Ukraine’s Critical Infrastructure During the Russian Invasion
May 2, 2022

Presenter: Thomas Popik
The Lights Are On in Ukraine. Why?
Agenda

- Executive Summary
- Timeline of Infrastructure Attacks
- Ukrainian Infrastructure Sectors
  - Electric Grid
  - Nuclear Power
  - Natural Gas
  - Telecommunications
  - Petroleum
  - Rail Transport
  - Agriculture
- Key Takeaways
- Summary Conclusions
Executive Summary

- Ukraine’s infrastructure inherited from the Soviet Era
- Electric grid is the Crown Jewel of Ukrainian infrastructure
  - Over 50% of power from nuclear reactors
- Continued electric grid reliability during invasion
  - Russia’s Rosatom is operating Zaporizhzhia nuclear reactors and feeding power into high voltage transmission system
- Attacks on infrastructure apparently calibrated to weaken Ukraine but not totally collapse its society
  - Rational goals: Preserve gas transmission and nuclear safety
  - Increasing attacks on petroleum and rail transport systems
- If Russia stalemated on battlefield, infrastructure attacks may escalate—imperiling Ukraine’s population and causing a refugee crisis for the European Union
Russian invasion of Ukraine, as of April 29

- Approximate Russian-occupied Ukrainian territory
- Nuclear power plants
- City surrounded by Russian forces
Timeline of Attacks on Critical Infrastructure

- Cyber attack on Viasat telecom provider—February 28
- Shelling of Zaporizhzhia Nuclear Plant—March 3
  - No Meltdowns or Radiation Release
  - Loss of Two High-Voltage Transmission Lines
- Attack on Ukraine’s largest salmon processor—March 13
- Shelling of 750kV transmission lines for Zaporizhzhia nuclear plant—March 16
  - Three out of four plant transmission lines lost
- Cyber attack on Ukrtelecom telecom provider—March 28
- Attack on Europe’s largest food warehouse—March 30
- Missile strike on Kremenchuk refinery—April 2
  - Destroyed fuel tanks, refinery destruction claimed by Ukraine

Source: Resilient Societies research, Euronews.green
Attacks on Ukraine Critical Infrastructure (cont.)

- Attack on Odessa fuel storage and refinery—April 2
- Interference with control system at Novopskov compressor station for natural gas pipeline—April 8
  - One-third of gas transiting Ukraine potentially affected
- Missile attacks on rail traction substations in western Ukraine—April 24-25
- Missile attacks on railroad bridge across the Dniester Estuary leading to Danube ports—April 24-25
- Second attack on Kremenchuk oil refinery—April 25
- Attack on airport runway in Odessa—May 1
- According to WHO Surveillance System For Attacks On Health Care (SSA), 148 attacks on health care facilities with heavy weapons between February 24 and May 1
Electric Grid
Ukraine's Critical Infrastructure During the Russian Invasion

Ukrenergo Video Dated March 2, 2022

Armed forces of Ukraine and civilian consumers have electricity

Source: YouTube
High Voltage System Map For Ukraine Grid

Source: energydata.info
Ukraine's Critical Infrastructure During the Russian Invasion

Ukraine Generation Capacity By Energy Source
56 GW in 2020
- Solar PV: 13%
- Wind: 3%
- Hydro: 8%
- Natural gas: 9%
- Nuclear: 24%
- Coal: 43%
- Other: 0%

Ukraine Electricity Generation by Energy Source
143,400 GWh in 2020
- Nuclear: 53%
- Coal: 30%
- Natural gas: 8%
- Hydro: 5%
- Wind: 1%
- Solar PV: 1%
- Other: 2%

Source: IEA, Global Energy Monitor, GlobalData, U.S. EIA, Resilient Societies estimates
Ukraine Generation Capacity Factors by Energy Source—2020

- Nuclear: 64%
- Coal: 21%
- Natural gas: 25%
- Hydro: 19%
- Wind: 16%
- Solar PV: 3%

