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Ukraine's Coming Electricity Crisis
How to Protect the Grid from Russian Attacks

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After 11 months of war and nearly four months of relentless Russian attacks on Ukraine's energy sector, the country's electric grid comes nearer to collapse each day. In addition to its brutal barrages on residential areas, Russia has targeted power plants, substations, and other critical infrastructure that electrifies the country. Ukrainians are now habituated to rolling blackouts, but the electricity supply falls far short of what the country needs, inducing severe economic disruption. Further strikes could cause the total failure of Ukraine's electric grid, plunging tens of millions of people into darkness.

Deaths from a grid collapse could be far greater than the casualties caused by a Russian use of tactical nuclear weapons. A grid collapse could also lead to a humanitarian and refugee crisis for Europe, the meltdown of nuclear reactors, flooding from breached hydroelectric dams, and a deeper food crisis for countries dependent on exports from Ukraine.

But the West has the wherewithal to avert this catastrophe. Kyiv's friends in NATO and elsewhere should deliver swift and targeted aid for the country's electric grid, help that is commensurate with the financial resources and diplomatic attention devoted to weapons systems. After all, electric power, not just weapons, sustains Ukraine's war effort. If Western democracies take effective action and reinforce the country's tottering electric grid, they will show how societies can be protected from such attacks on critical infrastructure. But if these democracies do not rise to this challenge, bad actors worldwide will gain confidence that striking the electrical underbelly of a country is the best way to bring it to its knees.

UNDER ASSAULT

Electric grids are among the largest and most complex machines ever devised by humans. They consist of five basic categories of facilities and equipment: generation plants, transformers at plants that increase voltage for transmission, long-distance transmission lines that carry current from place to place, transformers that lower voltage at intermediate substations, and distribution networks that bring power to homes and

businesses. The Achilles' heel of electric grids are the large transformers that raise and lower the voltage of the electricity, which are called "generator step-up transformers" and "autotransformers." Often the size of a small house, these devices weigh hundreds of tons and must be transported by special railcars and trucks. By necessity, transformers need to be placed in open spaces to allow the free circulation of air for cooling. This open-air design makes large power transformers a prime target for long-distance attacks by bombers, missiles, and drones.

Life in Ukraine without a functioning electric grid would soon become torturous—and for many, unlivable. Electricity powers the pumps on which Ukrainian cities' water treatment systems rely. It provides refrigeration for the production and distribution of food. In the large cities, combined heat and power plants keep homes and businesses warm and lighted through the winter months. Electricity powers the country's telecommunications, including what is needed for Ukrainian President Volodymyr Zelensky's nightly address and other essential governmental functions. ATM machines, payment cards, and mobile wallets depend on electricity. Because electricity is used to pump fuel into and out of storage, it underpins the logistics network used by the Ukrainian military.

In the initial stages of the war, Russia showed restraint in attacking critical infrastructure, largely sparing Ukraine's electric grid. Shelling near battle lines caused some damage to power plants, but the Kremlin was not deliberately trying to destroy such facilities. If Russia had succeeded in a quick campaign, it could have diverted electricity from captured plants to its own grid—or even sold Ukraine's electricity at high prices to Europe. But as the Russian advance slowed, the Kremlin reevaluated its strategy and started attacking Ukrainian infrastructure.

Ukraine has a well-developed rail network that extensively uses electric locomotives. Specialized transformers convert electricity from transmission lines into the lower voltages necessary for railroad use. Last April, Russia targeted rail traction substations in western Ukraine, destroying their transformers and hampering rail service. In April and early May, Russia conducted three rounds of missile attacks on the Kremenchuk energy complex, a key facility in central Ukraine for petroleum refining, electricity generation, and oil storage. The Kremlin claimed that the purpose of these attacks was to make it harder for NATO to supply weapons to the Ukrainian war effort.

