

Preserving Ukraine's Electric Grid During the Russian Invasion

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ABSTRACT

In February 2022, the Russian Federation invaded Ukraine, a country with an interconnected electric grid.¹ While most analysts have concentrated on the military dimensions of Russia's attack, the implications for energy infrastructure are both unprecedented and critically important. Russia has incentives to preserve reliable operation of Ukraine's electric grid. Both sides have shown restraint in attacking energy infrastructure. An apparent Russian objective is keeping hard-to-replace infrastructure intact, especially hydroelectric and nuclear plants. Ukraine's natural gas pipeline system depends on grid electricity for its centralized control. Russia profits from transmission of its natural gas through Ukraine's pipelines to Europe. All countries seek to avoid infrastructure accidents and human migrations that are disruptive to their own societies. Nonetheless, by export ban, naval blockade, and physical attack, Russia has disrupted fuel supplies for Ukraine's generating plants. Interconnected electric grids are vulnerable to cascading collapse after forced outages of generating plants, transmission system disruptions, and deliberate attacks. As winter approaches, fuel supplies for Ukraine's electric grid will be constrained and the possibility of grid collapse increases. If Ukraine's electric grid were to be inoperable for a prolonged period, the result could be widespread death by famine, disease, and, in winter, hypothermia. Nuclear reactor meltdowns and spent fuel pool fires could also result, with radiation release extending beyond Ukraine's borders. Millions of refugees would cross the borders of Poland, Russia, Belarus, and other regional neighbors. Ukraine should develop a robust plan for electric grid restoration, including asking the Ukrainian people for their assistance during emergencies. To this end, financial and other targeted support for Ukraine's electricity sector by European

¹ Ukraine's electric grid is an Interconnected Power System, sometimes also referred to as an Integrated Power System (IPS). Ukraine uses the terminology "Unified Energy System" (UES). For easier understanding of this paper by non-technical readers, the term "electric grid" is used throughout to mean the UES of Ukraine.

and other allies may be essential to reduce the prospect of long-term grid collapse. Events in Ukraine have public policy lessons for all nations with electric grids vulnerable to cascading collapse and long-term outage.

Keywords: Ukraine, Russia, invasion, infrastructure, electric grid, collapse

Introduction

For centuries, the geography and natural resources of Ukraine have made it a target for conquest, a subject of forced famine, and a venue for mass casualty events. Historical and geographic context is vital to understand the significance of famine in the Ukrainian national ethos, the most recent Russian invasion, and the prospect of massive population loss if the country's electric grid were to collapse.

Since establishment of the medieval state of Kyivan Rus', Ukraine has had its own political identity, language, and culture. The current boundaries of Ukraine are situated between European Union (EU) countries and Moldova to the west, the Russian Federation to the east, Belarus to the north, and the Black Sea and Sea of Azov to the south. In the latter part of the 18th century, most of Ukrainian ethnographic territory became part of the Russian Empire. Ukraine had a brief period of independence from 1917-20 but again came under Russian domination as part of the newly formed Soviet Union. In 1991, Ukraine regained its independence after the breakup of the Soviet Union, leaving a large minority of ethnic Russians living within its territory, especially in the Crimean Peninsula in the south and Donbas region in the east.

Ukraine's population before the 2022 invasion was 41 million, with a Gross Domestic Product (GDP) of US\$517 billion, and per capita income of US\$12,400 (2020 estimates). Seventy percent of the population lived in urban areas. Approximately 78 percent of Ukraine's citizens have Ukrainian ethnicity and 17 percent have Russian ethnicity; most of the remainder have eastern European ethnicity.²

Ukraine has a substantial land area of 550,000 square kilometers, about the same area as the state of Texas in the United States. The country's fertile black earth and ample rainfall makes for some of the most productive farmland in the world, a natural advantage that has provided persistent motivation for political domination and military conquest by other European states.

Despite its immense food production capacity, Ukraine has experienced repeated famines in which significant percentages of its population perished. Soviet policy precipitated the Povolzhye famine of 1921-23 in which one million died and

² Unless otherwise noted, statistics in this article referring to Ukraine exclude the occupied territory of Crimea.

the Holodomor of 1932-33 in which four million died. (Internet Encyclopedia of Ukraine, 2022) Ukraine suffered 1.5 million civilian deaths due to famine and disease during World War II, many in urban areas. (World Population Review, 2022) In 1946-1947 Ukraine was hit with another famine, with 350,000 registered excess deaths. (Elman, 2000)



Figure 1. Map of Ukraine. (CIA Factbook, 2022)

The climate of Ukraine is temperate, but temperatures can fall to -20 degrees Centigrade (-4 degrees Fahrenheit) during the Siberian Anticyclone. Heating of homes and businesses is essential during winter months. Apartment buildings in Ukraine's cities rely on district heating systems constructed during the Soviet era. While some district heating systems are boiler-only, many are Combined Heat and Power (CHP) systems that use byproduct steam from electricity generation and industrial processes. Approximately 20 percent of heating in Ukraine is supplied by CHP plants. (Tsarenko, 2007)

Energy infrastructure has a prominent role in the history of Ukraine and the Soviet Union. Russia has the apparent objective of keeping energy infrastructure intact, especially Ukraine's four nuclear power plants, hydroelectric dams, and natural gas pipelines. Two major rivers, the Dnieper and the Dniester, have existing hydroelectric plants and significant undeveloped hydroelectric capacity. Ukraine's natural gas transmission system took decades to build and became an important energy source for Europe commencing with the Soyuz pipeline in 1978 and the Brotherhood pipeline in 1984.

Construction of the Dnieper Hydroelectric Station was one of the greatest infrastructure accomplishments of the early Soviet Union and part of the first

Five Year Plan. Its reservoir source, the Dnieper River, is the fourth largest river in Europe. The river runs north to south, entering Ukraine near the abandoned Chernobyl nuclear plant; flowing past the cities of Kyiv, Cherkasy, Dnipro, Zaporizhzhia, and Kherson; and exiting into the Black Sea. Original construction of the Dnieper Hydroelectric Station took place from 1927 to 1932, a period that overlapped the first stage of the Holodomor in 1932. Retreating Red Army troops dynamited the dam in 1941, causing between 20,000 and 100,000 Ukrainian civilians to be killed by the flood surge. The Soviet Union rebuilt the dam and hydroelectric facilities from 1944 to 1949 using turbines manufactured by General Electric. Installed capacity of this single hydroelectric plant is approximately ten percent of the peak demand of the Ukrainian electric grid post-invasion.

In February 2014, Russia invaded and then annexed the Crimean Peninsula. Shortly after the Crimea annexation, Russian separatists in Donbas began a proxy war with the Government of Ukraine. On February 24, 2022, the Russian Federation invaded Ukraine from Belarus in the north and Russia on the east with a military force of 100,000 troops.

Wartime disruption has already caused large population migrations. As of June 16, 7.7 million Ukrainians had evacuated across international borders. On June 18, the head of Russia's national defense, Mikhail Mizintsev, stated that 1.9 million Ukrainians had been "evacuated" to Russia since the invasion. Approximately 2 million Ukrainians evacuated early in the war but have since returned home after seeing that basic services, including supply of electricity, have continued to reliably operate.

Faced with an unprecedented challenge for the electricity sector, the Government of Ukraine and its utilities have been notably successful thus far. Operation of the electric grid during the invasion has been reliable, with no persistent outages except those caused by attack on local transmission and distribution facilities. Nonetheless, for reasons explained in this article, the Ukrainian electric grid is at risk of wide area, long-term collapse—especially as the next winter approaches. If such a collapse were to occur, infrastructure accidents, cross-border migrations, and mass casualties are likely outcomes. Prompt action by the Government of Ukraine with categorical financial support from western democracies can reduce the probability of long-term electric grid collapse.

Ukraine's Electric Grid and Supporting Infrastructures

While Ukraine's per-capita GDP is among the lowest in Europe, it possesses the infrastructure of an industrialized nation. Much of Ukraine's infrastructure, including its electric grid, was inherited from the Soviet era. Electricity infrastructure is oversized for the current demand and well past its design life. Since independence from the Soviet Union, Ukraine has spent significant societal resources in

upgrading electricity infrastructure, including reducing carbon dioxide emissions through wind, solar, and biomass generation.

The electric grid is the keystone of Ukraine's infrastructure. Without a functioning electric grid, infrastructures in modern societies will fail, including those that provide services essential for human survival: water treatment and sanitation, food production and distribution, and winter heating. Without electricity for critical infrastructure, massive human casualties could result from famine, disease, and hypothermia.

The electric grid and its supporting infrastructures—telecommunications, nuclear, natural gas, coal, petroleum, railways, and seaports—are interdependent. Long-term collapse of the electric grid will cause failure of supporting infrastructures. In turn, degradation of supporting infrastructures puts the electric grid at risk.

Electric Grid

Ukraine's electric grid consists of electricity generating plants, high voltage transmission lines, transmission substations, distribution lines and substations, and customer loads. The transmission system operator, Ukrenergo, dispatches generating plants and controls the flow of electricity to distribution system operators. Because the electric grid is interconnected, all parts are synchronized, operating at the system frequency of 50 cycles per second (50 hertz).

Figure 2 shows major transmission lines of the Ukrainian electric grid operating at 220 kilovolts (kV), 330 kV, 400 kV, and 750 kV. In its current configuration, transmission lines connect the Ukraine grid to the systems of Poland, Slovakia, Hungary, Romania, and Moldova. A combination of long transmission lines and non-optimal power characteristics results in electricity losses of approximately 15 percent, a higher proportion than for most countries with interconnected electric grids. As a comparison, transmission and distribution losses in most European countries are 2-8%. (Council of European Energy Regulators, 2017)

Ukraine's electric grid has ample generation capacity, making it resilient to disruption and attack. To understand operation of Ukraine's grid, both installed capacity and actual generation are necessary statistics. Installed generating capacity of 55 gigawatts in 2020 had a wide diversity of energy sources: 25% nuclear, 51% fossil fuels (coal, natural gas, and oil), 11% hydroelectric, 9% solar photovoltaic, 2% wind, and 1% biomass. (State Statistics Service of Ukraine, 2020) Electricity generated in 2020 of 142,200 gigawatt-hours was 54% nuclear, 30% coal-fired, 8% natural gas-fired, 5% hydroelectric, 1% solar photovoltaic, and 1% wind.³ (IEA, 2022) From 1990 to 2020, electricity generated in Ukraine fell by half. Because

³ Based on IEA data from IEA (2022) Electricity Information, IEA (2022), www.iea.org/statistics, All rights reserved; as modified by author.

much of Ukraine's generating capacity goes unused, the average capacity factor for 2020 was only 28%.

