OPERATIONAL ENERGY IN MOUNTAIN WARFARE

Discussion paper on operational energy challenges and opportunities for future mountain forces

Abstract

Modern mountain operations are increasingly shaped by the growing use of advanced technologies. Communication systems, sensors, digital situational awareness tools and unmanned platforms significantly enhance the effectiveness of mountain units but also lead to a rapidly increasing demand for reliable energy. At the same time, mountain warfare is conducted in remote, austere and logistically challenging environments where traditional energy supply and resupply are limited. Harsh weather conditions, difficult terrain and restricted mobility make energy availability a critical operational factor for mission success.

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Challenges and Opportunities for Future Mountain Forces - discussion paper for the Mountain Warfare Community

Purpose

To define the operational energy problem unique to mountain warfare before selecting technologies, and to identify priority areas for experimentation, standardization and cooperation with industry and the NATO innovation ecosystem.

The workshop (Event registration link: Mountain Warfare Technology Lab: Operational Energy in Mountain Warfare – MWCOE) is organized by the NATO Mountain Warfare Centre of Excellence (MWCOE).

Modern mountain operations are increasingly shaped by the growing use of advanced technologies. Communication systems, sensors, digital situational awareness tools and unmanned platforms significantly enhance the effectiveness of mountain units but also lead to a rapidly increasing demand for reliable energy. At the same time, mountain warfare is conducted in remote, austere and logistically challenging environments where traditional energy supply and resupply are limited. Harsh weather conditions, difficult terrain and restricted mobility make energy availability a critical operational factor for mission success.

Aim:

This workshop aims to address the emerging challenge of operational energy in mountain warfare by bringing together representatives from mountain warfare nations, industry innovators, research institutions and subject matter experts. The event will provide a collaborative platform to exchange ideas, identify operational energy gaps and explore innovative solutions tailored to the specific requirements of mountain operations.

By fostering dialogue between the military mountain warfare community and industry partners, the workshop seeks to promote practical and sustainable approaches that support future mountain forces operating in remote and demanding environments

Participants will examine technologies and concepts that can enhance the energy resilience and autonomy of mountain units, including portable energy generation, cold-resistant energy storage, efficient energy management systems and power solutions for emerging digital and autonomous capabilities.

Objectives:

- Define energy-related capability gaps that directly affect mountain operations.
- Share operational requirements and recent observations among mountain warfare nations.
- Assess available and emerging technologies against representative mountain missions.
- Identify requirements for operational integration, interoperability, training and sustainment.
- Develop a common direction for more energy-resilient and autonomous mountain forces.

Following Article is discussion paper for the Workshop and addresses some topics to think of, prior the Event. Enjoy the reading.

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"On the battlefield the main feedback it is the manner to manage/use energy. The goal is to have one more drop of fuel or one more electron than the enemy."

Executive Summary

Mountain forces are becoming increasingly dependent on electrical power while operating in terrain that makes energy generation, storage and distribution exceptionally difficult. Dismounted soldiers routinely carry radios, navigation devices, thermal sights, sensors and digital command-and-control systems. Units increasingly employ uncrewed aerial systems (UAS), uncrewed ground systems (UGS), unattended sensors, electronic-warfare equipment and increasingly capable edge-computing devices. These systems improve awareness, precision and protection, but they also create a continuous requirement for charging, energy management and resupply. Recent conflicts demonstrate that units possessing superior sensors, drones and command-and-control systems can still lose operational tempo if charging, battery replacement and fuel distribution are disrupted. The central operational question is therefore not which single technology should be adopted, but how mountain units can generate, store, distribute and prioritize energy while dispersed, moving and exposed to extreme weather conditions and adversary action in order to maintain freedom of action.

