequences of the dam's destruction follows in chapter 5. The report concludes by presenting the key conclusions of the Energy Community Secretariat's assessment of the possible consequences of the dam's destruction.

2 The power system of Ukraine

Before the Russian invasion, electricity consumption in Ukraine was around 153 TWh/year (gross) and 125 TWh/year (net). The peak load occurs during winter months and amounted to 24 GW. Total electricity production in 2021 was 156.6 TWh, meaning that domestic power plants could cover domestic consumption and export electricity to neighbouring countries (net export in 2021 was 1.8 TWh).

At the end of 2021, the generation mix consists of nuclear units (13.8 GW[1]), thermal units - mostly coal-fired (21.8 GW), hydropower plants (6.3 GW in total, 4.8 GW in run-of-river and 1.5 GW in storage HPPs), combined heat and power production facilities (6.1 GW), solar power plants (6.3 GW), wind power plants (1.5 GW) and biofuel plants (0.37 GW). The total installed capacity of the power production facilities was 56.2 GW. By participating with 25 % of the total installed capacity in the generation mix, nuclear power plants (NPP) usually accounted for 50-55 % of the total electricity production in Ukraine on an annual basis. The rest was produced by coal-fired units (23 % of total electricity production in 2021), gas-fired units (7 %), hydro (7 %) and renewables (8 %).

Currently, many generation capacities are out of operation due to maintenance works or damage caused by military attacks. The largest nuclear power plant in Ukraine (Zaporizhzhia NPP or ZNPP,

[1] 4 nuclear power plants, 15 units

nameplate capacity 5.7 GW) is out of operation due to Russian occupation, as well as four large thermal power plants, which are either located in the occupied territory or damaged. The same is valid for wind and solar power plants, with more than half of the total capacities currently unavailable. There are also 35 hydro-generation units under maintenance activities. Due to military aggression, electricity consumption in Ukraine has dropped by 30 - 35 % compared to 2021. That is also valid for maximum daily loads.

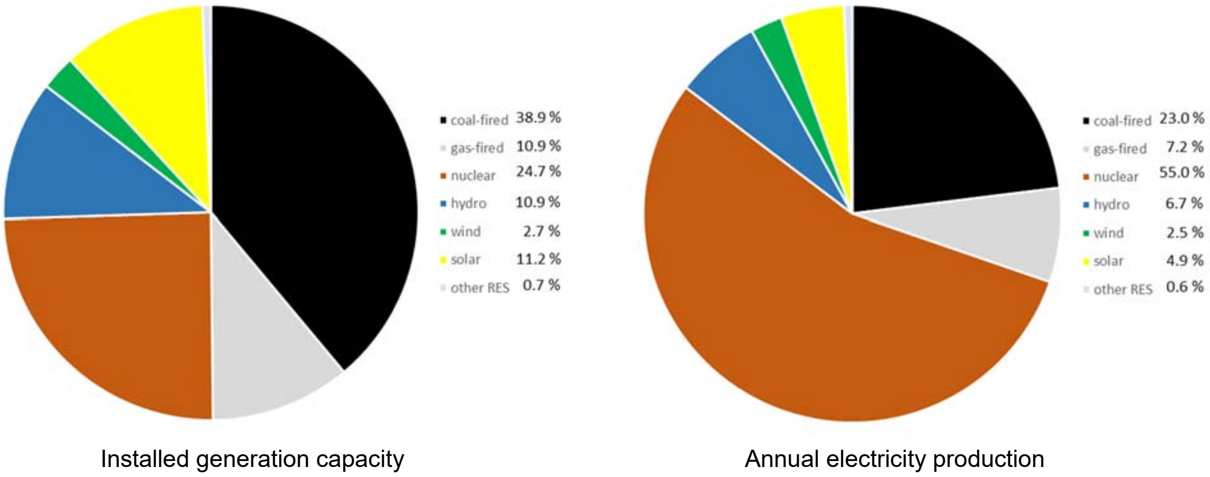

Figure 1: Generation mix in Ukraine
Source: Energy Community Secretariat

The majority of the transmission grid consists of 750 kV (4400 km), 330 kV (~13000 km) and 220 kV (~3000 km) lines, but there are facilities operating under 800 kV (~100 km), 500 kV (~375 km) and 400 kV (~340 km) as well. The 750 kV network is the grid's backbone, while regional transmission is performed mainly at the 330 kV voltage level. The national transmission grid was administratively divided into six regional grids (Central, Dnipro, Northern, Southern, Western and South-Western) and two temporarily uncontrolled by Ukrenergo regional grids (Crimea and Donbass).

Ukraine was previously interconnected with Russia and Belarus, operating in the IPS/UPS synchronous area. Following the permanent disconnection from Russia and Belarus in February 2022, which was immediately followed by military aggression by Russia and after emergency synchronisation with ENTSO-E in March this year, the Ukrainian power grid now operates in parallel with the Continental European network. However, restrictions on the possible commercial power exchange between the Ukraine/Moldova control block and neighbouring countries are in place (now the limit is set at 400 MW for export and 500 MW for import to the MD/UA control block).