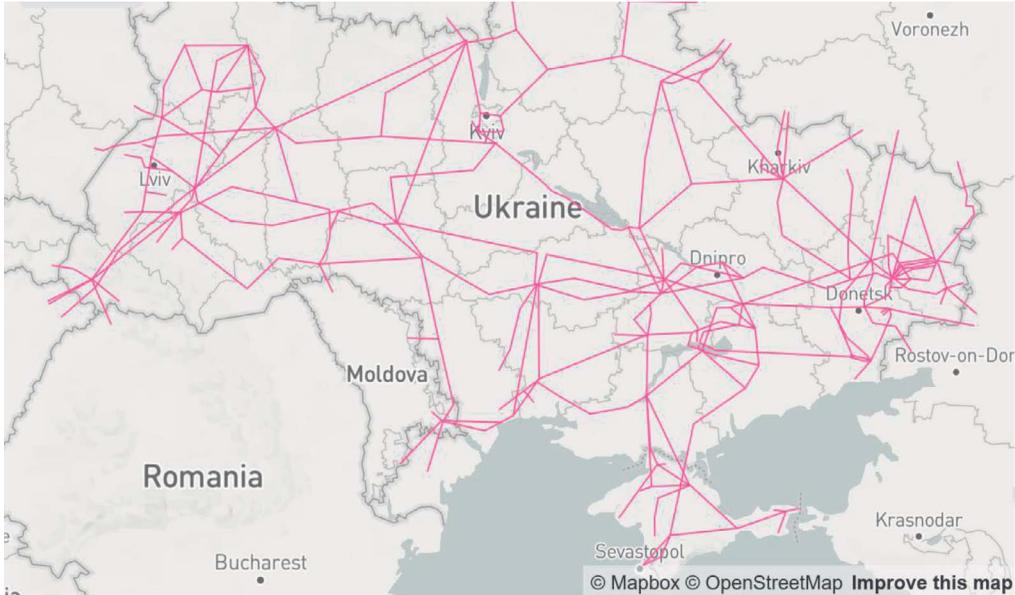


Figure 2. Major Transmission Lines of Ukraine's Electric Grid (Energy.info, 2022)

Electricity generation post-invasion has declined by 30-35% as compared to the same time the previous year. Installed capacity of dispatchable generation resources post-invasion is essentially the same as in 2020, although one-third of the capacity is now in captured territory and 5% has been destroyed. Nearly all wind resources are offline since the invasion. In regard to reserves of generating capacity, Ukraine's issue is not a lack of installed capacity, but the fuel required to reliably operate generating plants—particularly in winter months.

Ukraine's electricity exports were 4,754 gigawatt hours in 2020, representing average transmission of 543 megawatts. Current electricity export capacity to the ENTSO-E grid is 1,690 megawatts; with proper reactive power support, the same import capacity might be achieved.

Urban generating plants in Ukraine are commonly designed to supply by-product steam for district heating, so-called Combined Heat and Power plants. Eleven percent of Ukraine's generation capacity is CHP plants; before the invasion, these plants supplied 9% of Ukraine's electricity. (State Statistics Service of Ukraine, 2020) Ukraine's gas-fired CHP plants often have fuel oil as a backup energy source.

Nearly all of Ukraine's fossil fuel generation fleet is past its design life, making these facilities prone to breakdowns. The median commissioning year for Ukraine's thermal power plants is 1966; the median commissioning year for CHP plants is 1964.

Before the invasion, the Ukrainian grid was interconnected (and synchronized) with Russia's grid. On February 24, just a few hours before the invasion, the Ukrainian transmission system operator, Ukrenergo, disconnected from the Russian grid and initiated an "islanding" test.⁴ Operation in island mode persisted until Ukraine interconnected with the ENTSO-E grid⁵ on March 16, an acceleration of the prior 2023 integration timeline. Soviet-era transmission lines connecting Ukraine's system and former Eastern Bloc countries made this accelerated timeline possible.

Integration with ENTSO-E provides Ukraine with the opportunity to profit from export of electricity to European countries. On June 30, Prime Minister Denys Shmyhal announced 100 megawatts of exports to Romania, with potential exports of 2.5 gigawatts to Europe; this would provide state revenues of UAH 70 billion annually (US\$ 2.4 billion). On July 1, the Ukrainian News Agency reported that Energoatom will supply 30% of Moldova's electric needs in July.

The integration of Ukraine's electric grid with ENTSO-E presents a new risk: a collapse of the Ukraine grid could cascade into the ENTSO-E grid. While settings on transmission system relays can prevent cascade, these settings could also reduce the resilience of the Ukraine grid to disruption and attack

Peak winter demand for Ukraine's electric grid before the invasion was 23.4 gigawatts, while average demand was approximately 16 gigawatts. (Ukrenergo, 2019) Peak demand has declined significantly since the invasion, with peak demand of 12 gigawatts for June 2022. (DixiGroup, 2022)

Transmission system operator Ukrenergo must manage daily fluctuations in electricity demand by maneuvering generating plants. Ukraine is a winter peaking system, with higher loads from heating systems during cold weather than from air conditioners during warm weather.

Before the invasion, the typical daily demand cycle in winter reached its low point in the early morning hours, rose to a morning peak around 10am, stayed nearly constant for much of the day, and rose slightly to a second peak around 6pm. Figure 3 shows the two daily load cycles in January 2019.

Ukraine has a deficit of generating plants that can maneuver to balance demand. The most maneuverable plants are the hydroelectric and pumped storage plants, but their flexibility is limited by seasonal river flows and run-of-the-river

4 According to the Ukrainian transmission system operator, Ukrenergo, the February 24 islanding test had been planned well in advance. Therefore, the timing of the invasion just a few hours later on the same day appears to be coincidental. Nonetheless, the Russian Federation would have had a significant motivation to avoid military attack of a country whose grid was synchronized with its own, because a collapse of the Ukrainian grid could have cascaded into the Russian grid, with unpredictable consequences.

5 European Network of Transmission System Operators for Electricity (ENTSO-E) is an association of transmission system operators (TSO) across Europe that maintain a frequency-synchronized electric grid. The ENTSO-E service area contains 39 TSOs in 35 countries across Europe.

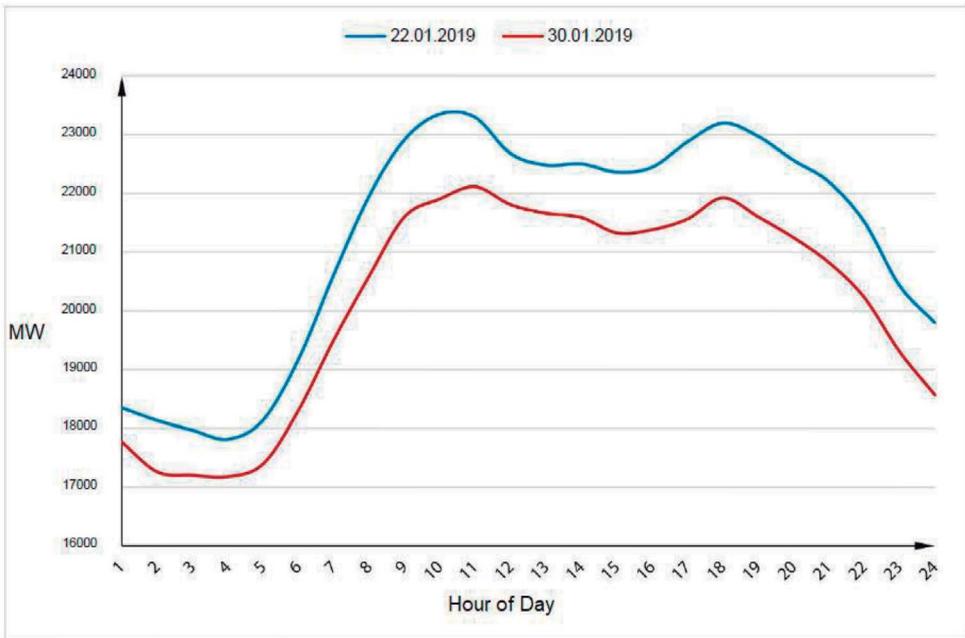


Figure 3. Graph of electricity consumption in the Interconnected Power System (IPC) of Ukraine on the working day of January 2019 at temperatures higher (1.5 ° C) and lower (-9.4 ° C) than the average monthly (-3.9 ° C) (Ukrenergo, 2019)

configurations at some plants. Seasonal river flows reduce the annual capacity factor of Ukraine’s hydroelectric plants to approximately 20%, with flows peaking in springtime but low in winter. For 2020, the hydroelectric capacity factor was only 13%. (State Statistics Service of Ukraine, 2020) Ukraine has no significant capacity of fast-ramp aeroderivative turbines or combined-cycle gas turbines.⁶ Steam turbines used in CHP plants are somewhat maneuverable, but in winter these plants must be run to match heating demand rather than electricity demand. As a result, Ukraine is forced to use smaller capacity coal-fired units to balance generation with demand. These coal-fired units are operated in start/stop mode over a 24-hour cycle, which causes equipment fatigue and increases the chance of forced outages.

Cyberattack is a threat to Ukraine’s electric grid. A 2015 cyberattack on a distribution system operator caused a blackout for 230,000 consumers. The 2015 attack demonstrated that the Ukraine’s electric grid is vulnerable to cyberattack, at least at the distribution level. (Zetter, 2015) Russia has apparently used Ukraine as a testing ground for cyberattack techniques that could be used on other electric grids.

⁶ Aeroderivative turbines are based on the design of aircraft engines, running on natural gas. These turbines have low weight, high efficiency, and can respond quickly to changes in electricity demand. Combined cycle gas turbines (CCGT) combine first-stage gas turbines with second-stage steam turbines that use waste heat from the gas turbines.