By late September, Russian and Ukrainian ground forces had reached a rough stalemate. On September 26, unknown actors sabotaged the Nord Stream 2 pipeline, which was built to supply Russian gas to Germany but had not yet begun operating. The next day, Russia conducted an attack on Ukraine's electric grid. Three explosions occurred in the

eastern Ukrainian city of Kharkiv, including one at the site of a power transformer; Internet monitoring showed that the city suffered a large blackout.

Russian officials claimed that on October 8, Ukrainian operatives detonated a truck bomb on the Kerch Strait Bridge between Crimea and Russia. Two days later, on October 10, Russia conducted its first massive aerial assault on Ukraine's electric grid. Putin announced that the grid attack was in retaliation for the bridge bombing. The resulting blackout in the western city of Lviv shut down Internet routers and reduced connectivity in the city and surrounding province by two-thirds. A full-fledged infrastructure war had begun.

THE ELECTRICAL UNDERBELLY

Russia was intimately involved in the design of Ukraine's grid and is familiar with its vulnerabilities. Nearly all of Ukraine's electric grid was constructed in the Soviet era. Over half of Ukraine's electric generation capacity is supplied by 15 nuclear reactors at four plant locations. (One nuclear power plant, Zaporizhzhia, has been captured by Russian forces and has been intermittently cut off from Ukraine's grid.) With deliberation and increasing frequency since the Kerch Strait Bridge bombing, Russia has attacked vital transmission nodes. Ukraine's air defenses successfully block about 80 percent of these strikes, but the missiles and drones that get through have had a devastating impact, especially on the large autotransformers that convert high-voltage electricity from Ukraine's nuclear plants into the lower voltages used in urban areas.

The Russian attacks have so damaged the grid that its operator, Ukrenergo, has been forced to institute rolling blackouts throughout the country. The grid is able to meet about 75 percent of normal customer demand, with occasional dips below 50 percent. Measurements of Ukraine's Internet connectivity, a good proxy for electricity service, are trending downward.

On November 23, Russia nearly landed a knockout blow on Ukraine's grid when it used around 70 cruise missiles and kamikaze drones to target important grid infrastructure. Ukrainian forces shot down most of the cruise missiles, but their efforts did not prevent most of the country from losing power, with only a handful of electrified pockets remaining. Grid operators skillfully used these islands of electricity to restore power the following morning, but the events of that night demonstrated the possibility of a total system collapse.

Russia has tried not only to devastate Ukraine's electric grid but also to shatter its supply chains for key electrical equipment. Before the invasion, the largest producer of

transformers in all of Europe and the former Soviet states was the Ukrainian-based company Zaporozhtransformator, also known as ZTR. The company has a skilled workforce of 3,500 employees. ZTR supplied over 95 percent of the transformers used in Ukraine's grid and some key transformers for Russia, too. ZTR's principal factory lies in the Zaporizhzhia region of Ukraine, near the current frontlines. Until Ukraine nationalized the company last November, ZTR was jointly owned by Ukrainian and Russian entities. In the first week of December, Russia conducted an aerial attack on ZTR's transformer factory, damaging production lines and storage areas.

WHEN THINGS FALL APART

The breakdown of an electric grid can be both a cause and a result of societal instability. For a country's electric grid to keep operating, it requires the coordinated resources of a sophisticated society: skilled engineers and technicians; fuel supplies for the generation of electricity, physical and cybersecurity defenses; telecommunications; and supply chains for spare parts. Russia has eroded each of these pillars. In the wake of incessant attacks and only patchwork repairs, the possibility of a full collapse is real. Since complex societies cannot long survive without electricity, a broader societal collapse may follow.

Millions of Ukrainians have already fled the country, and the wartime population now stands at approximately 35 million. The destruction of the electric grid would send many millions more scrambling toward the country's borders, plunging Europe into a new refugee crisis. Although duty may require the operators of nuclear power plants and hydroelectric dams to remain at their posts, some will invariably decide to escape with their families. Already, three-quarters of the workers at the Zaporizhzhia nuclear plant, now in Russian hands, have left.