Ukraine is interconnected with Poland (one 220 kV line operating radially, one line 750 kV is permanently out of operation), Slovakia (one 400 kV line), Hungary (one 750 kV line, one 400 kV line and two 220 kV lines) and Romania (one 400 kV line; one 750 kV line is permanently out of operation). There are also seven 330 kV interconnections with Moldova. At the moment, some interconnection lines toward Continental Europe are out of operation, additionally limiting possibilities for power exchanges between the UA/MD control block and EU countries.

Since 10 October, the Ukrainian power system has been heavily destroyed but continues to operate under daily military attacks. Shelling was mainly directed at power substations, either within the grid or within the ones connecting large thermal power plants to the grid. At the moment, at least 33 large power transformers (750/330 kV, 330/110 kV and 220/110 kV) have been destroyed or damaged, which makes the grid vulnerable in terms of maintaining normal operation. This alert mode of operation is possible due to quick repairs, constant rearranging of the power system configuration, rolling load-shedding and maximum engagement of the power plants that are still available (around 10 GW is not available).

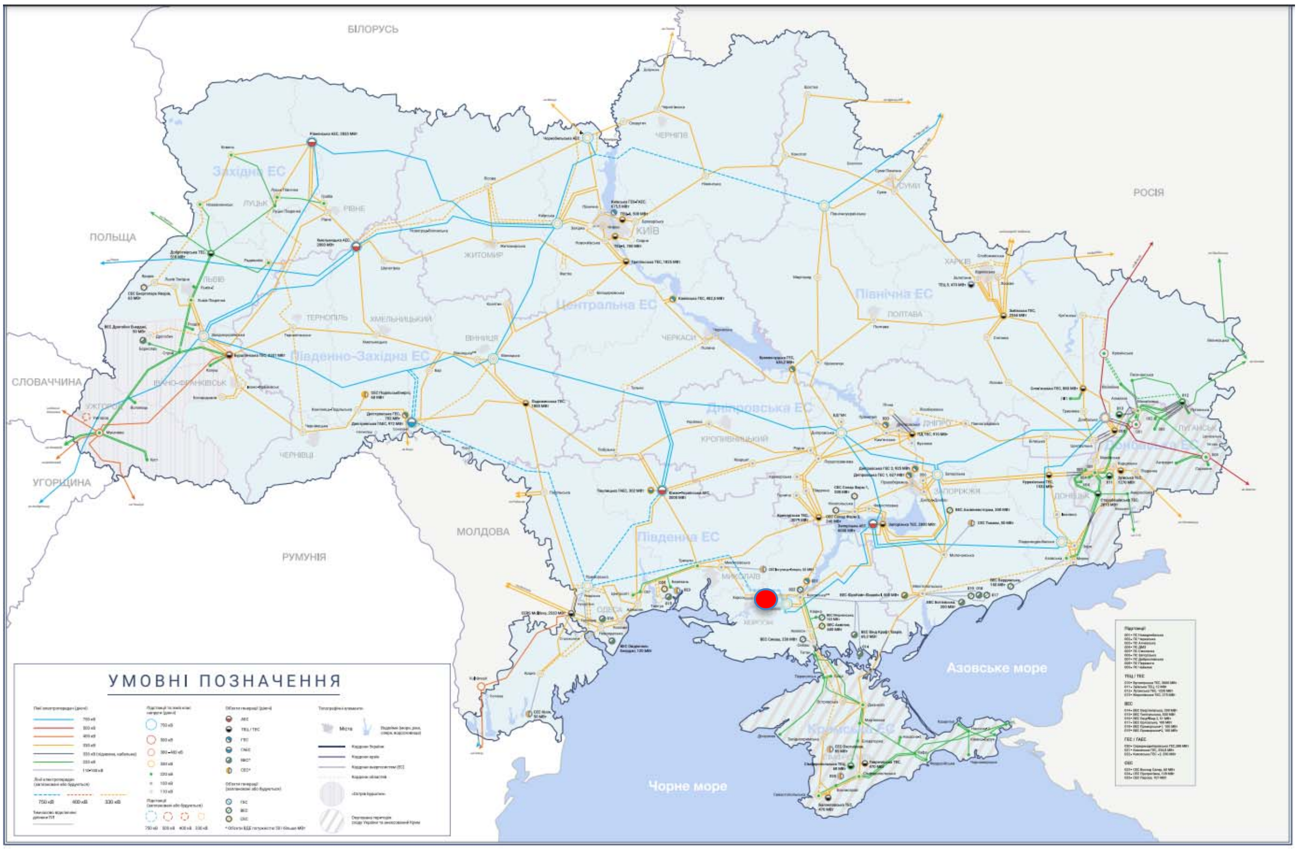

Figure 2: Transmission system of Ukraine and location of the Kakhovska HPP (red circle)
Source: Ukrenergo