There have been several attempts to cyberattack Ukraine's electric grid since the Russian invasion. The first attack reportedly began on March 19 shortly after integration of Ukraine's grid with ENTSO-E. (O'Neill, 2022) Another attack reportedly took place in early April. (Bajak, 2022). If successful, these attacks would have affected 2 million consumers, approximately 12% of Ukraine's 16.8 million household consumers and 579,000 non-household consumers.

Physical attacks on Ukraine's generating plants have been few and while deliberate, appear to be mostly incidental actions not designed to collapse the electric grid. Physical attacks on generating plants include Vuhlehirsk Thermal Power Plant (TPP) at 3600 megawatts capacity; Kryvyi Rih TPP at 2,925 megawatts; Trypillska TPP at 1,825 megawatts; Sievierodonetsk TPP at 260 megawatts; Kremenchuk TPP at 255 megawatts; Chernihiv CHP at 210 megawatts; and Okhtyrka CHP at 13 megawatts. The attack on the Zaporizhzhia Nuclear Power Plant (NPP), with capacity of 6,000 megawatts, had the apparent objective of intact infrastructure capture; this plant has continued to operate and feed power into the transmission system. A significant number of Ukraine's generating plants have been captured by Russia or are close to captured territory. Figure 4 shows the locations of Ukraine's dispatchable generating plants⁷ with capacity of 100 megawatts or more as of June 30, 2022.

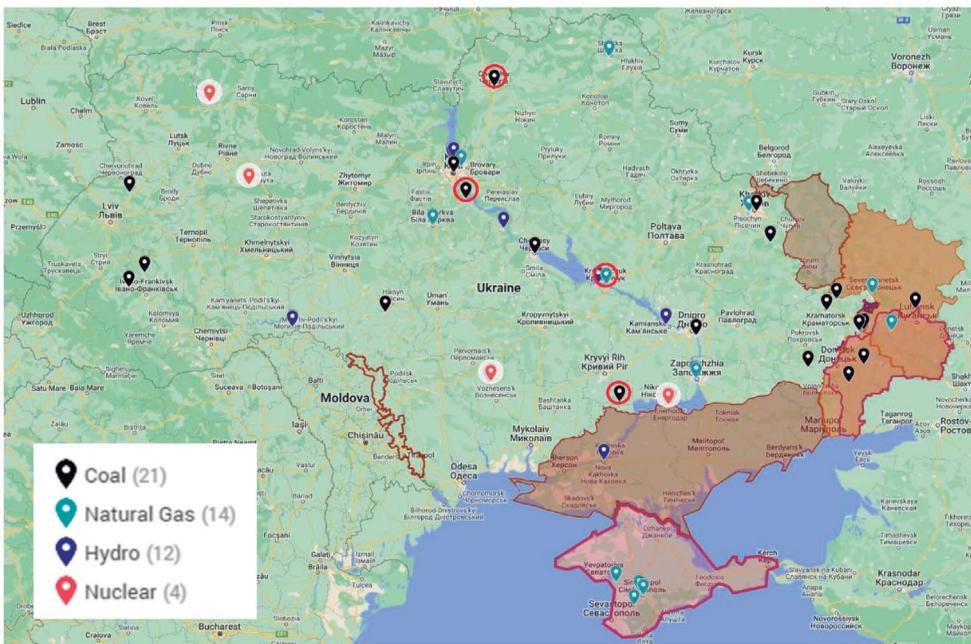


Figure 4. Dispatchable Generation Plants in Ukraine with Capacity of 100 megawatts or Greater. Territory captured by Russia as of June 30, 2022 is shaded. Red circles indicate intentional attacks on plants that are not in captured territory. (Google My Maps, 2022; Project Owl, 2022)

⁷ Dispatchable generating plants are those that can increase or decrease electricity generation on command.

Since the invasion, Ukraine's generating capacity has declined from attack damage, capture, and fuel shortages. On June 15, 2022 Ukraine's Minister of Energy Herman Halushchenko stated:

Ukraine's energy infrastructure continues to suffer devastating damage. Almost 650,000 consumers do not have access to electricity, and more than 180,000 households do not have gas. Almost 5% of the installed generating capacity was destroyed. In addition, 35% of generating capacity is now in the occupied territories. Russian aggression has disrupted more than 50% of heat capacity, 30% of solar, and more than 90% of wind generation. Gas production has fallen by about 12-15%.

There have been no reported attacks on major transmission system nodes in Ukraine's electric grid. Russian missile attacks on rail traction substations on April 24-25 were on the distribution system. System disturbance from these rail traction station attacks blacked out portions of Lviv, but for less than a day.

Telecommunications

Reliable telecommunications are essential for transmission and distribution control of wide-area electric grids. Ukraine has a well-developed telecommunications infrastructure, with long-haul connectivity provided by state monopoly Ukrtelecom. Thus far in the invasion, service has been reliable, as evidenced by continued voice, internet, and video communications among Ukraine and other countries.

Since the invasion, two notable telecom service interruptions have occurred. On March 28, internet tracker NetBlocks reported a "massive cyberattack" on core telecommunications infrastructure, with connectivity across Ukraine collapsing to 13 percent of prewar levels. A Tweet by the State Service of Special Communication and Information Protection (SSSCIP) of Ukraine reported that the attack had been neutralized by 12:35pm. (Condon, 2022) Also according to SSSCIP, on April 30, internet broadband and cell phone service to the Kherson region was cut off. By May 4, internet service was restored. An analysis by Cloudflare, an American content delivery network, revealed that Russian occupiers had shifted routing of internet traffic from Kyiv data centers to Moscow data centers and then back to Kyiv, a probable cause of the outage. (Tome, 2022)

Nuclear

Ukraine has an extensive nuclear sector with 15 nuclear reactors at four plant locations, for a total of 13.8 gigawatts capacity. Before the invasion, half of Ukraine's electricity was generated by nuclear power plants. Ukraine's nuclear fleet is significantly oversized (or underutilized) with a capacity factor of 59% in 2020. During the invasion, eight reactors at four plants have continued to operate and feed pow-

er into the electric grid: two at the Zaporizhzhia NPP, three at the Rivne NPP, two at the South Ukraine NPP, and one at the Khmelnytskyi NPP. (International Atomic Energy Agency, 2022)

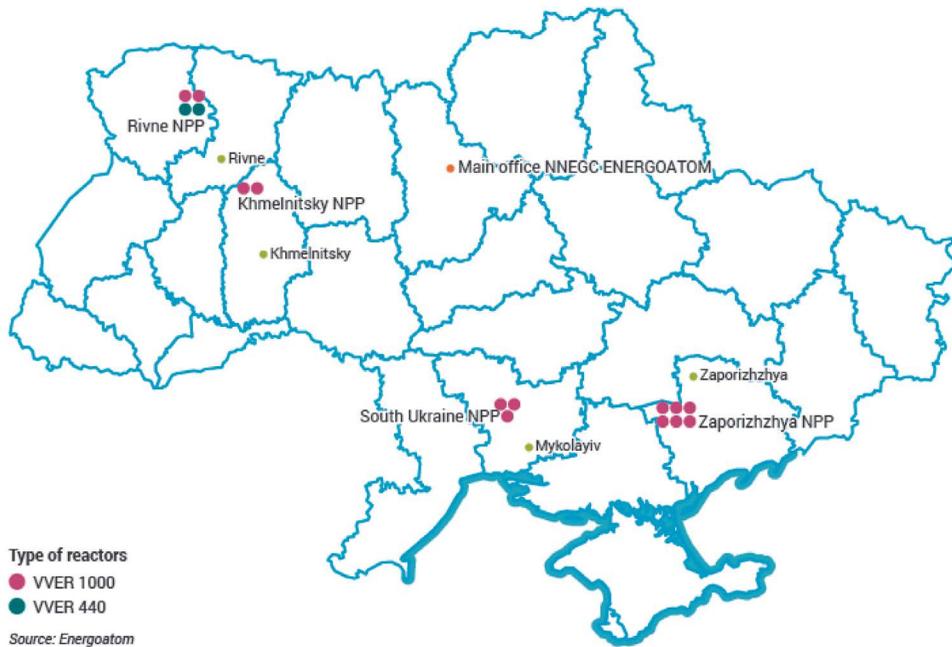


Figure 5. Location of Ukraine's Nuclear Power Reactors (Energoatom)

Ukraine's reactors have a Water-Water Energetic Reactor (VVER) design, similar to U.S. Pressurized Water Reactor (PWR) designs. Unlike the RBMK reactors at Chernobyl, VVER reactors have steel and concrete containment vessels. The safety systems of VVER reactors are similar to PWR designs. VVER reactors in Ukraine have backup diesel generators to allow safe shutdown and continued cooling when grid power is unavailable. (Nuclear Energy Institute, 2022).

On March 3, Russian forces captured the Zaporizhzhia NPP, the largest nuclear plant in Europe, having six reactors with a total capacity of 6,000 megawatts. During the attack, artillery shelling set an administrative building on fire and hit one of the containment vessels. Fortunately, no radiation release occurred. Russian forces have held the plant's operators captive since March 4. Rosatom, Russia's nuclear utility, has sent engineers to Zaporizhzhia NPP to monitor plant operations.

On a visit to occupied Ukraine, Russia's Deputy Prime Minister Marat Khusnullin threatened that Zaporizhzhia's electricity will be diverted to Russia if Ukraine does not pay for the power, saying, "If Ukraine's power system will be ready to pay, then we'll work; if it won't, the plant will work for Russia."

The owner of the Zaporizhzhia nuclear plant, Energoatom, has dismissed diversion of its generated electricity to Russia as a technical impossibility, because

the plant is not connected to the Russian electric grid. (The Moscow Times, 2022) Moreover, the Ukraine and Russian grids are no longer synchronized.