Mountain terrain fundamentally changes the operational energy equation. Restricted roads networks, steep gradients and vertical separation increase the cost and vulnerability of resupply. Cold reduces available battery power and capacity; snow, ice, cloud and terrain shadowing limit renewable generation; high winds and icing affect UAS and UGS; and lower air density at altitude reduces rotorcraft performance. Terrain masking also increases reliance on communications relays, while long evacuation and repair times increase the need for local endurance. Energy must therefore be treated as a combat-enabling capability and a design constraint for every digital and autonomous system, not merely as a logistics commodity. Recent observations from Ukraine/Russia, Iran clearly demonstrate that energy infrastructure is now a target set. Russian fiber-optic FPVs have reportedly targeted Ukrainian substations, while Ukrainian long-range drones have attacked Russian oil/refining logistics.

Recent U.S. and Iranian operations further illustrate that energy infrastructure has become a strategic target. This supports hardening, dispersion, camouflage and decoy energy nodes.

The most credible near-term approach is a hybrid, modular and energy-aware architecture – Commercial Off-The-Shelf (COTS[1]). Standard batteries remain essential, but they should be combined with intelligent power managers, foldable solar systems, fuel cells, conventional generators where appropriate, and niche wind or micro-hydro systems when local conditions support them. Resilience comes from diversity, interoperability, decentralization, prioritized loads, signature control and the ability to operate in a degraded mode. Future capability development should prioritize cold-tolerant storage, safer high-energy chemistries, common connectors and data standards, autonomous docking and recharging, cyber-secure energy management, and realistic mountain qualification. **The objective is not complete independence from logistics; it is to extend operational reach, reduce the frequency and signature of resupply, and preserve essential functions when the primary energy chain is disrupted**[2].

Keywords: *operational energy; mountain warfare; UAS; UGS; autonomous systems; digitalization; energy resilience; portable power; military microgrids*

[1] In military context, it means commercially available equipment or technology that is bought from the civilian market and used without major modification. For example: **COTS batteries** = ordinary commercial batteries or power systems such as drone batteries, Li-ion/LiPo packs, USB-C power banks, e-bike/tool batteries, or portable power stations that can be adapted for military use.

2 NATO should have trusted-source requirement: modular power systems using COTS batteries, BMS, chargers, inverters or UAV components - especially from large dual-use suppliers - should be screened for cyber, counterfeit, fire, battery-health and supply-chain risks before NATO use.

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1. Introduction: Technology-Enabled Warfare in a Demanding Environment

The character of land operations has changed: electrical power is now required to sense, communicate, navigate, decide, protect and engage. Operational energy—energy required to train, move and sustain forces and weapons platforms—can no longer be treated primarily as fuel for vehicles and generators. In mountain warfare, it is a prerequisite for digital command and control, precision effects, medical support and autonomous systems. NATO identifies artificial intelligence, autonomy, energy and propulsion, novel materials and next-generation communications as mutually reinforcing technologies. Their convergence extends operational reach and accelerates decision-making, but also makes tactical advantage increasingly dependent on reliable electrical power.

The operational issue is not the number of devices but the dependency they create. A mountain unit may employ UAS for reconnaissance and communications relay, UGS for logistics or casualty evacuation, unattended sensors for persistent surveillance and digital soldier systems for navigation and command and control. Each has a different load profile: continuous low power, high-power bursts, high specific energy or rapid bulk charging. Unless these demands are planned as one architecture, advanced equipment can become unavailable at the decisive moment because incompatible batteries, chargers or resupply arrangements were treated as an afterthought.

Terrain converts this technical dependency into a command problem. Movement is channeled through valleys, passes, roads and trails; short map distances may require major climbs and descents. Energy supplies that are routine on level terrain may have to move by porter, pack animal, cableway, specialized UGS, UAS or repeated manpack lift. Every additional battery competes with ammunition, water, food, protective equipment and winter clothing. A commander who increases digital capability without accounting for this trade-off may reduce the unit's mobility and endurance.