The Ukrainian power system is presently experiencing the following technical challenges under war conditions:

- to continue operating and to provide electricity supply to consumers to the largest possible extent,

- to balance the system, keeping frequency under the permitted range, not relying too much on the neighbouring power systems because available cross-border capacities (which are still restricted by ENTSO-E) should be kept for commercial trade and emergency power exchanges if needed,
- to regulate voltages in all power system nodes, under conditions of lower generators availability (which also operate as the source of reactive power[2]), to avoid voltage collapse situations and local or system-wide blackouts,
- to repair and restore, as fast as possible, destroyed and damaged network facilities to reach the minimum level of operational security[3],
- to avoid system separation into smaller islands and to operate the unified system under one frequency value.

Following the end of the war, the power system will be restored, reconstructed, renewed and redesigned, and the following technical challenges will appear:

- ENTSO-E requirements for synchronous operation will have to be fulfilled, meaning that the Ukrainian grid must be capable of operating even under isolated mode of operation, capable of regulating frequency and voltages by using domestic sources,
- technical issues will have to be resolved[4], in order not to limit possible commercial exchanges between market players in Ukraine and the EU,
- electricity interconnections to neighbouring EU countries will have to be reinforced by constructing new 400 kV lines toward Romania, Slovakia and Poland,
- the internal transmission grid will have to be further developed and adapted to the new situation,
- due to expected decarbonisation efforts and large-scale integration of renewables, followed by mid to long-term coal phase-out, flexibility resources will have to be expanded by installing new batteries, constructing pump-storage hydropower plants and developing other short to long time-scale flexibility resources.

Even before the war, system adequacy has been constantly under pressure due to financial problems resulting in accumulated debts in the market and caused by the wholesale electricity market price caps/wholesale market regulation issues. Regulated non-cost reflective end user prices for household consumers, based on a non-compliant public service obligations, lack of coal and low liquidity of production companies have created difficult situation at the electricity market.. Requests for the introduction of a capacity mechanism were constantly under discussion. At the same time, the integration of new renewable capacities posed a number of challenges, especially from the

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[2] Production and consumption of reactive power directly influence voltages in a power network.

[3] The network shall be capable of operating under normal conditions (within permitted frequency and voltage ranges) even in a situation of sudden outage of any network facility (line, transformer), generator or large demand center.

[4] Like the one with the small-signal area oscillations that now prevent larger power exchanges between Ukraine and Continental Europe.

balancing point of view. System balancing was identified as the main issue because of the old and inflexible generation fleet, especially inflexible nuclear units and coal facilities, which is around 80 % of total electricity production. TSO's (Ukrenergo) adequacy evaluations have systematically demonstrated a need of additional 2000-4000 MW in the accumulation, manoeuvrable production with quick start and half peak capacities. This is precisely why the value of hydropower plants increases, as they can balance the system in the best technical (large ramping rate) and economically optimal way (small OPEX and comparatively low electricity production marginal price).

3 Hydropower plants in Ukraine

On the territory of Ukraine, there are about 63 thousand rivers with a total length of about 206 thousand km, including about 3 thousand with a length of more than 10 km and 115 with more than 100 km. The total average amount of water resources in Ukraine is estimated at 94.1 billion cubic meters. The main part, 92.6 %, falls on river runoff. As of 2020, there were 10 HPPs over 10 MW, four pump-storage power stations and about 50 HPPs of up to 10 MW in Ukraine[5].