The loss of such workers could be very dangerous. Never before has a country dependent on nuclear power plants experienced such a barrage on its electric grid. Nuclear power plants require highly trained technicians to keep their facilities running safely. If grid power fails for more than a week or two, reactors could melt down or fires might start in the spent fuel pools, releasing radiation into surrounding areas.

So, too, could the loss of key workers lead to catastrophe at hydroelectric facilities. Ukraine has an extensive network of dams on the Dnieper and Dniester rivers. The safe operation of these dams requires on-site personnel to adjust water flows, clear debris on spillways, and respond to emergencies. Dam gates, which are opened and closed by electric motors, need to be actively managed. Without personnel on hand and a supply of reliable electric power for the operation of the gates, water can surge over the top of

the dam in a process called overtopping, which could lead to erosion and the dam's eventual failure.

Earthen dams are particularly susceptible to breaches caused by overtopping and rapid erosion. Just upstream of the capital is one of the longest earthen dams in the world, the 11-mile left bank dam of Kyiv Reservoir. The sediment in the bottom of the reservoir contains radioactive material from the 1986 Chernobyl nuclear disaster. A surge of water from a dam breach here could contaminate Kyiv as well as other cities and bodies of water downstream. During World War II, Stalin ordered the demolition of the Dneprostroi dam in the south of Ukraine to impede the advance of German troops; the resulting flood tore through villages and towns on the banks of the river, killing tens of thousands. A dam failure north of Kyiv, with water surging down the Dnieper valley, could have even more horrific results: the deaths alone could exceed the civilian toll to date of the current war.

Beyond such disasters, a total collapse of the grid would have calamitous consequences for Ukraine's military, undermining its logistics networks. Western powers have spent over $100 billion supporting Ukraine, but the amount required to aid both the country's military and humanitarian relief efforts would increase dramatically in a country without a functioning electric grid.

A complete electric grid collapse would likely kill a significant proportion of Ukraine's population. Batteries for communication networks would run down. Government services would cease. Many of Ukraine's citizens would attempt to evacuate, but when the electrically powered pumps at gas stations stopped functioning, motorists would not be able to refuel. Roads would soon become clogged with stalled vehicles. Some people would strike out on foot, but others would be left behind with dwindling supplies of food and water. Within weeks, famine would probably sweep the country. Without clean water from treatment plants, epidemics could flare.

The wider world would also suffer. In the year before the Russian invasion, Ukraine's agricultural exports supplied 40 percent of the wheat for the UN's World Food Program and made up 12 percent of global corn exports and nine percent of wheat exports. Ukraine's much-reduced grain exports are mostly passing through the port of Odessa. The city's electricity supply has already been hit hard, with only about half the existing demand met by the available supply. If Ukraine's electric grid were to collapse, grain exports could stop entirely, deepening hunger in the world's poorest countries.

HOW TO KEEP THE LIGHTS ON

In the initial stages of the war, Ukraine rushed to obtain weapons from NATO member states. Foreign aid to support critical infrastructure, including Ukraine's electric grid, was an afterthought. But if the country's electric grid collapses, the billions of dollars spent on advanced weapons systems may come to naught.

Russia's aerial attacks are destroying critical grid equipment faster than it can be repaired or replaced. Every single major transmission substation and thermal generation plant in Ukraine has experienced at least one attack, and some have been struck more than five times. Dozens of autotransformers, the most critical component of the grid, have been destroyed. The procurement of autotransformers has become an urgent priority for the Ukrainian government.

Through Western embassies, Ukraine has distributed a "priority" shopping list of grid equipment. The list includes hundreds of costly items, including 55 urgently needed autotransformers. On January 18, the U.S. State Department announced $125 million in funding for Ukraine's electric grid, in addition to $53 million announced in November. As of this February, the Ukraine Energy Support Fund established by the EU Energy Community Secretariat had raised $157 million and disbursed $118 million. But this is woefully inadequate: the autotransformers alone on Ukraine's shopping list would cost more than the entire sum raised. More resources are urgently needed. It will take billions of dollars to prevent the collapse of Ukraine's electric grid, an outlay of great magnitude even if it is considerably less than what has already been spent to supply the country with weapons.