While the dispute over the Zaporizhzhia nuclear plant's electricity may be wartime posturing, existing transmission infrastructure could make the Russian power diversion scheme eventually feasible, even if Russian territory capture is limited to the Donbas and southern Ukraine. The Volgograd–Donbass High Voltage Direct Current (HVDC) transmission line runs from the Mikhailovska converter station, situated northeast of Pervomaisk, to a terminal at Volga Hydroelectric Station in Russia. (Pervomaisk is a city with population of 38,000 in the self-proclaimed “People’s Republic of Luhansk,” an area of Ukraine controlled by Russian separatists.) This 475-kilometer line, originally designed to carry 750 megawatts, is currently operated at 100 megawatts. (Wikipedia, 2022) Renovations for the line are ongoing. Because AC current from the Ukrainian grid would be converted to DC for transmission, it could be technically possible to supply the Russian grid with power from Zaporizhzhia NPP. This potential scheme gives Russia incentive to keep the Zaporizhzhia nuclear plant operating, which may explain why Russia made it a priority to capture the plant in the first two weeks of the invasion.

Natural Gas

Natural gas is an important fuel for Ukraine’s electric generating plants, especially CHP plants providing district heat to cities. Ukraine has significant natural gas resources with over 1 trillion cubic meters of reserves, the second largest in Europe after only Norway. These gas reserves provide a motive for Russian capture of Ukraine’s territory. A small proportion of Ukraine’s natural gas reserves is available for use during the war. Development of Ukraine’s gas reserves requires unconventional technologies, such as horizontal drilling.

Ukraine has an extensive natural gas pipeline system inherited from the Soviet era. This system is used for transit of gas from Russia to Europe, as well as in-country distribution. The pipeline operator is Gas Transmission System Operator of Ukraine (GTSOU), a regulated monopoly. Before the February 2022 invasion, one-third of Europe’s natural gas transited Ukraine.

Figure 6 shows the pipeline network transmitting gas from Russia to Europe. Gas from the Soyuz (capacity of 32 billion cubic meters (bcm)/year) and Brotherhood (28 bcm/year) pipelines transit Ukraine; additionally, a branch from the Yamal-Europe pipeline transits Ukraine. Other Russian natural gas pipelines supplying Europe include the Nord Stream 1 (59.2 bcm/year), the Yamal-Europe (33 bcm/year), and the TurkStream (31.5 bcm/year). Nord Stream 2 has double pipelines with capacity of 27.5 bcm/year each, but this facility has never gone into operation.

Taken together, shipments of Russian gas to Europe at the end of June 2022 have been running at about one-third of their pre-invasion levels. Sanctions have



Figure 6. Major Natural Gas Pipelines of Europe.
(Wikimedia Commons, Samuel Baily, CC BY 3.0 NZ; 2022)

prevented use of the Nord Stream 2 pipeline since its completion in September 2021. On June 15, 2022, Russia reduced flow in the Nord Stream 1 pipeline to about 40% of capacity for compressor maintenance. Deliveries of gas to Europe through the Yamal pipeline had been intermittent; on May 12, Russian banned all shipments of gas through this pipeline due to a payment dispute with Poland; some flow has since resumed. The TurkStream pipeline has continued to operate except for maintenance during June 21-28; gas flow has since resumed.

On May 11, the Gas Transmission System Operator of Ukraine (GTSOU) shut down flow through the Sokhranivka interconnector station after interference by Russian forces; since then, flows of Russian gas through the remaining Sudzha interconnection station have been in the range of 40-45 million cubic me-

ter (mcm)/day, down from the pre-invasion “contract volume” of 109 mcm/day. Ukraine’s pipelines still carry about 30% of gas transit to Europe because of reductions in Nord Stream 1 flows and intermittent flows in the Yamal pipeline.

Ukraine’s natural gas consumption for electricity generation, heating, and industrial use in 2021 was 26.1 bcm while production was 18.6 bcm. (British Petroleum, 2022) Gas to fill the past production gap of 7.5 bcm had been contractually supplied by European countries, although most gas imported by Ukraine is “resold” Russian gas. For 2022, the government estimated annual gas production of 16-19 bcm; estimated consumption for the year is 21-24 bcm. (Interfax, 2022)

Storage capacity for natural gas in Ukraine is 31 bcm, the largest in Europe and approximately one year’s consumption. As of March 12, stored gas was 9.5 bcm, according to Ukraine Prime Minister Denys Shmygal. (Watts, 2021) As of June 1, stored gas was 10 bcm, with a Government of Ukraine goal of 19 bcm stored by the beginning of the next heating system.

Non-critical attacks on Ukraine’s natural gas system have reduced supply. For example, on February 27, a Russian attack caused a pipeline explosion in Kharkiv. On March 13, a Russian attack severely damaged a gathering station for the Shebelinka gas field.

There have been no physical attacks on major compressor stations of Ukraine’s natural gas system, but there has been Russian interference with contracted gas flow. On April 8, GTSOU reported gross interference by groups allied with Russia at the Novoposkov compressor station in the Luhansk separatist region. Nearly one-third of Ukrainian gas transit to Europe had passed through this station. On May 10, GTSOU declared force majeure and refused to accept gas from the Novoposkov compressor station for transport through its Sokhranivka pipeline. (GTSOU, 2022)

Coal

Along with natural gas, coal is an important fuel for Ukraine’s electricity generation. Ukraine’s coal reserves are the seventh largest in the world. There are three major coal basins in Ukraine: Lviv-Volyn with bituminous coal, Dnieper with lignite coal, and Donbas with bituminous and anthracite coal. The vast majority of Ukraine’s coal reserves are in the Donbas region, the same area increasingly under Russian control.

Before the invasion, Ukraine depended on imports for approximately half of its coal consumption. (IAE, 2020). In the period from January to November 2021, Ukraine received 75% of its coal imports from Russia, 17% from Kazakhstan and 8% from the US. (The Coal Hub, 2021). In November 2021, Russia stopped exporting coal to Ukraine. Nor can Ukraine presently import coal through its seaports, as they have been blockaded by Russia.

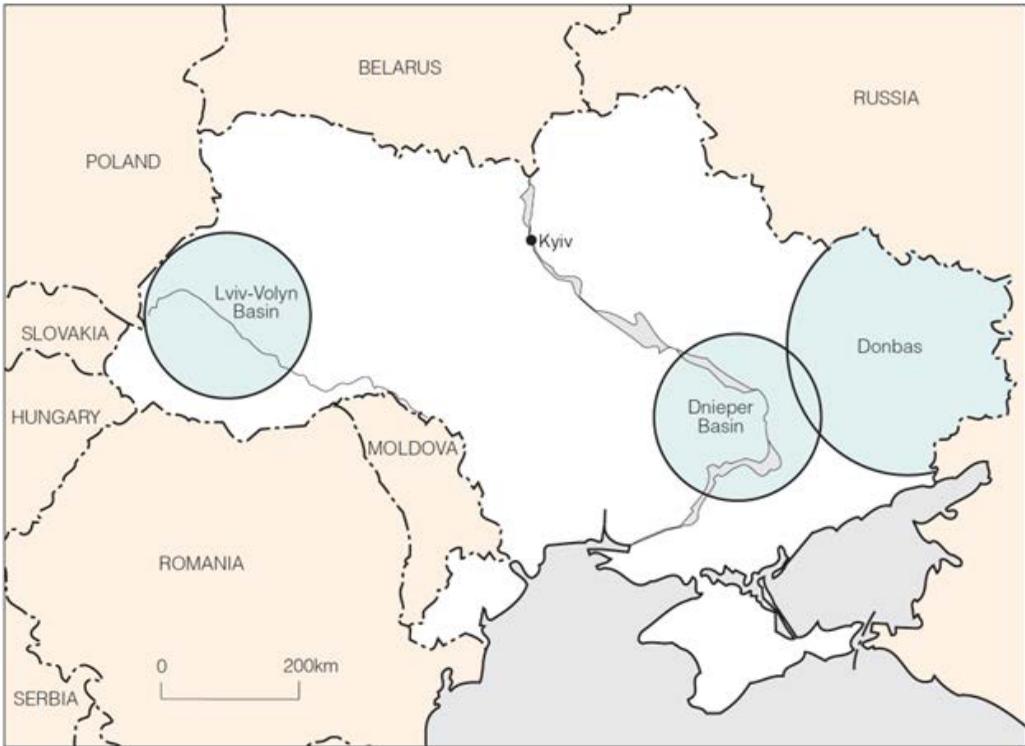


Figure 7. Coal Basins in Ukraine. Source: IEA/Oprisan (2011), “Prospects for coal and clean coal technologies in Ukraine,” www.iea.org. All rights reserved. With author annotation for city of Kyiv.



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Figure 8. Oil Pipelines in Ukraine. Source: IEA/Oprisan (2011), “Prospects for coal and clean coal technologies in Ukraine,” www.iea.org. All rights reserved. With author annotations for Kremenchuk Refinery and Thermal Power Plant; Odesa-Kremenchuk pipeline.

Petroleum

Petroleum is a backup fuel for a significant number of Ukraine's generating plants, but supplies have been interrupted since the invasion. In 2021, Ukraine consumed 239,000 barrels per day of petroleum liquids while in-country refinery production was 73,000 barrels per day. (British Petroleum, 2022) Before the war, seventy percent of refined petroleum had been imported from Belarus and Russia, with most of the remainder supplied by in-country refineries. Crude oil had been refined in the Kremenchuk refinery with throughput of up to 68,000 barrels per day. Additionally, the Shebelynka gas plant has capacity for approximately one thousand barrels per day of refined petroleum.

The southern branch of Russia's Druzhba pipeline network passes through Ukraine and supplied crude oil to Slovakia, Hungary, and the Czech Republic before the invasion. Ukraine's pipeline operator, Ukrtransnafta, has a contract with Russia's Transneft to transport oil through 2030. Approximately 244,000 barrels per day of Russian crude oil traveled through Ukraine in 2020. (U.S. Energy Information Agency, 2022).

The bi-directional Odesa-Brody pipeline with a capacity of 70,000 barrels per day between Poland and the Yuzhne maritime terminal near Odesa had been an additional channel for oil transit. In some years, the pipeline had been used to transport Russian oil from Poland to Yuzhne. In 2020, the Odesa-Brody pipeline resumed the transit of oil from Yuzhne to Poland.