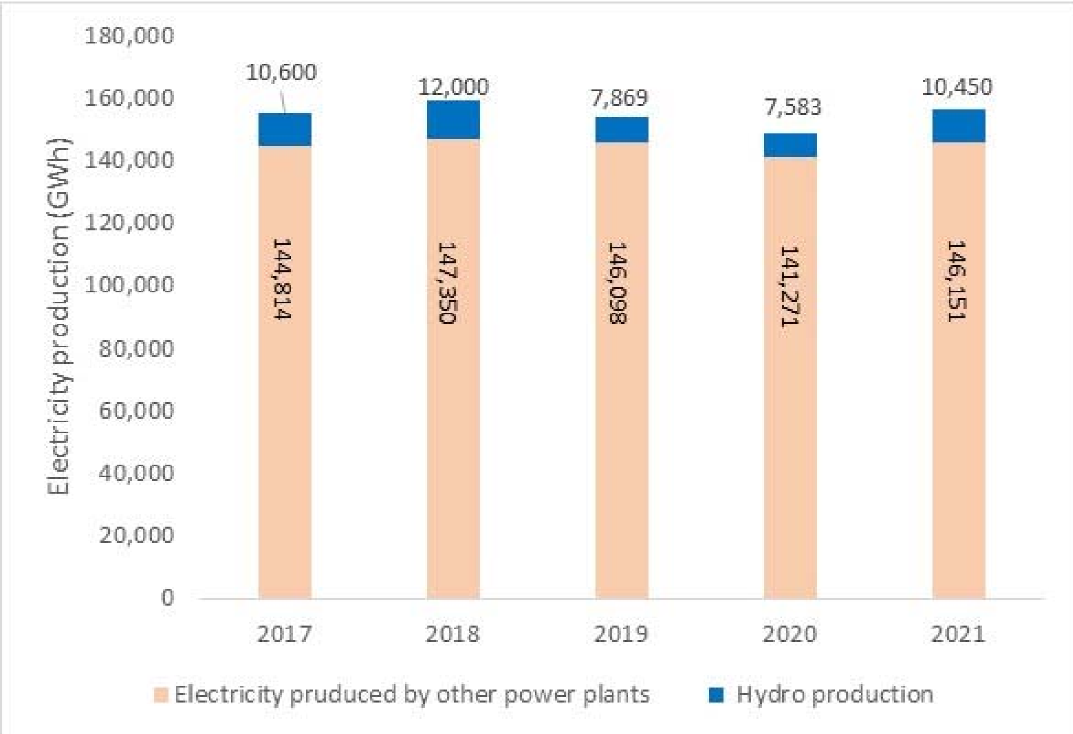

Figure 3: Annual hydro production in the last five years in Ukraine
Source: Energy Community Secretariat

[5] Source: Ukrhydroenergo

With a total installed capacity of 6.3 GW, hydropower plants in Ukraine typically produce around 10 TWh of electricity annually (in a range between 7.5 TWh and 12 TWh depending on hydrology), which is, on average, 7 % of the total domestic electricity production. Although this is not a significant amount in a power system the size of the Ukrainian one (total annual hydro production is lower than the average production of two nuclear units in the Zaporizhzhia NPP), it is important in order to cover peak loads and keep the power system balanced, especially because the majority of other power plants are inflexible (RES, CHPs, NPPs) or hardly flexible (coal-fired TPPs).

The largest hydro power company in Ukraine is Ukrhydroenergo, owning 104 hydropower units. The company's portfolio includes ten hydro facilities on the Dnipro (Kyivska HPP and Kyivska pump-storage hydropower plant, Kanivska HPP, Kremenchutska HPP, Serednyodniprovska HPP, Dniprovska HPP-1 and HPP-2, Kakhovska HPP) and the Dniester rivers (Dnistrovska HPP and Dnistrovska pump-storage hydropower plant).

Figure 4: Location of large hydro power plants in Ukraine
Source: Ukrhydroenergo

Hydro facilities are the main source of primary and secondary power and frequency control in Ukraine (or the main providers of the frequency containment reserves FCR and frequency restoration reserves aFRR/mFRR). Hydropower plants are one of the main providers of balancing services, providing peak load coverage, frequency and power regulation, acting as an emergency reserve in the power system. HPPs actively participate in the ancillary services market to ensure the reliable operation of the power system and proper power quality.

Hydropower plants are considered the most important factor for allowing larger-scale renewables integration. Variable wind and solar power plants increase the flexibility needs of a power system, on all time scales (from intra-hourly to seasonal and annual). Hydro production facilities may start up, shut down and change their power output very fast, within seconds and minutes, so they are the most suitable flexibility source to balance variable renewables. However, since their capability to produce depends on the hydrological conditions and actual water flow, they have to be supported by other flexibility resources (gas-fired units, batteries, other energy storage technologies, etc.).

IPS Zone

Ancillary service provider	Reserve volume, MW			
	FCR	aFRR	mFRR	RR
Required by TSO as per the Grid Code	±126	±372	628	1000
Currently Certified	±147	±814.5	3876	4500
Dnyprovska-1 HPP	0	183 (±91.5)	495	495
Serednyodniprovska HPP	0	178.8 (±89)	300	344
Kanivska HPP	0	144 (±72)	264	264
Kahovska HPP	0	197 (±98.5)	317	317
Dnyprovska-2 HPP	0	199 (±99.5)	479	479
Kremenchutska HPP	0	142 (±71)	542	645
Kyivska HPP	0	176 (±88)	336	336
Dnistrovska HPP	0	0	460	460
Kurahivska TPP	±88	230 (±115)	230	380
Kharkivska CHP	±27	0	90	180
Zaporizska TPP	±32	180 (±90)	183	363
Burshtynska TPP	0	0	95	145
Ladyzhynska TPP	0	0	85	92

BEI Zone

Ancillary service provider	Reserve volume, MW			
	FCR	aFRR	mFRR	RR
Required by TSO in auctions	±8	±100	60	140
Currently Certified	0	±194	235	390
Burshtynska TPP	0	±194	235	390

Figure 5: Ancillary service providers certified by Ukrenergo until October 2020
Source: USAID (Development of Ancillary Services Market in Ukraine)

After the Russian attacks on electricity infrastructure, all available hydro generation units operate at maximum capacity (as at 28 October 2022) to provide energy to the power system under extremely difficult conditions. This is possible thanks to the currently high water levels available for electricity production thanks to favourable hydrological conditions.

