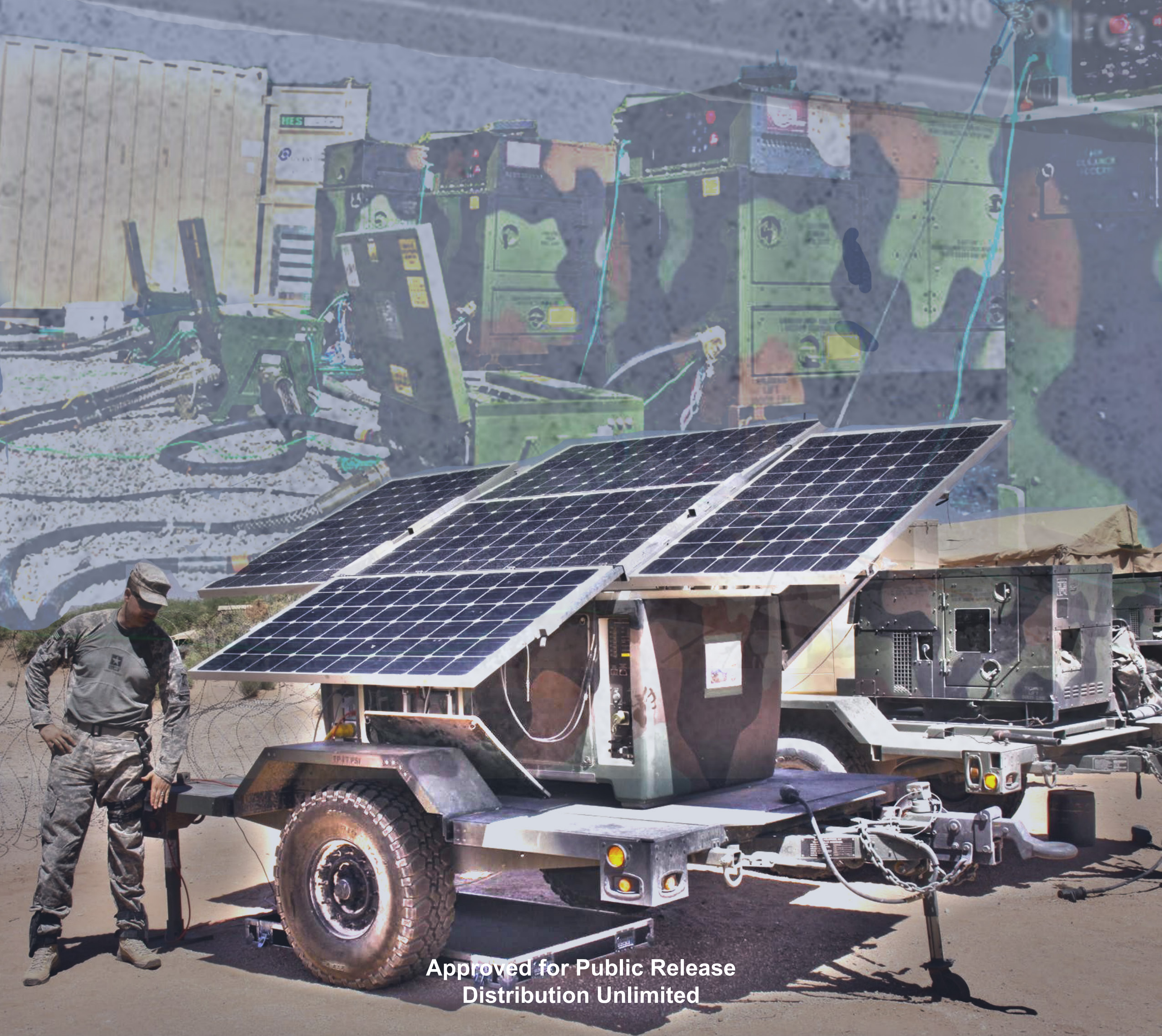
POWERING THE FRONT

Tactical Energy Delivery and Management in the Ukraine War



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Section 1
Introduction

Electricity has become one of the most decisive enablers of contemporary warfare. Where past army generations relied primarily on manpower, fuel, and ammunition, today's forces depend equally on the uninterrupted flow of electrical power to sustain operational tempo. Radios, drones, command-and-control systems, electronic warfare (EW) equipment, precision-guided weapons, and medical devices are all rendered ineffective without a reliable energy source. In the ongoing Ukraine War, electricity has emerged not only as a strategic target but also a tactical necessity. Russia has deliberately struck Ukraine's national power grid to disrupt civilian life and weaken morale, illustrating how energy infrastructure functions as a military objective and psychological warfare tool. Yet, beyond the strategic sphere of grid attacks[1] and national energy policy lies a more immediate and pressing concern: how small units at the frontline generate, deliver, and manage power under fire.

At the tactical level, electricity is the hidden lifeline of every platoon and company. Unlike fuel or ammunition, which are firmly embedded in established military supply chains, battlefield electricity presents unique challenges. Batteries deplete rapidly, generators are vulnerable to detection, and fuel convoys are high-value targets for artillery and drones. In Ukraine, where combat is fluid and dispersed, units cannot always rely on regular resupply or centralized infrastructure. Instead, they are compelled to improvise, adapt, and integrate military and civilian technologies to sustain operations. The result is a battlefield where energy management has become as critical to survival as camouflage, maneuver, and firepower.

This paper begins with the recognition that modern combat effectiveness is inseparable from battlefield power management. Electrical power is a critical enabler for all warfighting functions. Without it, mission command, protection, sustainment, and intelligence rapidly degrade.[2] Examination of the Ukrainian experience shows that the ability to generate and distribute electricity at the tactical level directly influences command and control (C2), situational awareness, and the lethality of armed forces. The following sections explore the rising energy demands of the modern battlefield, diverse sources of tactical power available to Ukrainian units and challenges they face sustaining it, and innovative adaptations that have emerged in response. The Ukrainian case highlights a broader lesson for modern militaries—tactical energy resilience is no longer an auxiliary concern, but a central pillar of combat readiness.

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[1] *Ukraine: Energy infrastructure attacks: outlook and impact during 2024-2025 cold season*. Thematic Report. 13 September 2024. https://www.acaps.org/fileadmin/Data_Product/Main_media/20240913_ACAPS_Ukraine_Analysis_hub_Attacks_on_the_energy_infrastructure_in_Ukraine.pdf.