The logistics of petroleum import to Ukraine during the invasion have been challenging, especially because Ukraine and Poland's rail gauges are incompatible. Moreover, attacks on Ukraine's petroleum transport, refining, and storage have contributed to severe shortages. As of May 13, Russia had destroyed 27 fuel storage facilities in Ukraine. (Reuters, 2022) The Shebelynka gas plant was shut down on February 26, two days after the start of the war. On April 2, a missile strike on the Kremenchuk refinery destroyed nearby fuel storage, resulting in the refinery's deactivation. The same missile attack targeted Kremenchuk TPP. Also on April 2, Russian forces attacked fuel storage tanks at the Port of Odessa and an inactive refinery nearby. On April 24-25, Russia attacked rail traction stations in western Ukraine to impede import of petroleum. Also on April 24-25, Russia again attacked the Kremenchuk refinery and nearby thermal power plant.

During President Zelensky's April 29, 2022 evening address, he stated:

The occupiers are deliberately destroying the infrastructure for the production, supply, and storage of fuel...Russia has also blocked our ports, so there are no immediate solutions to replenish the deficit... But government officials promise that within a week, maximum two, a system of fuel supply to Ukraine will be at work that will prevent shortages.

On May 13, Ukraine's Minister of Economy Yulia Svyridenko announced measures to increase refined fuel imports from the European Union via rail, truck, and pipeline. Imports were to be 12,000 tons/day or the equivalent of 82,000 barrels per day, approximately one-third of prewar consumption. (The Odessa Journal, 2022).

Railways

Railways are a major means of transporting coal for electricity generation. Ukrzaliznytsia, a state-owned monopoly, operates most of the Ukrainian rail system. Ukraine has 13,447 miles of track of which almost half—6,138 miles—is electrified. Because the rail sector was part of the Soviet system, it has a wider gauge than the EU rail system, necessitating car transloading terminals at borders. A single mountain passage, the Beskydy Tunnel, handles sixty percent of Ukraine-EU freight. Figure 9 shows the Ukrainian rail system and the locations of attacks.

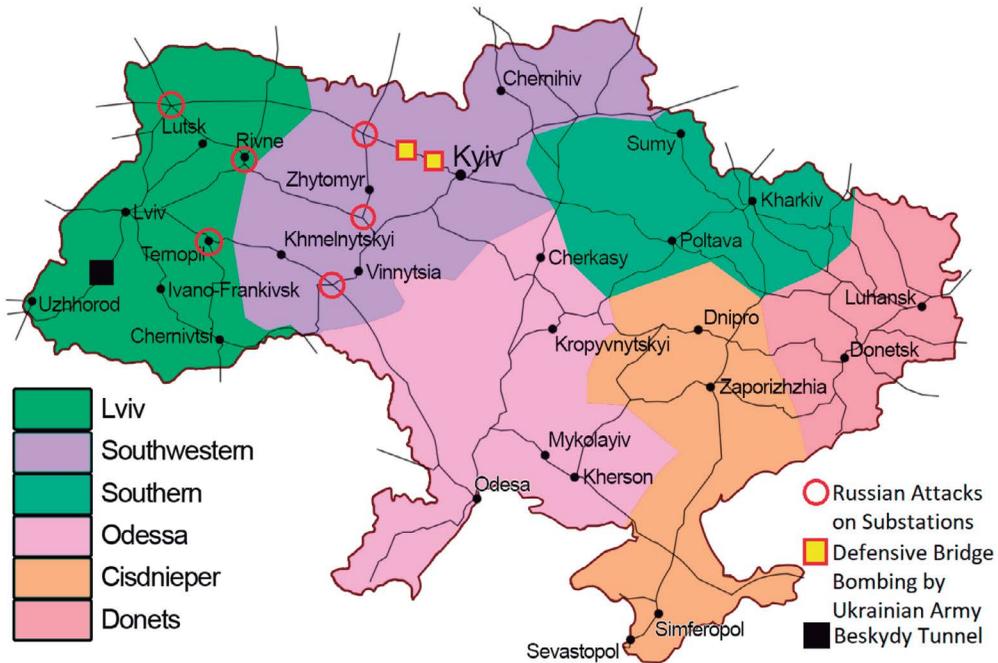


Figure 9. Attacks and Disabling of Ukraine Railway System as of April 25, 2022 (Wikimedia Commons, Terek, CC BY-SA 4.0; with author annotations.)

Until late April, there were few attacks on Ukraine's rail system and one of the attacks that did occur was directed at human evacuation rather than the transport of goods. On April 8, missiles hit the Kramatorsk station in eastern Ukraine, killing fifty of the crowd of 4,000 waiting for the first train of the day. Russian targeting of rail infrastructure escalated on April 24-25 when six rail traction substations in western Ukraine were hit by missiles, destroying transformers that convert high voltage electricity from transmission lines to lower voltages necessary

for use by electric locomotives. This disruption to the distribution system caused a temporary blackout for parts of the city of Lviv. Also on April 24-25, Russian forces attacked a railroad bridge across the Dniester Estuary leading to the Danube ports; these ports are an alternative to ports on the Black Sea. Despite these attacks, Ukrainian railway operators have continued substantial transport of goods.

Seaports

Before the invasion, Ukraine's Black Sea ports imported coal and oil for electricity generation. Major ports include Berdovsk with 9 berths and a capacity of 2.1 million tons annually; Chornomorsk with 29 berths and capacity of 21.5 million tons; Kherson with 10 berths and a capacity of 8 million tons; Mariupol with 21 berths and capacity of 7.6 million tons; Mykolaiv with 23 berths and capacity of 24 million tons; Odesa with 46 berths and capacity of 31.4 million tons; and Yuzhnye with 38 berths and capacity of 61.7 million tons. Yuzhnye had been a major terminal for coal and oil imports.

During the early invasion, Russian forces captured the ports of Berdovsk, Mariupol, and Kherson. The port of Mykolaiv had been captured, but Ukrainian forces repulsed the invasion by mid-March. Russia attacked the Odesa petroleum storage facility by missile on April 3.

As of the writing of this article, over ninety percent of Ukrainian port capacity (excluding annexed Crimean ports) is still controlled by the Government of Ukraine. Nonetheless, all of Ukraine's ports are closed due to mining of the Black Sea and an ongoing Russian naval blockade. Coal and petroleum imports through seaports have halted. Even if the Russian blockade were to end, maritime insurance companies have been unwilling to write coverage for ship charters to Ukrainian ports.

Russian Incentives

From the Russian invasion of Crimea in April 2014 until the current invasion in February 2022, Ukraine had been in de facto war with Russia, especially in the Donbas region. Nonetheless, the Russian and Ukrainian electric grids were interconnected throughout this period, with daily coordination of cross-border transmission capacity. Uncoordinated transmission of power from Ukraine to Russia could have caused a cascading collapse of the Russian grid. Likewise, uncoordinated disconnection of the Russian grid from Ukraine's could have caused a cascading collapse in Ukraine. Although at war, Russia and Ukraine had shared incentives not only for reliable electric grid operation, but also to avoid attacking the opposing side's energy infrastructure.

On February 24, 2022, the Russia-Ukraine incentive structure changed. Russia invaded. Ukraine disconnected from the Russian grid for an "islanding

test,” just hours before the Russian invasion. The Ukraine electric grid is now synchronized with the ENTSO-E grid. Russia and Ukraine have established a new incentive structure for energy infrastructure.

Russian incentives in the present instance are difficult to definitively determine but may be implied by behavior. Apparent Russian incentives include maintenance of mutual restraint on attacking energy infrastructure, keeping energy infrastructure intact, profits from transmission of natural gas to Europe, prevention of infrastructure accidents, and avoidance of disruptive human migrations. While the wartime goals of Russia and Ukraine are certainly opposed, Ukraine can nonetheless consider how Russian incentives may be consistent with its own interests.

Mutual Restraint

Since the invasion, Russia has infrequently attacked energy infrastructure. Ukraine has also avoided attack on energy infrastructure. Their patterns of behavior demonstrate a norm of mutual restraint.⁸ Thus far, mutual restraint appears to be in the interest of both sides. Of course, Russian incentives for restraint may change at any time.

Russia has attacked generating plants, but attacks with the purpose of destroying the capability to generate electricity have been few; Kremenchuk TPP, Sievierodonetsk CHP, and Okhtyrka CHP are examples of destroyed plants. Partial attacks include Zaporizhzhia NPP (attack on administrative building), Vuhlehrska TPP (attack on administrative building and fire on plant premises), Trypilska TPP (attack within plant grounds) and Kyiv CHP-6 (possibly an unintentional strike). Russia captured Kakhovka Hydro Power Plant (HPP) without damage and the plant has continued to operate. The extent of damage from attacks on Kryvyi Rih TPP is not publicly available. Russia has generally avoided attacks on high voltage transmission substations and has not attacked critical nodes of the Ukren-ergo transmission system. Russia has avoided attacking high-pressure gas transmission pipelines.

Like Russia, Ukraine has demonstrated restraint. Ukraine has not destroyed generating plants when retreating. In November 2021, former foreign minister Vladimir Ohryzko warned that Ukraine could target Russian nuclear plants with missiles (Allen, 2021), but there have been no public reports of Ukraine attacking electricity infrastructure inside Russia since the invasion. Nor have there been public reports of Ukraine attacking generating plants inside Crimea or the Temporarily Occupied Territories. However, Ukraine has attacked petroleum supplies within Russia, according to the Tass news agency.

8 Other observers have also noticed a pattern of Russian restraint. For example, see the May 2022 New York Times article, “[Russia’s War Has Been Brutal, but Putin Has Shown Some Restraint. Why?](#)” (Troianovski, 2022).

Russia's restraint is consistent with the unratified Transit Protocol of the Energy Charter Treaty. Russia advocated this Protocol to protect its commercial interests in energy transit after the breakup of the Soviet Union. Under the Protocol, Contracting Parties (signatories) would have had the obligation to ensure that energy transit is not interrupted. The Transit Protocol specifically defines energy "transport facilities." These facilities include "high-pressure gas transmission pipelines" and "high-voltage electricity transmission grids and lines." (Energy Charter Secretariat, 2002)

Keeping Infrastructure Intact

Keeping hard-to-replace infrastructure intact, especially hydroelectric and nuclear plants, is an apparent objective of Russia. The Kakhovka hydropower plant with capacity of 357 megawatts was captured intact on the first day of the invasion. Zaporizhzhia NPP with capacity of 6,000 megawatts was captured intact soon after the invasion, on March 4. Damage during the attack on the Zaporizhzhia NPP was minimal. Both plants have continued to operate and feed power into Ukraine's electric grid.