4 The Dnipro river cascade and the Kakhovska HPP

The Dnipro hydro cascade consists of the Kyivska HPP with an installed capacity of 408.5 MW constructed in 1964[6], Kanivska HPP of 444 MW from 1972, Kremenchutska HPP of 692 MW from 1959, Srednyodniprovska HPP of 352 MW from 1963, Dniprovska HPP of 1569 MW from 1932 and Kakhovska HPP of 335 MW from 1955. Several more hydropower plants are planned to be constructed: Kanivska HPP of 1000 MW and Kakhovska-2 HPP of 250 MW.

Due to the total installed capacity of hydro generation facilities, hydro reservoirs and water flow quantities, the Dnipro cascade is the main source of hydro production in Ukraine, also having an important role beyond the power sector, in water control, water supply and irrigation.

The Kakhovska HPP is the last hydro facility (the lowest position) on the Dnipro river, used mainly to control water supply to southern Ukrainian communities for irrigation and water control from Kherson to Zaporizhzhia. It consists of a 30 m high dam, creating the Kakhovska reservoir, the only water reservoir at the Dnipro cascade with annual accumulation. The size of this reservoir is the largest in Ukraine, with a length of 240 km, a surface area of 2155 km ^{2} and a volume of 18 km^3.

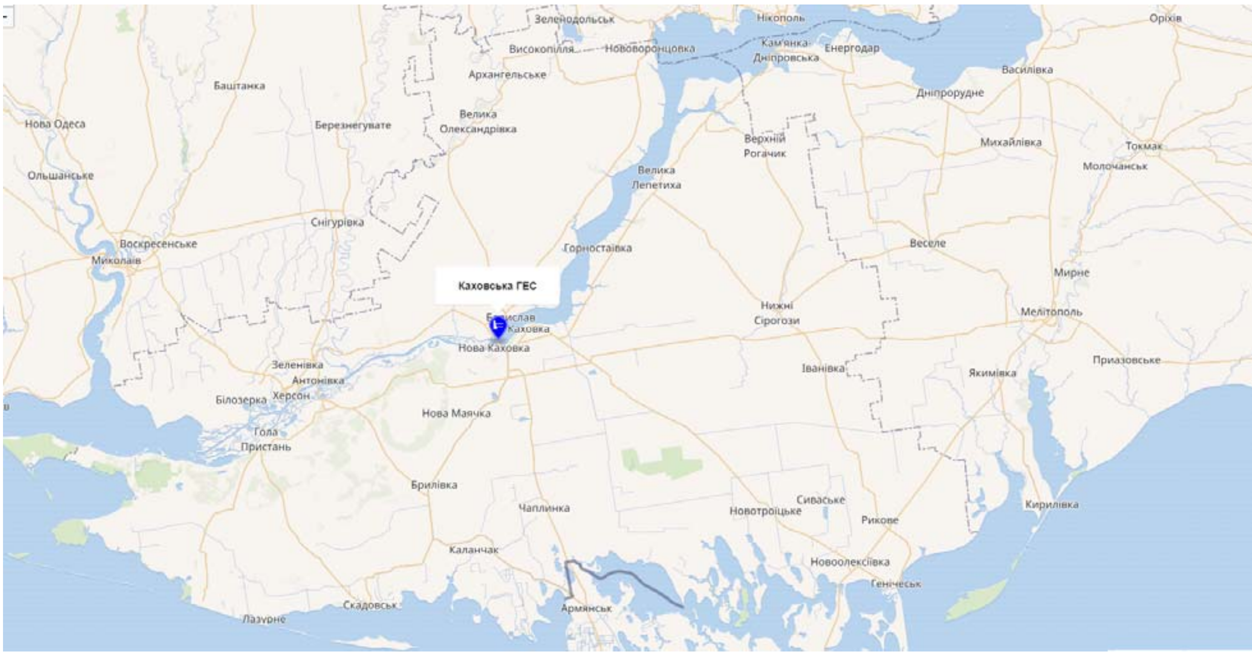

Figure 6: Location of Kakhovska HPP at Dnipro river cascade
Source: Internet[7]

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[6] Plus Kyivska pump-storage power plant of 235 MW

[7] https://uk.m.wikipedia.org/wiki/%D0%9A%D0%B0%D1%85%D0%BE%D0%B2%D1%81%D1%8C%D0%BA%D0%B0_%D0%93%D0%95%D0%A1

The Kakhovska HPP has six units with an installed capacity of 56 MW each, which gives a total installed HPP capacity of 335 MW. All generation units are connected to the 110 kV network, providing electricity to local consumers and controlling voltages with approximately 50 Mvar of possible reactive power support. The power plant operates typically in base or semi-base load mode. Annual electricity production was around 1 TWh or 0.65 % of total electricity production of Ukraine. Although its installed capacity amounts to only 0.6 % of total Ukrainian power plants installed capacity, its role is multifunctional such that the HPP provides electricity supply to neighbouring areas as well as water supply and irrigation throughout the entire region (the Kakhovsky Canal, the North Crimean Canal and the Dnipro-Kryvyi Rih Canal start at the reservoir).