[2] Army Techniques Publication (ATP) 3-34.45, *Electric Power Generation and Distribution*. 5 February 2024.

Section 2
Energy Demands of the Modern Battlefield

The modern battlefield is more electrically intensive than any in previous history. In Ukraine, this reality has been demonstrated daily. Tactical units that once required little more than ammunition and fuel now depend on a complex ecosystem of electrical power to function. This surge in demand comes from several converging trends in warfare—the proliferation of digital command systems, dominance of unmanned platforms, and reliance on precision and information superiority.

The Ukraine War illustrates a surge in electricity-dependent systems compared to past conflicts:

- **Command, control, and communications (C3).** At the heart of every military operation is the ability to communicate. Platoons and companies in Ukraine rely on encrypted radios, satellite uplinks, secure laptops, and data terminals for command and control (C2). These devices require frequent recharging, often in austere conditions where commercial power is unavailable. A typical company-level command post (CP) in Ukraine can run 10–15 radios, multiple laptops, and secure data links simultaneously, drawing 2–3 kilowatts (kW) of continuous power. A single Harris Falcon III tactical radio consumes about 35 watts, while satellite uplink terminals such as Starlink require 100–150 watts to operate. When aggregated, the demand of a modest forward command node may exceed the daily electrical consumption of a civilian household. Power interruptions can lead to breakdowns in coordination, delayed fires, or complete isolation.
- **Intelligence, surveillance, and reconnaissance (ISR) systems.** The proliferation of small drones in Ukraine has dramatically increased tactical electricity needs. Quadcopters used for reconnaissance, artillery correction, and strike missions demand near-constant charging of batteries, which may only provide 20–40 minutes of flight time each. The Ukrainian battlefield has seen the widespread deployment of quadcopter drones such as the DJI Mavic series, which are now indispensable for artillery correction and reconnaissance. Each battery provides 25–35 minutes of flight time and requires 60–90 minutes to recharge, meaning multiple batteries must be rotated constantly. A single drone team can cycle through 10–12 battery charges per day, consuming around 2–3 kilowatt-hours (kWh) of electricity. Larger fixed-wing drones like the Leleka-100 or Furia demand even higher charging capacity, sometimes using vehicle-mounted systems. In addition, night-vision goggles (NVGs) consume 0.5–1 watt per device, while thermal imaging sights require 5–10 watts each. For a platoon outfitted with such devices, this translates to several hundred watt-hours per day. The fight for situational awareness—to see first and strike first—is therefore directly tied to electricity availability.
- **Electronic warfare (EW).** Ukraine's frontlines have become EW laboratories, where jamming, spoofing, and counter-drone measures consume immense amounts of energy. Mobile jammers and radar stations are notoriously power-hungry, requiring continuous high-wattage supply. A portable jamming system such as the Bukovel-AD consumes 200–300 watts, while larger vehicle-mounted jammers may require 5–10 kW of continuous generation. Without uninterrupted supply, these systems become vulnerable gaps in the defensive network.
- **Medical support.** Electricity is not solely a combat enabler—it is also a lifesaving necessity. Field hospitals, stabilization points, and casualty evacuation hubs require

uninterrupted energy to operate their equipment. A small stabilization point with a ventilator, surgical lighting, refrigeration, and communications can consume 3–5 kW continuously. Refrigerators for blood and vaccines require 100–200 watts each, but the necessity of 24/7 operation makes them major consumers over time. Larger field hospitals, often set up in civilian basements near the front, may run on 20–50 kW diesel generators, especially when supporting surgical theaters. Donated systems like the EcoFlow Delta Max (2 kWh battery storage) or Honda EU2200i (2.2 kW portable generator) are now standard equipment in many Ukrainian casualty evacuation points. During Russian strikes on civilian grids, Ukrainian medical facilities have increasingly depended on portable generators and donated power stations to sustain life-saving functions. This underscores that energy demand at the tactical level is also directly linked to humanitarian survival.

- **Infantry essentials.** At the individual level, the modern infantry Soldier carries a growing suite of electrically powered devices such as radios, Global Positioning System (GPS) receivers, laser rangefinders, NVGs, and body-worn cameras. Soldiers also use personal power banks to recharge smartphones and tablets, which often double as mapping, translation, and targeting aids. Although individually modest in consumption, the aggregate demand across a company can be significant. Unlike fuel or water, however, electrical supply is less standardized—units must carry a mixture of cables, adaptors, batteries, and chargers, complicating logistics. A modern infantry Soldier's personal electronic load is considerable:
  - **Radio.** 5–10 watts (W) continuous draw.
  - **GPS receiver.** ~2 W.
  - **Night-vision device.** ~1 W.
  - **Thermal sight.** 5–10 W.
  - **Smartphone or tablet (used for mapping apps like GIS Arta).** About 10 W while active.

  On average, an individual Soldier may consume 50–100 watt-hours (Wh) per day just in personal electronics. At the platoon level (30–40 troops), this amounts to 1.5–3 kWh daily, equivalent to the full daily output of a small 1 kW generator. In practice, Soldiers rely on commercial-grade power banks of 20,000–30,000 milliampere-hours (mAh) (70–100 Wh), which often need recharging every 24–48 hours.

- **Emerging technologies and hidden consumption.** Beyond the obvious systems, less visible demands also weigh heavily on tactical power. Portable heaters, electronic fuzes, mine-clearing drones, and counter-battery radar sensors all require energy. Counter-drone laser dazzlers (experimental) require 10–15 kW surges. Portable heaters for trenches and bunkers consume 1–2 kW each, critical for winter survival. Mine-clearing drones and remote-controlled vehicles may draw hundreds of watts per mission, requiring repeated charging cycles. Even electronic fuzes for modern artillery shells and loitering munitions must be charged before use, creating hidden demand within artillery logistics.

- **Operational tempo and continuous load.** Unlike traditional resources, electricity cannot simply be stockpiled in bulk at the frontlines; it must be generated continuously. This creates a constant demand curve as batteries degrade with time and usage. Drones must be recharged after each sortie, communication nodes must remain powered, and medical systems cannot be switched off. A frontline company operating drones, radios, and a medical post may require 20–30 kWh per day just to sustain its activities. For perspective, this is the equivalent of running 10–15 household refrigerators nonstop. Maintaining this demand under conditions of artillery fire, disrupted logistics, and contested airspace forces units to rely on a patchwork of generators, vehicle alternators, and improvised renewable systems. Tactical commanders therefore face the challenge of maintaining uninterrupted energy supply in environments where concealment and survivability are paramount.