Source: IEA, Global Energy Monitor, GlobalData, U.S. EIA, Resilient Societies estimates
Ukraine Grid Synchronized with ENTSO-E on March 16

Source: Stiftung Wissenschaft und Politik
Nuclear Power
Ukraine’s Nuclear Power Plants

Source: Business Insider, IAEA
Risks for Ukraine’s Nuclear Power Plants

- 15 nuclear reactors at 4 plant locations—13.1 GW
  - 8 Reactors Operating on April 7; Approximately 7 GW
- Soviet-designed Water-Water Energetic Reactors (VVER)
- Steel and concrete containment for reactors
- Zirconium-clad rods used for reactor fuel
  - Before the war, fuel supplied by Russia
  - Pending transition to Westinghouse fuel
- Plants have spent fuel pools not in containment
- Spent fuel pools require electric power for cooling
- When water boils off from spent fuel pools, zirconium fires and radioactive plumes can result
- Without water for radiation shielding, spent fuel pools are highly radioactive and cannot be approached

Source: Resilient Societies research
Attack on Zaporizhzhia Nuclear Power Plant on March 3

Source: BusinessToday.in
Russian Operation of Zaporizhzhia Plant

- Zaporizhzhia nuclear plant captured on March 3
- Plant operators held captive
- Adjacent city of Enerhodar occupied by Russian forces and residents prevented from evacuating
- Russia’s Rosatom executives and engineers brought in to operate plant
  - Two out of six reactors continue to operate normally
  - Three out of four high-voltage lines disabled on March 16
- Open question: Where is Zaporizhzhia power going?
  - Ukrenergo transmission system?
  - Crimea annexed by Russia?
  - Eastern Ukraine now controlled by Russia?

Source: Dixi Group updates
Natural Gas
Ukraine’s Natural Gas Sector

- Production of 19 bcm annually
- Consumption of 29 bcm annually
- Gap-filling imports mainly from “Western Europe”
- Storage capacity of 31 bcm, approximately one year’s consumption
- Shebelynka gas processing plant shut down on February 26 to avoid risk of operating during war
- Pipeline system transports gas from Russia’s Gazprom to European Union customers
  - Gazprom transmission approximately one-half of contract
  - Declining gas transmission in recent weeks
  - Ukraine asks Germany for less Nord Stream 1 gas transit

Interdependence of GazProm and UkrTransGas Pipelines

Source: East European Gas Analysis
Ukraine’s Critical Infrastructure During the Russian Invasion

Source: Naftogas Group
Declining Natural Gas Transit Through Ukraine

- Gas Transiting System
- Contracted Volume with Gazprom

Source: GTSOU
Telecommunications
Internet Outage Detection and Analysis (IODA)

- Real-time monitoring of internet outages by Georgia Tech
- Active probing of internet IPv4 address space
- Ping-based measurements
- Border Gateway Protocol
- Measurement of internet background radiation
- *Proven usefulness during prior infrastructure disruptions*
March 28 Cyberattack on Ukrtelecom

IODA Signals for Ukraine

Mon, Mar 28 - 13:40
Active Probing (#/24s Up): 93%

Time (UTC)

02:00 AM 03:00 AM 04:00 AM 05:00 AM 06:00 AM 07:00 AM 08:00 AM 09:00 AM 10:00 AM 11:00 AM 12:00 PM 01:00 PM 02:00 PM 03:00 PM 04:00 PM 05:00 PM 06:00 PM 07:00 PM 08:00 PM 09:00 PM 10:00 PM 11:00 PM 12:00 AM 01:00 AM 02:00 AM 03:00 AM 04:00 AM 05:00 AM 06:00 AM 07:00 AM 08:00 AM

0% 20% 40% 60% 80% 100%

Active Probing (#/24s Up)  BGP (#Visible /24s)  Telescope (# Unique Source IPs)
IODA Signal Disruptions in Early April

IODA Signals for Ukraine

- Active Probing (#/24s Up): 65%

- Alert Bands: ON
- Normalized Values: ON

Graph showing signal disruptions from April 5, 2022, to April 13, 2022.
Petroleum
Ukraine’s Petroleum Sector