The transmission network configuration around Kakhovska HPP is shown in the following figure. The whole area is supplied over the 750/330 kV Kakhovska substation, which is connected with the Zaporizhzhia NPP with one 750 kV line and with Kherson, Kryvorizka, Zaporizhzhia and Crimea with five 330 kV lines. In normal circumstances (if all 750 kV and 330 kV lines were available), the role of Kakhovska HPP in local electricity supply would be minor since the region's extra high-voltage transmission grid is capable of providing electricity supply from distant areas, especially from Zaporizhzhia NPP with an installed capacity of 5.7 GW and Kryvorizka TPP with an installed capacity of 2.4 GW.

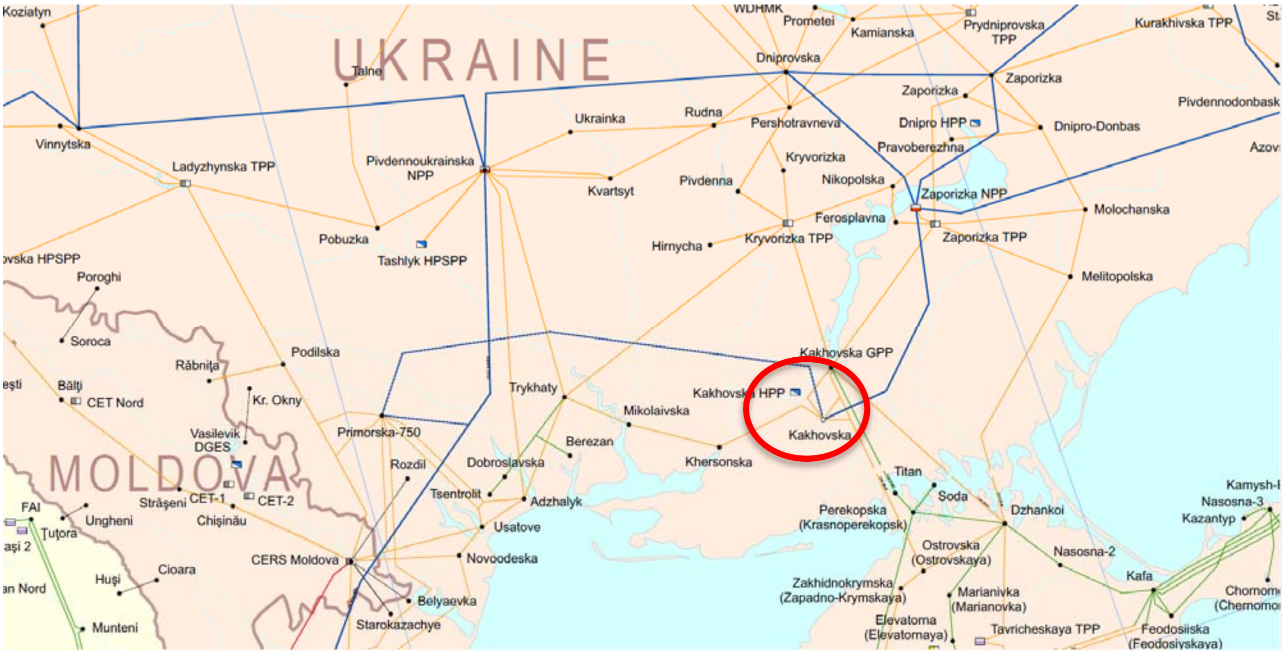

Figure 7: Transmission network 750 kV and 330 kV around Kakhovska HPP (Source: ENTSO-E)

With respect to the power and frequency regulation reserves within the Ukrainian power system, Kakhovska HPP has been certified to provide ±98.5 MW of the automatic frequency restoration reserve, which was about 8.15 % of all amounts of certified aFRR.

Currently, Kakhovska HPP is occupied by the Russian military, with four units operating (out of six) but disconnected from the rest of the Ukrainian power system and not controlled by Ukrhydroenergo and Ukrenergo dispatchers. The 750 kV line Kakhovka - Zaporizhzhia is permanently out of operation, and one may assume that the majority of 330 kV lines in the area are also switched off due to damages. This gives additional importance to Kakhovska HPP in terms of providing power supply to the local area, including the town of Kherson. Electricity production from Kakhovska HPP is now only relevant for the occupied territories since the power plant has been disconnected from the main part of the power system of Ukraine.