Table 2-1. Typical electronics (power load) seen on the battlefield vs power (watts)/duty cycle in hours/daily energy used in watts-hours[3]

Load	Typical Power (W)	Duty Cycle	Daily Energy (Wh)	Notes
Starlink Terminal (Gen 2/"Standard")	50–100	6–18 hours (h)/day	300–1,800	Use sleep scheduler; buffer with programable power supply (PPS) to avoid brownouts
Very High Frequency (VHF)/Ultrahigh Frequency (UHF) Handheld Radios (Per Charger)	10–30	1–3 h charging	10–90	Assume 1–2 spare batteries per radio/day
Manpack Radio Charger	40–90	1–3 h	40–270	Keep on PPS to smooth generator noise.
Tablet/Phone (Per Device)	5–15	2–4 h	10–60	Prefer USB-C PD; disable high-draw features
Laptop (Mission Planning)	30–60	2–6 h	60–360	Lower screen brightness; schedule updates
Small Quadcopter Unmanned Aerial Vehicle (UAV) Battery (Per Pack)	60–120 while charging	1–2 h/pack	60–240 per pack	4–8 packs/day common in ISR teams
First-Person View (FPV)/(Unmanned Aircraft System (UAS) Ground Station	20–60	2–6 h	40–360	Consolidate into CP where possible
Optical Devices (Thermals/NVG Battery Chargers)	10–40	1–3 h	10–120	Centralize charging by squad
LED Lighting for CP/Aid Post	10–50	4–8 h	40–400	Red/low-infrared (IR) light; motion sensors useful
Med Devices (Suction, Monitors)	20–100	intermittent	20–300	Keep on protected “critical” circuit

[3] MAJ Jakub Szulczyk. Polish Land Forces.

Table 2-2. Typical power drawing systems seen on the battlefield and their power requirements and impact[4]

System/Equipment	Typical Power Requirement	Tactical Impact
Company Command Post	2–3 kW continuous	Maintains communications, C2; equivalent to a household
Harris Falcon III Radio	35 W	Primary secure tactical comms
Starlink Terminal	100–150 W	Critical uplink for data and targeting
DJI Mavic Drone (Per Team, Per Day)	2–3 kWh per day	Vital for ISR, artillery correction
Thermal Sight	5–10 W	Enhances infantry lethality, night operations
Night-Vision Goggles	0.5–1 W	Enables 24/7 operations in low light
Portable EW Jammer (Bukovel-AD)	200–300 W	Drone defense, requires constant output
Vehicle-Mounted EW Jammer	5–10 kW	Large-area jamming; high consumption
Counter-Battery Radar (AN/TPQ-36)	10–20 kW	Essential for artillery counterfire; cannot fail
Small Stabilization Point (Medical)	3–5 kW continuous	Supports casualty stabilization; lifesaving
Field Hospital (Surgical Setup)	20–50 kW	Full medical capacity near frontline
Refrigeration Unit (Medical)	100–200 W	Preserves blood/medicine in all conditions
Infantry Soldier (Personal Daily)	50–100 Wh	Ensures Soldier communications, navigation, targeting
Platoon (30–40 Soldiers, Daily)	1.5–3 kWh per day	Aggregated demand = generator-level load
Portable Heater (Trench/Bunker)	1–2 kW	Critical for winter survival in trenches

As tables 2-1 and 2-2 illustrate, even relatively small electronic systems impose a cumulative burden on tactical energy supply. A single Soldier's load of 50–100 Wh per day may seem modest, but when scaled to a platoon, it amounts to 1.5–3 kWh daily, equivalent to running a 1 kW generator for several hours. Similarly, while a commercial drone consumes only a few kilowatt-hours across daily missions, the requirement for constant battery rotation and charging infrastructure creates a logistic dependency that rivals fuel or ammunition resupply.

The real outliers are EW and radar systems, which require continuous multi-kilowatt generation—loads that can only be sustained through vehicle-mounted or fixed generators. Medical facilities, particularly field hospitals consuming 20–50 kW, further underscore that tactical energy demand is not confined to combat operations but extends to lifesaving support functions. Taken together, these figures demonstrate that the modern battlefield requires units to function as self-sufficient micro power grids, balancing diverse demands under fire.

[4] Ibid.

“A sensor network that loses power becomes a dead node. A command post that goes dark loses tempo. A drone launch team without recharge capability becomes irrelevant after its first sortie.[5]” Therefore, energy on the modern battlefield is not a passive support function; it is a critical enabler of combat power. From reconnaissance to medical survival, every operational domain in Ukraine has demonstrated that uninterrupted electricity is decisive. The exponential growth of energy-hungry systems has turned tactical power into a vulnerability, forcing militaries to rethink energy planning as a core element of combat operations and primary sustainment factor. Energy planning therefore involves calculating peak loads, average consumption, and redundancy requirements to maintain operational continuity.

Moreover, as warfare becomes more network-centric, energy use grows exponentially. The future introduction of exoskeletons, powered armor, and laser-based weapons will push requirements even further. The Ukraine War is therefore a glimpse of tomorrow’s battlefield, where electricity is as critical as fuel or ammunition.

[5] MAJ Sean McLachlan. *Best Practices on Operationalizing Battlefield Energy: Power Generation, Storage, and Distribution in LSCO*. Center for Army Lessons Learned. NO. 25-1085. August 2025. Page 3.

Section 3
Sources of Tactical Power in Ukraine

The Ukrainian battlefield demonstrates that tactical power cannot depend on a single source; instead, units rely on a patchwork of generation systems adapted to different environments, missions, and mobility levels. Energy is produced from traditional military-grade systems and an increasing reliance on civilian technologies, often delivered by volunteers or nongovernmental organizations (NGOs),[6] or improvised from the commercial market. This dual character of Ukraine's tactical power supply—blending formal logistics with grassroots innovation—has been one of the defining features of its resilience.

Ukrainian units employ a mix of traditional and improvised sources:

- **Portable generators.** They are used at command posts, drone bases, and medical stations. Their advantages are high reliability and the ability to produce steady kilowatt (kW)-level outputs, but their drawbacks are considerable. They consume substantial amounts of fuel, create noise and thermal signatures that can be detected by Russian drones, and require frequent maintenance. In practice, units often disperse several smaller 1–2 kW generators instead of relying on one large 10–15 kW system, increasing redundancy and reducing the risk of catastrophic failure if one generator is destroyed. A small Honda EU2200i generator (2.2 kW) consumes about 1 liter of petrol per hour under medium load. A frontline drone team running two of these for charging and command equipment may burn through 20–30 liters of fuel daily, equivalent to a full jerrycan per machine. At larger facilities, Ukrainian units use 10–20 kW military-grade diesel generators, which can consume 3–5 liters of diesel per hour, creating a heavy logistic burden.