- Three-quarters of petroleum imported (2020 figures)
  - Consumption of 234,000 barrels/day
  - Production of 56,000 barrels/day
  - Before war, refined petroleum imports from Belarus and Russia
  - Crude oil import through Ports of Odessa and Yuzhnye (Pivdenny)

- Refinery throughput of 68,000 barrels/day
  - Capacity of 250,000 barrels/day, some refineries inactive
  - Kremenchuk was Ukraine’s only major operating refinery
  - Shebelynka gas processing plant also refined crude oil

- Bi-directional Odessa-Brody pipeline between Port of Yuzhnye and Poland

- Petroleum storage capacity is a Ukraine state secret

Source: BP Statistical Review, worldometer, Wikipedia, Resilient Societies research
Kremenchuk Oil Refinery Attacked on April 2 and 25

Ukraine’s Petroleum Situation

President Zelenskly on April 29

- "Queues and rising prices at gas stations are seen in many regions of our country"
- “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”
Rail Transport
Ukraine’s Rail Transport

- Vital means of transport for both people and goods
- Ukrzaliznytsia is state monopoly operator
- 13,447 miles of track
  - Almost half of track—6,138 miles—is electrified
- Rail is last major means of imports/exports
  - 1520 mm gauge tracks vs. 1435 gauge for EU system
  - Car transloading terminals necessary at EU borders
- Beskydy tunnel handles 60% of Ukraine-EU freight
  - Modern tunnel, completed in 2018
  - 1.1 miles long, double tracks, 46 trains/day capacity
- Until late April, few major attacks on rail system

Source: Wikipedia, Resilient Societies research
April 25 Attack on Krasne Rail Station Transformer

Source: State Emergency Service Of Ukraine In Lviv Oblast/SESU/Reuters
Attacks and Chokepoints on Ukraine Rail System

Source: [https://www.wikiwand.com/en/Ukrainian_Railways](https://www.wikiwand.com/en/Ukrainian_Railways), HerroqEnstein, Resilient Societies research
Black Sea Ports
Current Status: All of Ukraine’s Ports Closed

Ukraine’s Black Sea Ports

- Port of Berdyansk (captured by Russia)
  - 9 berths; 2.1 million tons annually
  - Russian ship destroyed in port on March 25
- Port of Chornomorsk
  - 29 berths; 21.5 million tons annually
  - Container port with train link to Bulgaria
- Port of Mariupol (city destroyed by Russia)
  - 21 berths; 7.6 million tons annually
  - Major terminal for Ukraine’s iron exports
- Port of Mykolaiv (Port of Olbia for passengers)
  - 23 berths; 24 million tons annually
  - Shipbuilding center of Black Sea
- Port of Odessa
  - 46 berths; 31.4 million tons annually
  - Petroleum storage terminal and inactive refinery
- Yuzhnye Port (formerly Pivdenny)
  - 38 berths; 61.66 million tons annually
  - Major oil and coal terminal

Source: Resilient Societies research
April 2 Attack on Odessa Fuel Storage and Refinery

Source: Bulent Kilic/AFP via Getty Images
Agriculture
Ukraine’s Agriculture Sector

- “Food basket” exporter that feeds 400 million people
  - Food is 41% of exports ($27.8B of $68B total)
  - China is No. 2 customer, behind only European Union

- Major crops include:
  - Wheat planted in fall, harvested in July and August
  - Barley planted in April, harvested in August
  - Corn planted in April/May, harvested September to November
  - Sunflower seeds planted in April, harvested in September to Oct.