If Russia's eventual intent is to capture much of Ukraine, it has incentive to avoid damage to energy infrastructure. Reconstruction would be an arduous and extraordinarily expensive process. For example, the Dnieper system of hydroelectric facilities has taken a century to develop. Ukraine's nuclear power plants took decades to build. Damage to Ukraine's natural gas transit and storage system could take years to repair. And if Russia does not succeed in its intent to capture territory, Ukrainian infrastructure can still support transmission of Russian energy to Europe.

While Ukraine certainly opposes Russian capture of its energy infrastructure, a Russian incentive of keeping infrastructure intact might nonetheless be consistent with Ukraine's interests. In Russia's apparent mindset, if Ukraine's generating plants were to be captured intact—especially hydroelectric and nuclear power plants—their electricity could be supplied to Russia or sold to Europe. President Putin is presumably aware that Europe has an impending shortage of baseload power, because he can see coal and nuclear plants being shut down in Germany and other countries without replacement by dispatchable generation. In fact, potential sale of baseload power to Europe—at high prices during electricity shortages—may be one of the primary reasons that Russia invaded Ukraine.

Transmission of Natural Gas

Russia has an incentive to preserve Ukraine's electric grid because this infrastructure is interdependent with pipelines that transmit natural gas to Europe. As long as Russia's economy profits from the sale of natural gas, and pipeline transits outside of Ukraine are sanctioned or constrained, the incentive to preserve Ukraine's

gas transmission system—and the electric grid that supports it—will remain. At current prices, Russia's Gazprom could receive approximately US\$20 billion of annual revenues from gas transmitted through Ukraine's pipelines.⁹ Moreover, because the price for natural gas in Europe has risen substantially over the past year—€144/MWh at the Title Transfer Facility (TTF) on June 30, 2022 vs. €22/megawatt per hour (MWh) a year earlier—the total value of gas transiting Ukraine has risen since the invasion.

To support natural gas transmission to Europe, Russian has incentives to keep Ukraine's other critical infrastructures reliably operating. The critical infrastructures most interdependent with the pipeline system are electricity and telecommunications.

Ukraine's natural gas pipeline system depends on electricity for its coordination and control. The pipeline system has hundreds of compressor and valve stations that are essential for its operation. Readings of gas pressure, flow, and temperature are transmitted to centralized control centers; in turn these readings are used to adjust compressor settings and valve positions.

Telecommunications are an integral part of the control system for natural gas pipelines, but telecommunications infrastructure relies on power from the electric grid. Without grid power for telecommunications, operation of Ukraine's pipeline system will become unreliable and hazardous. Risk of pipeline overpressure will increase. If pipeline explosions were to occur, natural gas transmission from Russia through Ukraine could halt entirely.

Prevention of Infrastructure Accidents

All countries seek to avoid infrastructure accidents. Infrastructure accidents impact human populations, cause economic losses, and harm the environment. It is in Russia's self-interest to avoid large-scale infrastructure accidents in Ukraine.

Hydroelectric dams depend on electricity and on-site staff for the safe operation of their turbines, gates, and spillways. If Ukraine's electric grid were to collapse and the dams were to be abandoned, uncontrolled water flow could result in self-destruction of the dams.

If grid power is interrupted to Ukraine's nuclear power plants and their fuel for backup generators runs out, reactor meltdowns and spent fuel pool fires could

⁹ A rough estimate of the value of gas transiting Ukraine can be determined by multiplying the flows through the Sokhranivka and Sudzha interconnector stations by the Title Transfer Facility price. Using the price and flows at the end of June 2022, this figure is about US\$25 billion (€23.8) annually. In January 2022, Ukraine gas transit fees were estimated at US\$1.2 billion annually (Harper, 2022). Subtracting Ukraine transit fees, Ukraine storage fees, and transit fees between Ukraine's exit point and the TTF in the Netherlands, a reasonable estimate of potential Gazprom revenues for gas transiting Ukraine would be US\$20 billion annually. Much of natural gas transiting pipelines is sold under long term contracts rather than at spot market prices, such as the TTF price. Over time, contract prices tend to converge with increased spot market prices.

result. Releases of radiation could extend to Russia and to its allies as well—especially to Belarus with the Rivne nuclear plant near its border with Ukraine.

Ukraine's nuclear power plants have a design that requires power from the electric grid for operation of their cooling and safety systems. It is a common misconception that nuclear plants can operate at low power and therefore supply their own electricity when off-site power from the electric grid is unavailable. Instead, when grid power is interrupted, backup diesel generators must supply power to safety systems, including motorized pumps for reactor and spent fuel cooling. The fuel duration for backup diesel generators at Ukraine's nuclear plants is approximately seven days. Without grid power—and with backup fuel exhausted—residual heat after reactor trips could cause core meltdowns.

Water-filled pools are necessary for cooling of spent fuel rods from reactors before they are transported to nuclear waste facilities. Water in the pools shields radiation from the rods; otherwise, the rods are highly radioactive, and it is impossible for humans to be nearby. Electric power for cooling pumps is necessary to keep water in spent fuel pools from boiling. Without electric power, water in spent fuel pools would heat up and boil off. As water vaporizes, the level of water in the pool declines, eventually exposing the zirconium cladding of the fuel rods to air. The time for water to boil off would be on the order of a few weeks, assuming no makeup water is added to the pools.

If the fuel rods are recently removed from the reactor core and still hot, the junction between air, water, and zirconium provides the conditions for a strongly exothermic chemical reaction akin to a fire. Heat can vaporize the centers of the rods, releasing massive quantities of radioactive particles.

While the design of Ukrainian reactors has both core and spent fuel pool containment, violent explosions during past reactor meltdowns have breached containment vessels.¹⁰ There can be no certainty that containment vessels would hold if Ukraine's nuclear reactors did not have off-site power from the electric grid.

Avoidance of Cross-Border Migration

Approximately two-thirds of Ukraine's population lives in urban areas. Without electricity, it is impossible for Ukraine's cities to support large populations for more than a few weeks in summer or a few days in winter. Water and sanitation systems cease functioning without grid power; pandemics from diseases such as cholera and dysentery become more likely. Food cannot be cooked, except on portable burners or wood fires. In the winter, unheated buildings become uninhabitable. Already, wartime experience in the city of Mariupol shows that when critical

¹⁰ The 2011 events in Fukushima, Japan demonstrated how interruption of off-site power can cause reactor explosions and breach of containment vessels. The spent fuel pools for Fukushima's reactors were not in containment vessels.

infrastructures go down, residents evacuate; for those that remain, significant casualties occur.

If the Ukrainian electric grid were to collapse over a wide area, millions of urban residents will attempt to evacuate. Thus far, evacuations of urban populations have been possible, because temperatures have been mild, transport systems have continued to operate, and outside assistance has been available. Regions of Ukraine with still functioning infrastructure have been a haven for evacuees.

During a wide-area electric grid collapse, all urban areas in Ukraine will become simultaneously uninhabitable. Residents who shelter in place will risk death; evacuation to rural areas and migration across international borders will be the only remaining options.

Russia may ultimately (and imprudently) adopt a war strategy to cause human migration to EU countries; intentional collapse of Ukraine's electric grid could be a part of this strategy. Already in Syria, Russia has demonstrated that migration can be a weapon of war. However, in the event of electric grid collapse, migration patterns would be not only flow west to EU countries, but also east to Russia and north to Belarus. Mass migration to Russia or its ally Belarus would place a resource burden on these countries—and could be politically destabilizing. Because of the potential burden of mass migration on its own society, Russia has an incentive to prevent an electric grid collapse in Ukraine. Evacuating Ukrainians may deliberately damage natural gas infrastructure, causing hardship to both Russia and Europe.

Electric Grid Scenarios

A number of scenarios are plausible for Ukraine's electric grid post-invasion. These scenarios range from the benign scenario of reliable operation to a scenario of cascading collapse followed by blackstart failure.

Nodal, relay-controlled electric grids are vulnerable to cascading collapse from unintentional failures or targeted attacks. (Cetinay, 2018) Gradual degradation of fuel supplies and resulting generation shortfalls can also cause electric grid collapse. Even before the invasion, a December 2020 analysis by a Ukrainian climate and energy policy expert warned of “cascading collapse of the power grid” in winter months due to generation shortfalls. (Savytskyi, 2020). Impaired generation and transmission capacity may prevent prompt grid restoration.

Reliable Operation

The most benign scenario for Ukraine's electric grid is its continued reliable operation, with localized outages in areas under Russian attack or occupation. Under this scenario, Russia will refrain from attacking key transmission nodes and control centers, which could cause cascading collapse. Continued supply of fuel for

generating plants would allow their dispatch by Ukrenergo, the system operator. Thermal power plants could be taken offline when fuel is temporarily unavailable. When in-country generation is less than electricity demand, power could be imported from Poland or other interconnected European countries.

Reliable grid operation would support interdependent infrastructures, including telecommunications; petroleum import, storage, and distribution; natural gas transmission, storage, and distribution; coal mining and transport; and railways. Grid operation would also support infrastructure for human needs: water treatment and sanitation, food production and distribution, and residential heating.

The benign scenario of reliable operation could be possible through the summer and early fall of 2022. However, if the war persists as winter approaches, continued reliable operation of the Ukrainian electric grid will become increasingly in doubt. Continued Russian attacks will disrupt fuel supplies and place thermal power plants into forced outage. Less generation resources combined with increased demand will make it increasingly difficult for the system operator to balance generation with demand. In areas not served by CHP plants, generating plants and boiler-only heating systems will compete for scarce fuel. Cold weather will increase electricity demand, especially in regions with shutdown CHP plants.