- **Vehicle-mounted systems.** Many Ukrainian units rely on their vehicles as mobile power stations. Armored personnel carriers, trucks, and even civilian pickups are used to power radar systems, radios, or medical equipment. This method allows for flexibility and mobility, but it increases fuel competition between propulsion and power generation. Moreover, stationary vehicles running engines continuously generate heat signatures visible to Russian drones equipped with infrared (IR) sensors. A typical truck alternator can provide 1–2 kW of usable electrical output, while specialized vehicle-mounted generators can deliver up to 15–20 kW. For example, the KRAZ or KAMAZ military trucks can sustain entire command posts, though at the cost of fuel capacity sacrificed for idle power production.

- **Batteries and power banks.** At the lowest tactical level, batteries are the lifeline of individual Soldiers and drone operators.[7] Ukrainian infantry members carry multiple lithium-ion packs to sustain radios, Global Positioning System (GPS) devices, and optics. Consumer-grade power banks, often delivered through crowdfunding, are a major feature of the frontline ecosystem. Larger portable battery stations, such as the EcoFlow Delta (1.2–2 kilowatt-hours [kWh] storage), are frequently used to charge drones, laptops, and radios without running noisy generators. These systems allow for "silent power," which is crucial for concealment, but eventually requires recharging from fuel generators or solar panels. A 20,000 milliampere-hours (mAh) (70 watt-hours [Wh]) power bank can recharge a Soldier's smartphone or radio 2–3 times.

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[6] *EcoFlow Charging Stations for the Military in Ukraine*. https://www.peoplesproject.com/en/ecoflow-sharging-stations-for-the-military-in-ukraine/.

[7] Ling, Justin. *Batteries Are Ukraine's Secret Weapon Against Russia*. 23 February 2023. https://www.wired.com/story/ukraine-russia-power-grid-batteries/.

Larger portable stations (for example, EcoFlow 2 kWh units) can recharge 15–20 drone batteries before needing replenishment themselves. This modularity makes them highly adaptable for dispersed units.

- **Renewables.** Although less common than generators, small-scale renewable energy solutions have become increasingly important. Portable solar panels, often commercial camping-grade equipment, are deployed to trickle charge batteries in rear positions or during long static deployments. In some cases, field hospitals and command centers use larger donated solar arrays combined with lithium battery banks, creating semi-permanent microgrids independent of fuel supply. However, renewable power is limited by weather conditions, seasonal daylight hours, and low output, making it an auxiliary rather than primary source. A foldable 100-watt (W) solar panel[8] produces only 300–500 Wh per day under Ukrainian winter conditions—enough to charge 4–6 drone batteries, but far from sufficient for a radar or hospital. Larger arrays of 1–2 kW capacity can sustain a command post if weather permits, but require considerable setup time and concealment measures.
- **Improvised/captured systems.** A distinctive feature of Ukrainian adaptation has been the creative use of civilian and even captured Russian equipment. Civilian diesel generators from construction sites, repurposed truck batteries, and off-the-shelf inverters are frequently pressed into service. Captured Russian generators and mobile power units are immediately repurposed to sustain Ukrainian operations. This improvisation provides stopgap solutions, but complicates logistics, as different systems require diverse spare parts, fuels, and connectors. Units often operate a mix of European 230V civilian systems and Russian/Soviet 220V military generators, creating compatibility issues that require adaptors and improvised wiring.

[8] Gurtova, Elizaveta. *The joint work of Starlink and the Temerland field charging station*. 16 February 2023. https://temerland.com/en/the-joint-work-of-starlink-and-the-temerland-field-charging-station/.

Table 3-1. Power producing/storage devices vs their output vs pro vs cons and how they are typically used[9]

Power Source	Typical Output/ capacity	Pros	Cons/Limitations	Typical Use Cases
Portable Diesel/Petrol Generators	1–20 kW	Reliable, steady output, widely available	High fuel consumption, noisy, detectable	Command posts, drone charging, field hospitals
Vehicle-Mounted Power Systems	1–20 kW	Mobile, flexible, dual-use (transport and power)	High fuel demand, thermal/noise signature	Mobile C2, radar, electronic warfare (EW) jamming
Batteries and Power Banks	50 Wh–2 kWh	Silent, portable, low maintenance	Limited capacity, must be recharged	Soldier electronics, drone operations, radios
Portable Solar Panels	100 W–2 kW	Renewable, quiet, low operational cost	Weather-dependent, low output, setup required	Rear positions, battery trickle-charging, fast message
Improvised/Captured Equipment	Variable	Readily available, cost-effective	Compatibility issues, inconsistent performance	Supplementary power, emergency backup
Large Mobile Diesel Generators	10–50 kW	Sustains entire command post or field hospital	Heavy, requires transport and fuel, thermal/noise signature	Field hospitals, radar sites, EW systems

Table 3-1 highlights how Ukrainian forces combine multiple power sources to meet diverse tactical demands. No single system is sufficient on its own; rather, units operate as microgrids, balancing high-output generators, vehicle-mounted systems, and portable batteries to sustain everything from drones and radios to medical facilities and electronic warfare (EW) equipment.

Ukraine’s tactical power supply relies on a hybrid system of generators, vehicles, batteries, renewables, and improvised assets. Each has distinct strengths and vulnerabilities. Generators provide high power but consume fuel and create signatures; vehicles add mobility but drain operational range; batteries and solar enable silent power but cannot sustain heavy loads. The reliance on civilian technology, often delivered by NGOs, illustrates how tactical power in Ukraine is not solely a matter of military logistics but also of societal mobilization. This hybrid approach provides redundancy, but also places significant strain on logistics chains. Table 3-2 shows a risk and mitigation matrix.

[9] MAJ Jakub Szulczyk. Polish Land Forces.