- Food warehouses and factories attacked by Russia
- Russia mined some fields that now must be cleared
- Shortages of diesel fuel for spring planting
- 30 million tons of wheat in storage, one year’s production
- Before the war, food exported through Black Sea ports
- Limited rail export capacity for agriculture production

## Ukraine Agricultural Production and Exports (2021/22 Marketing Year)

<table>
<thead>
<tr>
<th>Product</th>
<th>Production</th>
<th>Exports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume (1,000 MT)</td>
<td>Rank Among Global Producers</td>
</tr>
<tr>
<td>Corn</td>
<td>41,900</td>
<td>#6</td>
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<tr>
<td>Wheat</td>
<td>33,000</td>
<td>#7</td>
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<tr>
<td>Sunflower</td>
<td>17,500</td>
<td>#1</td>
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<tr>
<td>Barley</td>
<td>9,900</td>
<td>#4</td>
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<tr>
<td>Sunflower Oil</td>
<td>5,676</td>
<td>#2</td>
</tr>
<tr>
<td>Sunflower Meal</td>
<td>5,452</td>
<td>#2</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>3,015</td>
<td>#6</td>
</tr>
</tbody>
</table>

Source: Trade Data Monitor LLC via USDA
### Ukraine Agricultural Exports (2021 Calendar Year)

<table>
<thead>
<tr>
<th>Product</th>
<th>Value</th>
<th>Top Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>$27.8 billion</td>
<td>EU $7.7B</td>
</tr>
<tr>
<td>Sunflower Oil</td>
<td>$6.4 billion</td>
<td>India $1.9B</td>
</tr>
<tr>
<td>Corn</td>
<td>$5.9 billion</td>
<td>China $1.9B</td>
</tr>
<tr>
<td>Wheat</td>
<td>$5.1 billion</td>
<td>Egypt $0.9B</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>$1.7 billion</td>
<td>EU $1.1B</td>
</tr>
<tr>
<td>Barley</td>
<td>$1.3 billion</td>
<td>China $0.7B</td>
</tr>
<tr>
<td>Sunflower Oilcake</td>
<td>$1.2 billion</td>
<td>China $0.6B</td>
</tr>
</tbody>
</table>

Source: Trade Data Monitor LLC
Key Takeaways
Infrastructure Events Not Yet Observed

- Destruction of large electric generation plants
- Attacks on major dams
- Attack on Beskydy railroad tunnel
- Attack on Odessa-Brody pipeline
- Attacks on berths and cargo handling equipment at ports
- Successful cyber-attack on:
  - Electric grid control systems
  - Natural gas control systems
  - Telecommunications
- Physical attacks on key infrastructure nodes:
  - High voltage grid substations (outside of rail transport)
  - Natural gas compression stations
  - Telecommunication hubs

*Cascading collapse of critical infrastructure*
How Long Can Ukraine Keep the Lights On?

- Distributed electric grid infrastructure highly vulnerable to Russian missile attack and shelling
  - Risk of cascading collapse if key nodes targeted
- Ample energy supply for electric grid
  - Nuclear reactors operating with two years of fuel in reactor cores
  - Springtime levels for hydroelectric reservoirs
  - Large supplies of stored natural gas and coal
- Minimal disruptions to telecommunications system
- Attacks are degrading supporting infrastructures
  - Food processing and distribution
  - Petroleum refining and distribution
  - Rail transport system
- Electric grid attack appears to be “off limits” for now
Consequences of Critical Infrastructure Collapse

- Loss of Clean Water
- Food Shortages
- Looting/Foraging
- Disease and Pandemic
- Widespread Deaths
- Societal Collapse
- Refugees

Photo Credits, Top to Bottom & Background: Fernando Liano-AP, Reuters, The Atlantic, Getty Images
Summary Conclusions

- Russia’s attack on Ukraine unprecedented in Modern Era
  - Besieged country with wide-area, synchronized electric grid
  - Nuclear power sector supplies over 50% of electricity
  - Cross-border natural gas pipelines interdependent with grid

- Not yet the society-wide “Total War” of World War II
  - No attempts to cause total collapse of critical infrastructure

- Russian incentives to avoid infrastructure collapse
  - Continued transmission of Russian gas to European customers
  - Risk of nuclear plant meltdowns and radiation releases
  - Territory capture with hard-to-replace equipment left intact

- Battlefield stalemate may escalate infrastructure attacks
  - Total infrastructure collapse will cause refugee crisis for Europe