Rolling Blackouts

Fuel shortages causing rolling blackouts are a second scenario for Ukraine's electric grid. If the war persists into the winter, fuel shortages could make rolling blackouts an increasingly likely scenario. Due to reduced supply from Russia, Ukraine will compete with EU countries for limited supplies of natural gas, coal, and fuel oil.¹¹ Fuel shortages for thermal power plants—mostly coal-fired and gas-fired plants—could cause intermittent shutdowns. With flexible generating plants in forced outage, the transmission system operator would be forced to maneuver large thermal plants using start/stop operation. Stress on antiquated equipment not designed for frequent cycling can lead to mechanical breakdowns. Supply chain issues could make it difficult to maintain and repair generating plants. Faced with similar fuel constraints, capacity shortfalls in Europe's ENTSO-E grid could reduce imports as a source of electricity reserves for Ukraine.

Under the fuel shortage scenario, deficits in dispatch capacity would require the transmission system operator and local distribution providers to impose rolling blackouts. Rolling blackouts may occur only during periods of high electricity demand—for example, when weather is cold, and people are using resistive

11 As implied by the Government of Ukraine in its production and consumption estimates, imported natural gas to meet the production gap will decline by about one-third from 2021 to 2022, from 7.5 bcm to 5.0 bcm. However, because of the sharp reduction in Russian gas transmitted through Ukraine, the “resold share” of gas flowing through the Sokhranivka and Sudzha interconnections could go up substantially—from 18% to 32%—assuming that Poland, Slovakia, and other European countries are still willing to “resell” the gas to Ukraine.

heaters. Alternatively, increases in electricity demand around daily demand peaks could require regular blackouts.

Rolling blackouts would disrupt the operation of other critical infrastructure, especially infrastructure that requires continuous electric power. If blackouts become frequent or long duration, cities heated by CHP plants may need to be evacuated.

Suffering under rolling blackouts, some inhabitants will decide to evacuate to areas with reliable power while others will attempt to operate portable generators. Portable generators are woefully inefficient; their widespread use will consume scarce petroleum supplies and thereby degrade Ukraine's warfighting capability.

Cascading Collapse

A third scenario for Ukraine's electric grid is cascading collapse. For interconnected electric grids, the physics of electricity dictate that supply must be precisely matched with demand. Under normal operation, automatic generation control (AGC), generation dispatch, and transmission flow control allow the power balance to be maintained. Abrupt disconnection of generating plants, transmission lines, or customer load causes power flows to shift. Electricity imbalances surge through the system. Protective devices at grid substations—so-called “relays”—are designed to automatically disconnect customer load, bringing supply into balance with demand. However, sometimes rapid and uncoordinated relay tripping occurs. Much like a mountain avalanche, relay trips and power surges build on themselves, resulting in complete disconnection of customer load from generation—a so-called “cascading collapse.”

Even when a cascading collapse results from an accidental cause, these events can have major societal impact. For example, in August 2003, tripping of a transmission line in the Eastern Interconnection of the United States and Canada resulted in a cascading collapse affecting 55 million people; this collapse was initiated by a sagging transmission line contacting a tree branch. In September 2003, a cascading collapse in Italy and parts of Switzerland affected 57 million; this collapse was initiated by tripping of a single transmission line that flashed over towards a tree. (Sforna, 2006) In 2012, 2014, and 2015 cascading collapses impacted 620 million, 150 million, and 140 million people in India, Bangladesh, and Pakistan, respectively. Cascading collapses have simultaneous effects on infrastructure throughout large regions, greatly impacting societal functioning.

As the war persists, the probability of cascading collapse for Ukraine's electric grid increases. Worldwide experience with interconnected power systems shows that cascading collapse can occur from accidental events, such as a transmission line contacting a tree branch or misoperation of a circuit breaker. Decreases in reserve generating capacity and increased frequency of grid disrup-

tions raise the probability of cascading collapse. Competition for fuel resources and forced outages of generating plants will reduce Ukraine's reserve capacity in coming months.

Unscheduled plant outages, substation transformer fires, and customer load sheds are all examples of grid disruptions that have occurred since the Russian invasion—and such events are likely to recur as the war persists. Russian artillery and missiles have damaged generating plants, transmission lines, and distribution substations, but fortunately none of these disruptions have resulted in cascading collapse. Coordinated attack on the transmission system is a category of grid disruption that could cause cascading collapse. Likewise, attack on key nodes of Ukraine's natural gas transmission system could cause its collapse, impacting fuel supplies for gas-fired generators. No coordinated attack on Ukraine's electricity or gas transmission systems has occurred thus far—and this appears to be a deliberate choice of Russian war strategists.

Blackstart Failure

“Blackstart” is the process of restoring an electric grid without external power. Blackstart is initiated by generating plants that can restart without off-site power and without being connected to load. Throughout the blackstart process, grid operators must precisely balance electricity generation with demand or secondary collapse will occur. During successful grid restorations, grid operators have generally completed the process in 24 hours or less. For example, the September 2003 blackout affecting all of Italy was completely restored in 18 hours and 12 minutes. (Sforza, 2006) The August 2003 Northeast Blackout in the United States and Canada was restored within 24 hours.

Although reliable blackstart is essential, operator training for its complex sequence can never be practiced in real-world conditions, because electric grids are never deliberately collapsed for practice. Blackstart initiates with flexible, fast ramping generating plants, generally hydroelectric plants and aeroderivative gas turbines. Large thermal plants—nuclear power plants and coal-fired units—are “cranked” through transmission lines. As grid restoration progresses, grid operators connect customer load in an incremental manner.

Most electric generating capacity cannot be used to initiate blackstart. The pumps, blowers, and fuel handling equipment in thermal power plants typically consume 5-10% of the plant's generating capacity. It is not economically feasible to install and maintain auxiliary generators of this capacity; therefore, large thermal plants cannot initiate blackstart. Solar and wind power cannot be dispatched to balance generation with demand and therefore are not viable blackstart resources. The long transmission lines used for imported power make it a non-optimal blackstart resource.¹²

12 Both real power and “reactive power” are required for grid restoration. Reactive power losses occur

The technical characteristics of Ukraine's grid as currently configured imply a possibility for blackstart failure. Aero-derivative gas turbines and combined cycle gas turbines with fast-start capabilities are rare in Ukraine, with little remaining capacity of these types after Russian capture of the Donbas region. While Ukraine has significant hydroelectric generation capacity for blackstart, these plants are often distant from the thermal generators which must be "cranked." Moreover, river flow in Ukraine is highly seasonal, with less flow in winter months—the same time that grid collapse is more likely. Approximately three-quarters of the generation capacity of Ukraine are thermal plants with steam turbine technology that requires hours of "cranking" to achieve operational temperatures. In recent years, substantial investment has been made in Ukraine's wind and solar generation, but neither of these resources can be used in the initial stages of grid restoration. Ukraine's gas-fired steam turbines are interdependent with the natural gas system—and without electricity for its coordination and control, pipeline gas could be impeded during grid restoration.

During blackstart, Ukraine's four nuclear power plants with 13.8 gigawatts of capacity—a source of electric grid strength in normal times—will become an operational challenge. Grid collapse will cause tripping and emergency shutdown of nuclear reactors. Neutron poisoning in the cores could prevent restart for two days or more.¹³ "Cranking" from hydroelectric plants and restarted thermal plants will be required to blackstart the nuclear plants. The standard for emergency power at nuclear plants is seven days; once this duration is exceeded, efforts to truck in replacement fuel and otherwise prevent reactor meltdowns will consume scarce societal resources.

The phenomenon of "cold load pickup" will be a particular impediment to blackstart of Ukraine's electric grid during winter months. When grid power is interrupted during cold weather, the internal temperatures of residences and commercial buildings decline. At the point in time when power is restored, the sudden inrush of electricity into heating systems and appliances can trip grid protective devices—and again cause disconnection of customer load. (Friend, 2009) During winter blackouts in the United States, it has taken grid operators multiple attempts over several days to restore power for distribution feeders affected by cold load pickup.

Delayed blackstart can result in catastrophe, because as delays occur, grid restoration becomes progressively more challenging. Modern electric grids depend on telecommunications for their coordination and control. In turn, telecommunications equipment ultimately relies on power from the electric grid. The common

in the long transmission lines used to import power, reducing its utility in grid restoration.

13 For duration of neutron poisoning, the experience of nuclear plant operators in the U.S. is instructive. After the 2003 Northeast Blackout, it took tripped nuclear reactors a full week to return to 100 percent power. After tripping during the February 2021 blackout in ERCOT, it took the South Texas Nuclear Project reactor two days to restart and another 24 hours to return to full power.

standard for backup power for commercial telecommunications systems is 24-72 hours. (Popik, 2017). ENTSO-E requires 24 hours of backup power for voice communication systems used in blackstart.¹⁴ (European Union, 2017) Substation batteries store energy for just a few cycles of circuit breaker operation. Once backup energy sources are depleted, grid restoration must be manually performed by on-site personnel using satellite phones and line-of-sight radios. Satellite phones and their communications channels will be in short supply during emergencies.

Among system operators and electric grid regulators, there is growing realization that grid restoration after system collapse may take longer than 24 hours, with attendant impacts on human populations. For example, the U.S. state of Texas experienced Winter Storm Uri in February 2021. Low temperatures caused increased demand for electricity, fuel shortages at generating plants, and mechanical breakdowns. Insufficient generation reserves required rolling blackouts and nearly resulted in complete system collapse. After the crisis, ERCOT CEO Bill Magness testified before the U.S. House Energy and Commerce Committee:

Avoiding a complete blackout is critical. Were it to occur, the Texas grid could be down for several days or weeks while the damage to the electrical grid was repaired and the power restored in a phased and highly controlled process...As terrible as the consequences of the controlled outages in February were, if we had not stopped the blackout, power could have been out for over 90% of Texans for weeks.

Policy Recommendations

The Government of Ukraine and its utilities have kept the electric grid operating during wartime, a substantial accomplishment. At the time of this writing, there have been no persistent outages except those caused by attack on local transmission lines and distribution facilities. The transmission system operator, Ukren-ergo, continues to perform daily dispatch. The electricity market still operates. During the April 24-25 missile attack on six railroad substations, system operators were successful in preventing cascading collapse. For the most part, generating plants have been supplied with fuel. Plant operators—even those at the occupied Zaporizhzhia NPP—have stayed on station. Line crews have risked their lives to restore power. On March 16, the Ukraine grid interconnected with the ENTSO-E grid—a year ahead of the 2023 plan—and has continued to operate reliably. The policy challenge for Ukraine is to continue this outstanding performance. Recommendations are below.