Table 3-2. Risk and mitigation matrix[10]

Risk	Impact	Indicator	Mitigation
Fuel Resupply Disrupted	Loss of communications/ISR	Portable power station capacity <30 percent with no generator fuel	Increase solar, tighten charging windows, prioritize critical loads only
Acoustic/IR Detection of Generator	Targeting	UAV/thermal spotting; counter-battery risk	Buffer with batteries; baffle/relocate generator; run at pre-planned windows only
Cable/Adapter Failure	Charging stops	Heat buildup, loose connectors	Standardize connectors; carry two spares; strain-relief and labels
PPS Failure	Loss of uninterruptable power supply (UPS)/silent watch	Inverter trips: electric capacity will not rise	Keep a small backup PPS; diversify storage (separate units)
Power Quality Issues (Radio Frequency [RF] Noise)	Communications degradation	Intermittent desense	Use inverter-type generators; ferrite chokes; physically separate power from RF

[10] Ibid.

Section 4
Energy Production and Delivery Challenges

Despite advances in energy distribution and microgrid organization, Ukrainian forces face persistent challenges that require continuous innovation. Tactical energy management in a combat zone is dynamic, contested, and resource-constrained, demanding creative solutions that blend military discipline with technical improvisation.

Fuel availability remains the most significant challenge. Generators and vehicle-mounted power systems consume liters of diesel or petrol per hour, and fuel convoys are vulnerable to artillery, drones, and electronic surveillance. Units must calculate fuel consumption, schedule generator operation, and integrate renewable energy where possible to extend endurance. Operational planners must recognize tactical power is dynamic rather than static. As U.S. Army doctrine warns, "Operational planners should anticipate that power requirements will change over time and address new energy requirements within the operational plan.[11]" This lesson resonates strongly with Ukrainian practice. Units often rotate batteries, buffer generators with PPS, and create modular microgrids to balance survivability and load management. Failure to plan or run generators efficiently carries risks. "Continuously operating tactical generators to support relatively light demand loads (less than 30 percent of the generator output rating) can cause a condition 'called wet stacking.'"[12] In Ukraine, where generators are already strained by fuel shortages and exposure to Russian drone reconnaissance, avoiding such inefficiencies is as much about survivability as equipment preservation. In short, effective energy planning is not only about generating electricity but about aligning production with operational tempo and protecting scarce assets from overuse and enemy targeting. Ukrainian forces have implemented hybrid scheduling, running high-output generators during low-threat periods and switching to batteries or solar panels under threat, reducing fuel dependency and exposure.

Relying exclusively on the nationwide power grid at the tactical level would create severe vulnerabilities. "The war in Ukraine shows that the electricity transmission network equipment is highly vulnerable, and if one or several key substations are destroyed, it becomes difficult to avoid power supply interruptions.[13]" Because national grids are often centralized in "several main substations with few backup lines,"[14] a single precision strike can cascade into widespread outages, instantly cutting off frontline units that depend on fixed connections. In such a scenario, tactical formations lose not only power for command posts and sensors but also their capacity to recharge mobile systems, from unmanned aerial vehicles (UAVs) to radios, leaving them blind and disconnected. Repairing grid nodes under fire would further expose vulnerabilities. "It is very important to have the right number of trained electricians and other specialists ready to act in extreme war situations,"[15] but such specialists must operate close to enemy forces, making them highly exposed to artillery and drone attacks. Without mobile, self-sustaining power systems at a tactical level, units inherit all the fragility of the national grid while bearing the operational risks of sending repair teams into contested zones. Generators, cabling, and vehicle alternators are increasingly targeted by

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[11] Army Techniques Publication (ATP) 3-34.45, *Electric Power Generation and Distribution*. 5 February 2024. Page 1-4.

[12] Ibid. 2-2.

[13] Rimutis, Saulius. *Lessons of War: Ukraine's Energy Infrastructure Damage, Resilience and Future Opportunities*. Eastern Europe Studies Centre. 10 May 2024. Page 14. https://www.gssc.lt/wp-content/uploads/2024/05/v04_Rimutis_Ukrainos-energetikos-sektoriaus-zala_EN_A4.pdf.

[14] Ibid.

[15] Ibid.

Russian artillery and drone strikes. Tactical energy nodes are high-value targets because of their direct impact on communications, reconnaissance, and medical support. To counter this, Ukrainian units employ dispersed and mobile energy nodes, often relocating generators daily or concealing them with camouflage nets. Quick-disconnect systems allow microgrids to be partially dismantled in minutes, preserving energy assets from destruction.

Combining military-grade generators with civilian battery packs, solar panels, and captured equipment presents compatibility challenges, including voltage differences, connector types, and limited monitoring tools. Improper integration can cause system failures or inefficiencies. Overloading power generation assets degrades equipment, shortens operational life, and can result in complete failure at critical times.[16] To meet high demand, field engineers develop custom adaptors, modular wiring harnesses, and voltage stabilizers to create functional hybrid systems. Microgrid schematics are often standardized at the company level to simplify training and operation under fire.

Cold temperatures, mud, snow, and uneven terrain can impair generator operation, battery performance, and solar efficiency. Tactical units must account for these environmental factors when planning energy distribution. To maintain proper efficiency, generators are often elevated or insulated to prevent flooding, while battery packs are insulated or rotated to maintain operational temperatures. Solar panels are deployed on tilted or portable rigs to optimize energy capture despite variable sunlight.

Maintaining situational awareness of energy assets in dispersed, mobile operations is difficult without real-time monitoring. Manual tracking is labor-intensive and prone to error. Ukrainian forces increasingly rely on digital monitoring devices, portable load meters, and battery-management apps to track consumption, prioritize loads, and predict outages. These tools allow small units to make tactical energy decisions quickly and accurately.

The Ukrainian battlefield demonstrates that tactical energy management is as much about ingenuity as it is about equipment. By blending hybrid energy sources, modular microgrid design, mobility, and digital monitoring, units mitigate fuel and logistic constraints, counter enemy targeting, and maintain operational continuity in high-threat environments. These innovations highlight a shift in modern warfare. Energy is no longer a passive commodity but a tactical asset requiring active management, adaptability, and technical creativity.

[16] Army Techniques Publication (ATP) 3-34.45, *Electric Power Generation and Distribution*. 5 February 2024.

Section 5
Lessons Learned in Tactical Energy Management

In modern warfare, producing power is only half the challenge; efficient distribution and management of electricity at the tactical level is equally critical. Ukrainian forces have demonstrated that even the most advanced generators or batteries are ineffective if energy cannot be routed where it is needed, when it is needed, and without exposing the unit to unnecessary risk. Tactical energy management is therefore a continuous operational task, integrated into mission planning, unit movement, and risk mitigation.