5 Risks related to the destruction of the Kakhovska HPP dam

5.1 Flood

The reservoir of Kakhovska HPP has a total surface area of 2,155 km^2 in the Kherson, Zaporizhzhia and Dnipropetrovsk regions. It is 240 km long and up to 23 km wide. The depth varies from 3 m to 26 m and averages 8.4 m. The total water volume is 18.2 km^3. At the moment, hydrological conditions are favourable, and one may assume that the water level in the reservoir is high. Approximately 2000 m^3 of water comes to the dam and only 500 m^3 is used by the hydro units, while 1500 m^3 of water is released through the dam. The dam is 30 metres tall and 3.2 km long.

The destruction of the dam would lead to the sudden release of vast amounts of fast flooding water, which would destroy areas downstream of the dam, including the Kherson city. It is reasonable to assume that human victims would be counted in hundreds of thousands, with huge consequences for the agriculture and water supply of the entire southern part of Ukraine. This event would be a large-scale catastrophe, previously not seen in modern history.

Various dam-related accidents have occurred causing their collapse, but not of this size and not due to intentional human activities[8]. Large accidents on dams were recorded in USA, China, India and Italy, causing thousands of human casualties.

5.2 Cooling of reactors in the Zaporizhzhia nuclear power plant

The Zaporizhzhia NPP (ZNPP), equipped with six nuclear reactors VVER-1000 with a total power output of 5.7 GW, has been operating since the beginning of March 2022 under extremely difficult conditions, which have never been experienced anywhere else. Due to the Russian occupation, military presence in the power plant, war activities on the site and surrounding areas and finally

[8] One accident due to dam mining happened 29 years ago in Croatia, when the Peruca HPP dam (41.6 MW at the time) was mined. The explosive was detonated but did not cause the dam to collapse.

Russian attempted property theft, nuclear safety has been jeopardised, as confirmed many times by the IAEA[9].

At the beginning of the war, IAEA established seven indispensable nuclear safety and security pillars and has assessed the situation against these pillars on a regular basis. One of these indispensable pillars is the security of the power supply from the grid[10] (off-site power supply), which is necessary to operate the plant and provide cooling for the reactors, despite the fact that there are twenty diesel-aggregates (on-site power supply), which are in general considered by the nuclear industry as a less reliable power supply source than the grid[11]. Constant risks related to the safety of ZNPP, caused by Russian aggression, threaten the nuclear industry and reduce the prospects for the wide application of this zero-CO2 technology in the future.

Despite the fact that currently all six reactors are in shutdown mode (the last ones disconnected in September[12]), they still need water to run through their cooling systems. The power of decay heat in a VVER-1000 reactor, after its shutdown, is approximately 0.3 % of the nominal heat power, which is 20 times lower than the power of decay heat immediately after shutdown (6 % of the nominal heat power)[13]. Having in mind that the capacity of RHR[14] heat exchangers is less than 3000 t/h, the cooling needs should not be higher than 150 t/h for units 5 and 6. Temperatures inside the reactors are now significantly lower than when the plant was operating at full power, but reactor cooling is dependent not only on water quantities but also on the technical design of water abstraction. However, today, when all six reactors are in shutdown mode, any difficulties related to the reactor's cooling would require a longer time period to be resolved than before when units 5 and 6 were operating at full capacity.

Since ZNPP takes water from the reservoir directly connected to the reservoir of the Kakhovska HPP, any decrease in the water level would create additional disturbance related to the nuclear safety of the Zaporizhzhia NPP. In case of a significant drop in the water level, the future operation

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[9] For example, in the 1st and 2nd Summary Report by the Director General about nuclear safety, security and safeguards in Ukraine.

[10] Among the 750 kV four lines connecting the ZNPP to the grid, three lines are permanently out of operation with the forth line periodically switched off. Backup lines (330 kV) are also periodically disconnected which caused several loss-of-offsite-power (LOOP) situations. LOOP is considered by the nuclear industry as an important contributor to total risk at nuclear power plants.

[11] IAEA Nuclear Energy Series No. NG-T-3.8, Electric Grid Reliability and Interface with Nuclear Power Plants (https://www.iaea.org/publications/8754/electric-grid-reliability-and-interface-with-nuclear-power-plants).

[12] Units 5 and 6, other units are in the shutdown mode for a longer time.

[13] Z.Tabadar, S.Aghajanpour, M.Jabbari, M.Khaleghi, M.Hashemi-Tilehnoe, *Thermal-hydraulic analysis of VVER-1000 residual heat removal system using RELAP5 code, an evaluation at the boundary of reactor repair mode*, Alexandria Engineering Journal, Volume 57, Issue 3, September 2018, Pages 1249-1259.

[14] Residual heat removal.

of this power plant would also be at risk, not only due to a constant radiological threat but also possible damage to the reactor core in case of interrupted cooling.