Cold directly affects storage and charging. Low temperatures reduce battery power and usable capacity, while charging a cold battery may be unsafe without thermal control. Repeated transitions between warm shelters and cold positions create condensation; snow and ice can obstruct connectors, vents and mechanical components. Batteries and electronics must therefore be protected, warmed and managed as part of the unit's routine battle rhythm.

Environmental conditions also affect generation and mobility. Cloud, terrain shadow and short winter daylight reduce solar yield; strong and turbulent winds, wind shear, icing and obscuration constrain UAS operations; and high-density altitude reduces aircraft performance. These are routine planning factors in mountain warfare. Energy generation, storage and distribution must therefore be designed for the worst credible operating period, with reserves and alternate methods available when local generation falls below forecast.

The central challenge is not to identify the next breakthrough technology. It is to determine how dispersed mountain forces will generate, store, distribute and prioritize energy while moving, concealed and separated from fixed infrastructure. Commanders need an architecture that functions during darkness, cold-soak, precipitation, prolonged cloud cover and enemy interference—not only under laboratory or fair-weather conditions. Technologies should be selected only after this operational problem and the associated mission profiles are defined.

2. Future Energy Demands in Mountain Operations

Future operational energy demand will not be driven by a single energy-intensive platform, but by the cumulative effect of an increasingly networked force. Every additional sensor, drone, radio, relay node and autonomous system contributes incrementally to the unit's energy burden while simultaneously increasing its operational dependence on reliable electrical power. Digital mapping, three-dimensional terrain models, sensor fusion and edge AI reduce dependence on distant headquarters, but shift computing and storage loads forward. Counter-UAS sensors and effectors add further demand. The operational requirement is shifting from periodic battery replacement toward a continuous tactical energy cycle[3].

Demand is also likely to become more dynamic. A surveillance position may need modest continuous power until a threat is detected, after which communications, processing, electronic support and multiple UAS can create a surge. An autonomous vehicle may consume little power while waiting but require high peak power to negotiate snow, gradients or obstacles. A future architecture must therefore be sized for both energies, measured over time, and instantaneous power. Designing only for average consumption produces systems that fail during the decisive moment; designing every component for the worst case creates unacceptable weight.[4]

Current energy architectures remain largely centered on rechargeable lithium batteries, portable generators and vehicle power. Although these technologies are mature and widely available, they were not designed for highly distributed mountain operations characterized by prolonged dismounted movement, extreme cold and continuous digital connectivity. The U.S. Army is developing standard cells with improved hot- and cold-weather performance and emphasizes standardization so that new chemistry can benefit multiple systems without redesigning every platform. This direction is more important than pursuing a single “perfect” battery: mountain forces need a family of interoperable storage options matched to mission duration, temperature, power demand and risk. China currently dominates significant parts of the global supply chain for battery cells, photovoltaic panels, drone motors and numerous dual-use components. While this provides an important benchmark for industrial capability, it also highlights strategic risks relating to supply-chain resilience, trusted sourcing and technological dependency for NATO Allies

The near-term projection[5] is therefore hybridization.

Batteries will continue to provide silent power and high peak output, while renewable sources replenish storage whenever environmental conditions permit. Fuel cells offer quiet, persistent generation, whereas conventional generators remain indispensable for concentrated loads and rapid bulk charging. Intelligent energy management systems will increasingly coordinate these diverse sources.”

NATO DIANA’s energy resilience work similarly emphasizes modular microgrids, renewable generation, storage, adaptive power conditioning, autonomous reconfiguration and cyber protection rather than a single generating technology. At smaller scale, the same logic can be applied to a patrol or observation post as a “tactical-microgrid”: several sources, a managed storage layer and prioritized outputs.