The modern tactical unit is effectively a miniature energy ecosystem, where each kilowatt-hour is allocated to specific systems based on priority, mission phase, and threat level. Unlike traditional rear-area logistics, tactical energy management requires constant situational awareness, because a single failure—whether from fuel shortage, cable damage, or generator malfunction—can immediately degrade communications, surveillance, or medical support.

At the heart of this system is the concept of tactical microgrids. These are small, self-contained power networks that integrate generators, batteries, vehicle-mounted alternators, and solar panels. Microgrid design is often modular, allowing units to disconnect, relocate, or reconfigure segments rapidly without interrupting vital operations. Within a microgrid, energy is segmented by priority; critical loads (communications, unmanned aerial vehicle [UAV] links, radar, medical equipment) are separated from secondary or discretionary loads (lighting, auxiliary heating, or charging personal devices). This prioritization is dynamic; during active artillery or drone strikes, units may disconnect nonessential devices to preserve battery and generator power for mission-critical functions. In practice, current draw, fuel levels, and battery statuses must be monitored to make split-second decisions that affect unit survivability.

Load balancing is another essential principle. Generators and battery systems are staggered in operation to prevent overtaxing any single source. For example, two small generators might alternate operation every few hours to extend longevity, reduce thermal signatures, and conserve fuel. This is particularly important in Ukraine where small, dispersed units face persistent risk from enemy artillery and drone surveillance; keeping energy assets hidden and intermittent can be the difference between operational continuity and catastrophic disruption.

Cable and conduit management is a further tactical consideration. Long electrical lines are vulnerable to physical damage and detection by enemy forces. Ukrainian units frequently camouflage cable routes, use armored or buried conduits for high-value feeds, and employ short, modular connections to maintain flexibility. Quick-disconnect systems allow energy nodes, such as mobile drone charging stations or temporary field hospitals, to be redeployed under fire with minimal downtime.

Tactical energy management also emphasizes mobility and redundancy. Units frequently reposition under fire, requiring portable generators, battery packs, and vehicle-mounted power systems that can be quickly redeployed. Distributing energy assets across dispersed locations reduces the risk of total system loss if one node is attacked. Redundancy is critical; losing a single generator or battery cache should not halt operations. Once battery power is depleted, it must be recovered, recharged, and re-circulated through the distribution system. By mirroring this push-pull model, energy becomes a managed commodity that is tracked, forecasted, and resupplied with the same rigor as any other critical class of supply.[17]

[17] Ibid. Page 1-5.

Ukrainian experience shows that effective battlefield energy management requires redundancy, prioritization, and mobility. Tactical commanders must treat electricity as consumable—plan distribution, monitor usage, and dynamically reallocate resources under pressure. The integration of generators, vehicles, batteries, and renewable assets into microgrids allows units to maintain continuous operation, survivability, and mission effectiveness, even under fire and logistic constraints.

Additionally, according to *Best Practices on Operationalizing Battlefield Energy: Power Generation, Storage, and Distribution in LSCO*[18] and experiments conducted during the 2024 Joint Pacific Multinational Readiness Center (JPMRC) rotation by several units and subunits using energy storage modules (ESMs), inverter systems, and solar arrays, this concept of electricity support proved—

- Teams operated for 56 to 96 hours using a single ESM and power distribution module (PDM), without relying on generators or vehicles.[19]
- Radios, drones, and mission-critical electronics in remote locations were fully operable.
- Low thermal and acoustic signatures were maintained.
- There was no unnecessary movement for fuel needed.
- Fuel consumption and thermal/acoustic exposure was reduced by scheduling generators running while increasing efficiency by operating closer to optimal load capacity.
- Because of its modularity and plug-and-play architecture, using ESMs was easy to implement without any specific instructions or training.
- Subunits' reliance on constant fuel-based resupply was reduced.

Key Tactical Lessons

- **Expand doctrine beyond fuel.** Treat electricity as a parallel class of supply.
- **Redundancy is essential.** Multiple, independent sources ensure continuous operations, even under attack.
- **Prioritization saves lives.** Critical loads must be identified and always preserved.
- **Mobility matters.** Energy assets must be portable and deployable under fire.
- **Hybrid systems enhance resilience.** Combining generators, vehicles, batteries, and renewable sources allows units to adapt to fuel shortages, environmental constraints, and enemy action.
- **Silent power discipline protects assets.** Rotation schedules, charging plans, energy logs in battle rhythm, and camouflage reduce detection risks of generator use.
- **Continuous monitoring is nonnegotiable.** Tactical energy management is an active, ongoing task—not a one-time setup.

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[18] MAJ Sean McLachlan. *Best Practices on Operationalizing Battlefield Energy: Power Generation, Storage, and Distribution in LSCO*. Center for Army Lessons Learned. NO. 25-1085. August 2025. Pages 3 to 5.

[19] Ibid. Page 3.

Section 6
Conclusion

The Ukraine War demonstrates that energy is not just a logistic input but a combat multiplier. Recommendations for military planners include—

- Integrating energy planning into operation orders (OPORDs) at the battalion and brigade levels.
- Training Soldiers in field energy management—not only fuel handling.
- Expanding the role of renewables and hybrid systems in tactical doctrine to reduce reliance on fuel convoys.
- Considering signature management of power sources as part of survivability measures.
- Developing modular battlefield microgrids for rapid deployment.

At the tactical level, electricity is the invisible lifeline that sustains modern combat. The Ukrainian experience demonstrates that resilience, improvisation, and redundancy in power generation are as decisive as weapons and ammunition. Tactical units that fail to secure their energy supply risk paralysis in communications, situational awareness, and combat effectiveness.

Annex A
Step-by-Step Recommendations for Power on the Battlefield

1) **Assessment and Planning (Foundation)**

   Priority. Immediate

   - Conduct a comprehensive audit of current tactical energy assets (generators, vehicle alternators, batteries, and portable solar panels).
   - Map energy demands for typical company- and platoon-level operations, including communications, unmanned aerial vehicles (UAVs), radar, medical support, and electronic warfare (EW) systems.
   - Identify critical vs. secondary loads to define prioritization protocols under combat conditions.

2) **Standardization of Microgrid Architecture**

   Priority. High

   - Develop modular microgrid schematics for platoon- and company-level units, integrating generators, vehicles, batteries, and renewable sources.
   - Standardize connectors, voltage levels, and quick-disconnect systems to simplify integration of diverse energy sources.
   - Train engineering and logistics personnel on deploying and relocating microgrids rapidly under fire.