Obtaining replacement grid equipment for Ukraine—especially autotransformers—will be challenging, even if sufficient funding is available. Before the COVID-19 pandemic, the manufacturing lead time for autotransformers was about one year; European customers now have to wait up to three years. These transformers are expensive, costing around $5 million to $10 million per unit, and they are durable, lasting 40 years on average. They are often custom-designed as well. As a result, few spares are stocked.

Transformers operating at 750 kilovolts, such as the replacements needed for the transmission backbone of Ukraine's electric grid, are produced in volume in only a few countries; these include China, India, Japan, and South Korea. Smaller producers of autotransformers closer to Ukraine include the Netherlands, Spain, and Turkey. The United States has minimal capacity to build autotransformers. Although industry groups have been lobbying the U.S. government to apply the Defense Production Act to expand domestic capacity, their efforts have not yet succeeded.

NATO member states and other allies of Ukraine could supply replacement transformers from other sources: the spares kept by utility companies in their countries, transformers taken out of service near the end of their operational lives, and even newly manufactured units. Some of Ukraine's grid voltages and transformers are compatible with transformers used in transmission systems of the former Warsaw Pact countries but less so with those of other regions. Transformers are often operated until the time when monitoring shows they are about to fail, but some may still have useful life remaining.

Wartime resourcefulness may offer some solutions. Already, Ireland and Latvia have contributed one spare autotransformer each. Canvasses of used transformer brokers are locating some units that might be useful for Ukraine. High-voltage transmission networks have thousands of transformers. Each year, hundreds come out of service and are cannibalized for their components, especially copper wire that is valuable in the scrap metal market. As a stopgap measure, transformer vendors could remanufacture these used transformers, especially those decommissioned by utility companies in Europe and North America.

The United States and its allies should impose a moratorium on dismantling large transformers. Their reusable components—iron tanks and laminated cores made of specialized electrical steel—can be reshaped to approximately fit the frequency and voltage combinations of Ukraine's grid. The remanufacturing might be done in neighboring Poland, in other countries near Ukraine, or at the ZTR transformer factory in Ukraine itself. If necessary, ZTR's skilled workforce could move to sites outside Ukraine. Remanufacturing could cut the lead time for replacement transformers to months instead of years.

Ukraine will ultimately require custom-produced transformers to rebuild its transmission system. If all the materials needed are on hand, it takes less than two months to build and test an autotransformer, far less than the three-year lead time commonly quoted by most manufacturers. Concerted diplomacy could help persuade governments and private companies to fast-track Ukraine's transformer orders, putting them at the front of production queues.

FULL ATTENTION

The war in Ukraine is the largest conflict in Europe since World War II and the first since the widespread adoption of electric grids that extend hundreds of miles. Whole societies depend on the grids' custom-designed, hard-to-transport components, manufactured half a world away. Decades of peace and the economics of globalization have resulted in

the concentration of grid equipment manufacturing in just a few countries. The war has glaringly exposed such vulnerabilities in the current operation of electric grids. NATO leaders are currently concerned with the supply of M1 Abrams and Leopard 2 tanks, Bradley Fighting Vehicles, Patriot missile systems, and even F-16 aircraft. Advanced weapons may help to win the war, but a lack of autotransformers may lose it.

Ukraine's woes should serve as a reminder that esoteric technical matters, such as the pivotal role of large transformers in electric grids, can shape the outcomes of conflicts. Countries fight not just military battles but infrastructure battles, too. Modern societies will face calamity if electricity is out for an extended period. In Ukraine, epidemics caused by dirty water, starvation, mass migration, reactor meltdowns, dam failures, and even military defeat have become real possibilities. But policymakers should remember that Ukraine's electricity situation is also an opportunity to practice creative solutions, such as the remanufacturing of large transformers.

Ukraine's electric grid can be reinforced, but time is running short. NATO's leaders need to give their full attention to this looming crisis if they—and the Ukrainians—do not want to be left in the dark.

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