If the ultimate heat sink (UHS) is lost (ZNPP's primary UHS is the dam-lake and its secondary UHS is the pond-reservoir), then the operators have to rely on feed-and-bleed to remove heat from the reactors and spent fuel pools (SFPs), which will require water replenishment by other means. They will also need make-up water for essential service water to cool the equipment. During a stress test, the loss of UHS combined with a station blackout (SBO[15]) was analysed[16]. The analysis showed that the operators need mobile sources within 72 hours. Back-up UHS typically provides essential cooling water for 10-30 days, depending on the reactor design and the cooling schemes after the primary heat sink is gone (in ZNPP's case, the dam is blown up and the dam lake is drained). Providing that off-site and on-site power is available, it seems that the secondary heat sink at ZNPP would provide at least 10 days of water supply without the need of bringing in water trucks. If no water replenishment is available, the operators would have 200 hours before the core is damaged.

An additional threat should also be mentioned here, not directly related to the Kakhovska HPP dam. Attacks on Ukraine's energy infrastructure pose serious danger to the functioning of the country's power system, which could eventually lead to a system-wide blackout. In that situation, not only would ZNPP be affected but also three other nuclear facilities[17], including one radioactive material waste disposal site (Chernobyl). All of them could be left without external power supply. Such a situation would create serious nuclear safety risks as reactor cooling would be required simultaneously at multiple sites, and it would be harder and take longer to restore the power system due to the extensive infrastructural damage. In case power supply to all five nuclear sites, including Chernobyl, was lost, this would result in a much more difficult situation than if off-site power supply was lost only to ZNPP[18].

5.3 Consequences for the Ukrainian power system

The possible destruction of the Kakhovska HPP dam would result in minimal additional harm to the Ukrainian power system at this moment as its functioning continues to be jeopardised by Russian shelling, especially large substations 750/330 kV, 330/110 kV and 220/110 kV, including the extra-high voltage overhead lines. Since the Kakhovska HPP has been disconnected from the rest of the

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[15] A station blackout (SBO) accident refers to the occurrence of the hypothetical sequence of events that lead to the loss of all off-site and on-site (emergency diesel generators) alternating current (AC) power supplies, and failure of AC power restoration in a normal operating nuclear reactor.

[16] https://www.ensreg.eu/sites/default/files/National%20Report%20of%20Ukraine.pdf

[17] Khmelnytskyi, Rivne, Yuzhnoukrainsk

[18] No nuclear power plant has ever been designed to consider potential war-induced damage in its safety demonstration. WENRA, therefore, reiterates its previous position: it is imperative to exercise the utmost restraint and vigilance to prevent any direct or indirect impact of military operations on nuclear installation safety (WENRA position on the safety situation of Zaporizhzhya NPP after reported shelling activities).

Ukrainian power system and is not controled by Ukrenergo dispatchers and Ukrhydroenergo, power supply at the unoccupied Ukrainian territories depends on the availability of production facilities and their manoeuvring capabilities, their grid connection and transmission network integrity, which has to be maintained in order to preserve the operation of the whole power system without the creation of smaller islands within it. Power system operation also depends on connections with neighbouring EU countries and their possibilities to provide emergency support and balancing energy if needed. These issues will become increasingly important as the weather worsens and electricity consumption rises with the oncoming of winter.

In post-war conditions, the destruction of the Kakhovska HPP would lead to economic losses as the HPP would no longer produce electricity and important aFRR quantities within the power system would be lost and needed to be replaced by other flexibility sources like battery energy storage systems (BESS). According to the current base-load average electricity price at the Hungarian power exchange (HUPX) of 391 EUR/MWh (average in September 2022), this loss would be around 400 MEUR/year or around 75 MEUR/year by assuming the average electricity price at the Ukrainian power exchange of 75 EUR/MWh[19]. Investment in new BESS to replace the HPP to provide aFRR would be around 200 MEUR. It is assumed that other HPPs at the Dnipro cascade would not be influenced by the destruction of the dam since they are all placed upstream of the Kakhovska dam.

6 Conclusions

In case the Kakhovska dam is destroyed, a large-scale human and environmental disaster would be likely to arise, causing the destruction of irrigation and water supply systems in Southern Ukraine and possibly hundreds of thousands of casualties.

Without the Kakhovska dam, the Zaporizhzhia NPP would be under additional stress, resulting in an even more unacceptable situation at this site since the Russian occupation started in March 2022. However, the risk of a nuclear incident at ZNPP is now lower since all six reactors are now in a shutdown mode. The long-term consequences of the Russian military aggression with respect to this power plant cannot be estimated at this moment. The situation could lead to negative impacts not only on the ZNPP and the Ukrainian power system but also on the nuclear industry as a whole.

The loss of Kakhovska HPP would not cause additional harm to the Ukrainian power system at the unoccupied territories as the HPP is already disconnected from that part of the system. In the period after the war, its destruction would create economic loss worth hundreds of millions of euros per year and decrease the overall automatic frequency restoration reserves within the Ukrainian power system making the power system balancing more challenging and costly.

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[19] This would depend on the hydrological conditions and annually produced electricity, prices at the power exchanges/bilateral contracts (still impacted by wholesale prices regulation) and the amount of capacity offered to provide aFRR reserve.