3) **Acquisition and Modernization of Energy Assets**

   Priority. Medium-High

   - Procure portable, durable generators (1–5 kilowatts [kW]) suitable for tactical deployment.
   - Expand battery pack inventory, including high-density lithium-ion units for UAVs, radios, and optics.
   - Introduce hybrid energy sources (for example, foldable solar panels, vehicle-to-grid charging systems, and modular energy storage units).

4) **Mobility and Redundancy Protocols**

   Priority. Medium

   - Develop standard operating procedures (SOPs) for dispersal, camouflage, and mobility of generators and battery caches.
   - Train units to relocate energy nodes quickly, minimizing vulnerability to artillery, drones, or sabotage.
   - Introduce redundant power paths so loss of a single generator or battery pack does not halt operations.

5) **Tactical Prioritization and Load Management**

   Priority. Medium

- Create reassessment of load-prioritization guidelines identifying critical vs. secondary systems.
- Implement dynamic load balancing protocols, especially during high-threat operations.
- Equip units with load meters and monitoring devices to track consumption in real time.

6) **Training and Doctrine Integration**

Priority. High

- Include tactical energy management in standard training exercises, war games, and field maneuvers.
- Develop digital and printed manuals on microgrid deployment, prioritization, and hybrid system integration.
- Train officers and noncommissioned officers (NCOs) to make split-second energy allocation decisions under combat conditions.

7) **Innovation and Field Adaptation**

Priority. Medium

- Encourage field engineering innovations, such as custom adapters for civilian batteries, solar integration, or captured equipment.
- Conduct lessons-learned exercises to adapt procedures based on real-world challenges and environmental conditions.
- Explore digital monitoring apps or simple Internet of Things (IoT) devices for unit-level situational awareness.

Annex B
Case Vignettes from Ukraine

Vignette A
Small-Unmanned Aerial Vehicle Team "Charging Hub" at Company Level

Situation. A company intelligence, surveillance, and reconnaissance (ISR) cell supporting daily first-person view (FPV)/quad units needs continuous battery turnover despite relocations and strikes.

Setup. Two 2–5 kilowatt-hour (kWh) portable power stations (PPS) act as buffers; a-3 kilowatt (kW) quiet inverter generator runs twice daily for 60–90 minutes to bulk-charge; folding 200–300 watt (W) solar panels add trickle during good weather. Charging boards and fire-safe cases standardize workflows. The team schedules charging waves aligned with flight windows and keeps a spare PPS dedicated to radios/Starlink as an always-on uninterruptible power supply (UPS).

Why it mattered. Buffering with PPS enables silent periods and reduces acoustic/infrared (IR) signature while maintaining high battery throughput (15–30 packs per day). The generator operates at optimal load, improving fuel efficiency and reliability.

NATO implication: Institutionalize a company-level UAV charging hub kit (≥5 kWh storage, 3–5 kW generator, safety kit, and standardized connectors) and drill "charging waves" in training.

Vignette B
Starlink Survivability and Scheduling

Situation. Company and battalion command posts (CPs) rely on satellite communications (SATCOM) backup for command and control (C2) and ISR feeds amid unreliable terrestrial links.

Setup. Terminals sit on PPS (not directly on generators) to avoid brownouts and radio frequency (RF) noise. Units implement communications windows (for example, morning or evening synchronization), with terminals in sleep the rest of the time. Vehicle alternators top up PPS during moves; workshops repair damaged terminals; spare kits are pre-provisioned.

Why it mattered. Scheduling cuts daily draw and signature while preserving bandwidth for priority traffic. PPS as UPS reduces equipment faults and data corruption during starts and stops.

NATO implication. Publish SATCOM energy standard operating procedures (SOPs) (PPS-first power, scheduled windows, and protected circuits) and maintain a small stock of pre-configured spares at battalion.

Vignette C
Battalion Aid Station as a Microgrid

Situation. Stabilization points must operate during grid outages, with clean power for monitors, suction, and cold chain (medical only).

Setup. 10–15 kWh storage behind a 5–7 kW inverter generator, medical-grade UPS for critical devices, labeled circuits (critical, priority, or comfort), fuel filtration and water separators, and light-emitting diode (LED) task lighting and headlamps.

Why it mattered. The battalion aid station (BAS) rides through generator outages and relocations without losing critical care. Clear circuit discipline prevents nonessential loads from collapsing the system.

NATO implication: Standardize a role 1/role 2 power package (storage + generator + UPS + filtration + labeling) and include energy drills in medical validation exercises.

Vignette D
Volunteer-Sourced PPS Bridging Unit Shortfalls

Situation. Frontline platoons require immediate power for radios, optics, UAVs, and SATCOM, but procurement cycles lag.

Setup. Nongovernmental organizations (NGOs) deliver commercial PPS (2–5 kWh class) and small generators; units integrate them into CP layouts with USB-C PD and SB50/Anderson harnesses; solar used opportunistically.

Why it mattered. Rapid fielding filled urgent gaps and created a de facto standard for connectors and workflows.

NATO implication. Convert ad-hoc fixes into programs of record. Issue PPS + distribution kits as basic equipment and mandate connector standards across formations.

Vignette E
Low-Signature Generation for Reconnaissance Teams

Situation. Reconnaissance/UAV teams need power close to the line without drawing attention.

Setup. Trials of low-heat, low-noise fuel-cell generators to charge optics/UAV batteries and power SATCOM at small outposts. Cartridges are cached at company trains; PPS provides the buffer for silent periods.

Why it mattered. Reduced acoustic/IR signature and fewer refuel convoys in exposed areas; improved uptime for sensors.

NATO implication. Expand experimentation with fuel cells and vehicle export power, but anchor tactics, techniques, and procedures (TTPs) around battery-buffered, timed generation.

Vignette F
Ukrainian-Made Field Charging Stations

Situation. Company CPs need consolidated, ruggedized charging with solar inputs.

Setup. Rugged PPS units (about 1.5–3.0 kWh) that can charge multiple devices simultaneously, accept solar input, and survive field conditions; integrated into CP energy plans as modular bricks.

Why it mattered. Simplified cabling and reduced adapter failures; rapid deployment after relocations.

NATO implication. Favor rugged, modular PPS and enforce connector discipline; treat PPS as swappable “batteries” at the company level.