14 In 2017, the EU established a network code on electricity emergency and restoration that specified coordination of blackstart plans among ENTSO-E members. It is notable that the EU code specifies a minimum of 24 hours of backup power for voice communications used in grid restoration, “in case of total absence of external electrical energy supply.”

Consider Russian Incentives

Ukraine should continually evaluate Russian incentives to preserve energy infrastructure. In fact, communications between Russia and Ukraine continue on a variety of levels. Past experience during the 2014-2022 Ukraine-Russia conflict in Donbas shows that infrastructure incentives can be aligned.

Aside from eliminating Ukraine as a nation and capturing its territory, a strong Russian incentive is keeping energy infrastructure intact. A system of mutual restraint has emerged. To support this incentive, Ukraine could leave energy infrastructure intact when retreating and expect the same of Russian forces. Ukraine could refrain from targeting energy infrastructure in Russian-controlled regions (and Russia itself) and expect the same from Russia. Ukraine should avoid direct military assault of the Zaporizhzhia nuclear plant currently in Russian hands.

Gas transmission through Ukraine reinforces Russian incentives for profit. Already, Ukraine is advocating for Russian shipments of natural gas to Europe to go through Ukrainian pipelines rather than the Nord Stream 1 pipeline. Reliable transmission of natural gas requires a reliable electric grid.

Prevention of infrastructure accidents should be an imperative for all countries. An electric grid collapse would dramatically increase the chance of infrastructure accidents. Ukraine should continue its demands for Russia to refrain from military actions that could cause accidents at nuclear plants under Ukrainian control. There should be an absolute prohibition on attacking hydroelectric dams.

Ukraine's actions to preserve reliable operation of its electric grid and other energy infrastructures will reduce the chance of disruptive human migrations. Foreign aid spent to reinforce Ukraine's electric grid would cost far less than money spent on assisting cross-border refugees; the Government of Ukraine should make this point to allies through public statements and diplomatic communications.

Enhance Electric Grid Resilience

Ukraine and its allies can take a number of near-term actions to enhance the resilience of its electric grid to disruption and increase the prospects for successful restoration if a collapse were to occur. Potential steps include adding reserves from electricity imports, adding flexible generation, managing consumer demand, and establishing contingency plans for quick replacement of damaged equipment.

Ukraine has already enabled electricity imports by interconnecting with Europe's ENTSO-E grid. This interconnection will provide energy during generation shortfalls and also enhance resilience to grid disruptions. Planned installation of reactive power compensation devices (STATCOM) will make imported power more useful for both normal operations and blackstart. When generating plants

break down and cannot be repaired, utilities should consider using them as synchronous condensers to bolster reactive power.

Ukraine has a deficit of maneuverable, fast-response generation, especially during winter months and in regions distant from hydroelectric plants. Mobile gas-turbine generators are a common solution for stressed electric grids. These generators can provide spinning reserves to respond to grid contingencies and also initiate blackstart. Mobile gas-turbine generators have capacity of 10-50 megawatts per unit; run on natural gas, propane, and fuel oil; and can generate power in as little as two days after arrival.

Management of consumer demand will be important, especially during winter months. For example, approximately 20 percent of Ukrainians depend on district heating from CHP plants. If fuel supply is interrupted to CHP plants, or CHP generation is reduced for grid maneuverability, electricity consumers will be tempted to use plug-in resistive heaters. If 1.7 million households use plug-in heaters of 1,500 watts each during the Siberian Anticyclone, the additional load will be 2.5 gigawatts—an approximate 15% increase to winter peak demand.^{15 16} A public communication campaign to reduce consumer demand during grid emergencies will be critically important.

When substation transformers are destroyed by accidental cause or deliberate attack, manufacturing and installation of replacements takes 1-2 years in normal times. Likewise, substation circuit breakers have ordering lead times of 1-2 years. Ukraine should acquire and pre-position spare transformers and circuit breakers. Ukraine can also acquire truck-deliverable, interchangeable recovery transformers, similar to the 600 mega volt amperes (MVA) RecX design developed under contract to the U.S. Department of Homeland security. (Electric Power Research Institute, 2014) Portable substations, including transformers, are also commercially available and could be pre-positioned in Ukraine.

Plan for Reliable Grid Restoration

A top priority for Ukraine should be the development of a robust grid restoration

15 There are 16.8 million household consumers of electricity in Ukraine. Approximately 20% of households rely on CHP plants for district heating. The Ukraine Minister of Energy disclosed that 50% of heating capacity has been lost. This implies that approximately 1.7 million households could use resistive space heaters as a replacement for CHP heat (16.8 million household electricity consumers * 0.20 * 0.50=1.68 million). Peak demand in June 2022 was 12 gigawatts but could be 15-20 gigawatts in winter 2022-2023.

16 Cold weather from Winter Storm Uri impacted the ERCOT system in Texas in February 2021. The unexpected increase in peak demand over the ERCOT generation adequacy plan is illustrative of the issues the Ukraine IPS could have during the Siberian Anticyclone. Starting on February 14, temperatures in Texas were much colder than normal. The ERCOT system operator planned for a winter peak load of 75.2 gigawatts, but use of resistive heating caused an additional 9.6 gigawatts of demand over the planning scenario. ERCOT imposed rolling blackouts that impacted approximately one-third of electricity consumers at their peak on February 15. (Popik, 2021)

plan. While Ukraine's fundamental electric grid configuration cannot change in the near-term, utilities can take steps to increase the probability of successful restoration. Potential steps include development of a restoration plan that is coordinated with ENTSO-E; simulator practice of blackstart by grid operators; coordination of the restoration plan with natural gas pipeline operators and telecommunications providers; acquisition of satellite phones for transmission system operators, plant operators, and distribution providers; stocking of fuel oil at dual-fuel generators; stocking of larger-than-normal reserves at coal-fired generators; installation of reactive power devices to allow imported power to be used in blackstart; installation of mobile gas-turbine generators adjacent to large thermal plants; stocking of spare high-voltage transformers and circuit breakers; maintenance of high reservoir levels at hydroelectric dams and pumped storage plants; and operation of nuclear plants at power levels that would reduce restart delays from neutron poisoning.

Ukraine has continued to operate an electricity market during the Russian invasion. Advance coordination with merchant generators would build resilience and aid grid restoration. Potential steps include ancillary services contracts for generation reserves, reactive power, and blackstart services; tests of blackstart generators under realistic conditions (without auxiliary grid power); payment to generators for stocking of fuel oil and coal reserves at generating plants; payment to gas pipeline operators for firm capacity during restoration; and Reliability Must Run (RMR) contracts with generators (payments outside of the electricity market). Contractual and operational provisions should be made for suspension of the electricity market under emergency conditions.

Electricity consumers can assist with grid restoration if expectations are publicly communicated before a blackout.¹⁷ Potential steps include disconnecting (or unplugging) resistive space heaters; unplugging refrigerators and freezers; and generally turning off lights and appliances until after power is restored. All of these steps will reduce the challenges of “cold load pickup.” A government communications program should advise home dwellers and building managers to turn off main circuit breakers before abandoning buildings.¹⁸

Conclusions

Ukraine has reliably operated its interconnected electric grid during wartime—a feat that is unprecedented and notably successful thus far. Ukraine's electric grid is

17 In the United States, some utilities have launched public communication campaigns so that their electricity consumers will mitigate the effects of cold load pickup. For an example, see “[Prevent Cold Load Pickup – Unplug!](#)” (Rio Grande Electric Cooperative, 2021)

18 In its publication “[Power Outages — What to do?](#)” the Government of Canada recommends turning off appliances, saying, “power can be restored more easily when there is not a heavy load on the electrical system” and also directs evacuating residents to “Turn off the main breaker or switch of the circuit-breaker panel or power-supply box.” (Government of Canada, 2011)

increasingly stressed as the Russian invasion continues. Consideration of Russian incentives can reduce the probability of adverse infrastructure events. Military actions may degrade grid reliability or, alternatively, mutual restraint on infrastructure attacks may prevail—either outcome is possible. But as winter approaches, it is nearly certain that Europe will run short of energy and Ukraine’s generating plants will compete for scarce fuel supplies. Without support from Europe and other allies, the probability of a cascading grid collapse in Ukraine increases. A cascading grid collapse followed by blackstart failure could cause a humanitarian and environmental disaster of the first order—not just for Ukraine, but also for bordering countries. Technical assistance and funding provided to Ukraine’s electricity sector can significantly reduce the probability of long-term grid collapse. Moreover, the Government of Ukraine can take practical, low-cost steps on its own to increase grid resilience, such as a public communications campaign to reduce customer demand during emergencies. Support of Ukraine’s electric grid during wartime has lessons for all industrialized nations dependent on critical infrastructure reliability and resilience.

Acknowledgements

The daily DiXi Group Alerts, “Russian War Against Ukraine: Energy Dimension,” have been an invaluable source of information for this article. The author acknowledges the efforts of Tabor French as research analyst for this article.

Acronyms and Abbreviations

AC	Alternating Current
AGC	Automatic Generation Control
bcm	Billion Cubic Meters
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
DC	Direct Current
GDP	Gross Domestic Product
EHV	Extra High Voltage
ERCOT	Electric Reliability Council of Texas
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GTSOU	Gas Transmission System Operator of Ukraine
HPP	Hydropower Plant

HVDC	High Voltage Direct Current
IAEA	International Atomic Energy Agency
IPC	Interconnected Power System
mcm	Million Cubic Meters
MVA	Mega Volt Amperes
MW	Megawatts
MWh	Megawatt-hour
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
SCADA	Supervisory Control and Data Acquisition
SSSCIP	State Service of Special Communication and Information Protection
STATCOM	Static Synchronous Condenser
TTF	Title Transfer Facility
TPP	Thermal Power Plant
TSO	Transmission System Operator
RBMK	High-power Channel-type Reactor
RMR	Reliability Must Run
UAH	Ukraine Hryvnia
U.S.	United States
VVER	Water-Water Energetic Reactor

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