Annex C
Power Delivery and Management in Acoustic Reconnaissance

ZVOOK (PASSIVE ACOUSTIC SENSORS) ARCHITECTURE

Node Power Design

Zvook nodes are deliberately low-cost and low-power (reported about $500 per node), which allows Ukraine to field thousands across about 20,000 km.[2] Each sensor package typically consists of—

- Microphone arrays + acoustic "mirrors" to amplify distant drone/missile noise.
- Embedded AI microcomputer (for example, Raspberry Pi or similar ruggedized single board computer [SBC]) to run sound-filtering algorithms.
- Communications module to uplink detections into the Delta situational awareness system within about 12 seconds.

Each unit consumes only a few watts, meaning it can be powered for 24–72 hours on a modest lithium pack or portable power station. This ultra-low draw makes large-scale deployment feasible.

Battery Rotation and Recharging

Zvook operators follow a disciplined cycle to keep the network online:

- 2–3 battery packs per node are cycled in rotation. Although one is live, another is charging at a nearby outpost, and a third is held as reserve.
- Portable power stations (EcoFlow or Ukrainian-made equivalents) act as the buffer, enabling "silent watch" mode so the node can run without any generator nearby.
- Charging is scheduled in windows (for example, once or twice daily), where small inverter generators bulk-charge portable power stations (PPS) units. This minimizes acoustic/IR signatures since generators are noisy and visible to Russian drones.
- For long static deployments, solar trickle charging is attached to nodes. Even a 100-watt (W) panel can extend runtime by 12–24 hours, though it cannot fully replace a generator charging in winter.

Failure and Continuity Management

- If a Zvook node battery drains, the node instantly drops offline, creating a blind spot in the acoustic net. In Delta, this appears as a "dead node," and operators cannot triangulate from that location until power is restored.
- If several nodes in a cluster fail, detection accuracy falls sharply because triangulation depends on multiple overlapping sensors.
- To prevent outages, Zvook teams maintain redundancy buffers. Each cluster of nodes has more than the minimum required for triangulation, so even if one or two nodes die, the network continues to function.
- Operators often hot-swap PPS units rather than individual batteries, so downtime is reduced to minutes.

Integration with AI Filtering

Power is also critical for running Zvook's AI sound filtering, which discards irrelevant civilian or environmental noise. When voltage drops or unstable generator output is fed directly into a node, AI processors can produce false alarms or fail to classify correctly. To avoid this, Zvook nodes run on PPS "clean power," and generators recharge the PPS rather than feeding the node directly.

Operational Implications

Zvook's power discipline transforms a fragile sensor into a resilient acoustic network:

- Nodes can stay deployed for days or weeks with battery swaps and occasional generator bursts.
- The system maintains a false positive rate as low as 1.6 percent, partly because power stability allows AI algorithms to work consistently.
- By ensuring acoustic networks never go fully dark, Ukraine gets persistent drone and missile early warning, even in sectors where radar coverage is thin.

In effect, Zvook is not just an acoustic surveillance system; it is a distributed microgrid of cheap, low-power AI sensors, kept alive by disciplined battery rotation, silent power buffering, and generator scheduling. Without this energy management model, the coverage area (20,000 km^2 and growing) would collapse into unreliable patches; but with it, Zvook delivers dependable and cost-effective early warning at scale.

SKY FORTRESS ARCHITECTURE

Minimalist, Passive Sensor Design

Sky Fortress sensors are built around extreme simplicity:

- Each node consists of a microphone and a cell phone (initially Android-based), mounted on a six-foot pole, often hidden among grasslands or mounted on existing structures.
- The phone serves two roles—powering the microphone and capturing ambient sound and sending acoustic data to the central command system Virazh.

Power Sources: Battery and Solar

- The system is generally powered by internal batteries within the cell phone or separate attachable battery packs.
- In some deployment areas, solar panels are added for passive trickle charging—enough to extend runtime and reduce manual battery reloads.
- In semi-urban areas or along infrastructure corridors, nodes can tap into the national grid, reducing the burden of battery swaps.
- The design purposefully avoids more complex or high-power solutions to keep each node lightweight, inexpensive, and silent.

Scale and Operational Reach

- Sky Fortress, an expansive network focused on detecting low-altitude threats like Shahed drones, consists of approximately 9,500–10,000 sensors deployed throughout Ukraine.
- Data from each sensor—acoustic detection events—is relayed to the C2 system (Virazh), where threat tracking and alerting happen in real time.

SYSTEMS COMPARISON

Powering Model

- Sky Fortress is built for extreme simplicity; each node is just a microphone plus a smartphone. Power comes from the phone's internal battery or small external packs, with solar trickle charging sometimes added. It is ultra-low-power, silent, and requires little maintenance, but runtime per charge is limited, so batteries must be swapped or recharged frequently.
- Zvook, in contrast, uses slightly more power-hungry nodes (microphones, acoustic mirrors, AI processors, and radios). To stay online, nodes rely on PPS, backed by scheduled generator runs and sometimes solar. The system is more demanding but also more resilient; PPS buffering allows longer runtimes and stable "clean" electricity for AI.

Battery Rotation and Resupply

- Sky Fortress depends on constant battery rotation. Because each unit is essentially a phone, its endurance is short (often <24 hours continuous). Operators must visit nodes frequently or rely on solar, which is weather dependent. In practice, this makes Sky Fortress manpower intensive, though the cost per node is low.
- Zvook is designed for longer operational cycles. With 2 or 3 battery packs per node and PPS in the loop, nodes can stay deployed for 48–72 hours before a swap. Generator top-ups mean logistics teams can plan rotations in bulk, rather than chasing dying batteries daily.

Scalability and Coverage

- Sky Fortress excels in scale. With about 10,000 sensors, it forms a giant low-power mesh across much of Ukraine. Even if nodes drop offline because of battery loss, the network has redundancy from sheer density. Its weakness is reliability at the individual node level.
- Zvook trades quantity for quality. With fewer nodes (about 20,000 km^2 coverage and about 5 percent of territory), each unit is kept alive longer, with better power management. Its reliability per node is higher, but it cannot match Sky Fortress in sheer blanket coverage.

Resilience and Energy Discipline

- Sky Fortress favors cheap ubiquity. Even if many nodes go dark, enough remain to provide coverage. But its energy system is fragile—with a short battery life, high human workload, and reliance on solar in some cases.

Zvook favors disciplined energy management. PPS buffers, hot swapping, and generator schedules minimize downtime. It is more complex logistically but offers steadier, cleaner, and longer-lasting operation.

CENTER FOR ARMY LESSONS LEARNED

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