Over the medium term, higher-specific-energy batteries, lithium-sulfur, silicon-rich anodes, solid-state concepts and safer chemistries may reduce carried mass, but military adoption will lag headline laboratory performance because qualification must address shock, puncture, fire, altitude, cold, electromagnetic compatibility and long storage. Fuel cells may expand where their energy-density advantage offsets the burden of specialized fuel. Hydrogen can extend UAS endurance, but storage, refueling and cold-weather procedures remain limiting. Methanol-based systems offer a more mature logistics pathway for low-signature charging, though they still require cartridges and produce heat and exhaust products. Micro-wind and micro-hydro can provide persistent low power at suitable sites, but their value is highly dependent on terrain, flow, icing, noise and deployment time.

At the base and hub level, deployable microgrids will become increasingly software-defined and able to combine generators, renewables, batteries and vehicle-to-grid resources. Transportable nuclear

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3 High-power C-UAS loads. Emerging portable counter-drone lasers, EW systems and drone interceptors create short-duration kilowatt-class demand, cooling burdens and rapid recharge requirements. Mountain energy profiles should include these peak loads.

4 Average energy, peak power, thermal/acoustic/EM signature and resupply risk.

5 Russia and Ukraine show that adaptation may be cheaper and faster than breakthrough technology. Fiber-optic FPVs trade payload/weight for EW resistance; similar trade-offs should be expected in mountain UAS/UGV designs.

microreactors may eventually support large, enduring sites[6], but they are not a solution for dismounted or maneuvering mountain units. Project Pele remains a prototype demonstration intended for transport in multiple shipping containers and megawatt-scale generation. It should be monitored as a base-resilience development, not conflated with personal or autonomous tactical power.

Equally important is reducing demand at the source. Future soldier systems and autonomous platforms should increasingly incorporate intelligent power-saving functions, adaptive sensor management and mission-aware computing that minimize energy consumption without degrading operational effectiveness. Every watt that does not need to be generated, transported or stored directly increases operational endurance. **Just as ammunition expenditure is estimated during operational planning, future mountain operations will increasingly require commanders to estimate electrical energy[7] consumption, charging requirements and resupply intervals as part of the planning process.**

[6] Survivability criteria: camouflage, thermal/acoustic discipline, redundant cable routes, protected inverters, dummy heat/electrical signatures, remote start/stop, fast battery replacement and local manual operation when software control fails.

7 Examples: intelligent sleep modes, adaptive sensor management, AI-assisted power scheduling, mission-aware, computing, low-power communications, duty cycling, edge processing.

3. Impact of Digitalization and Autonomous Systems

Digitalization is transforming operational energy from a passive logistics commodity into an actively managed combat resource. Sensors, software and data links make it possible to measure state of charge, forecast demand, allocate power and identify failing components. A commander can theoretically view energy status in the same way as ammunition, communications or vehicle readiness. AI-enabled energy management can schedule charging, preserve reserve capacity, prioritize mission-essential loads and use weather forecasts to determine when solar, wind or hydro generation is likely to be effective. This transforms energy from a static supply calculation into a continuously managed operational variable.

The same digital dependence introduces vulnerabilities. Energy management systems are cyber-physical systems: compromise of their software, communications or sensors can produce physical mission failure. An adversary[8] may manipulate battery data, disable charging, force inefficient operating modes or identify positions from electromagnetic emissions. DIANA therefore includes cyber protection and adaptive reconfiguration as integral parts of resilient microgrids. [4] Mountain units need local manual control, trusted defaults and graceful degradation so that a loss of network connectivity does not become a loss of power.

Autonomous systems create a second-order logistics problem. UAS and UGVs may reduce risk to personnel and perform tasks that are slow or dangerous for humans, but a force that deploys large numbers of robots also creates a requirement to charge, swap, refuel, recover and maintain them. Endurance claims measured in benign conditions can fall sharply in cold, high wind, snow or steep terrain. Lower air density at altitude adversely affects aerial performance, and hovering or carrying payloads demands high power. Ground systems face wheel slip, track resistance, snow compaction and steep gradients. Energy must therefore be included in autonomy testing from the outset, using representative altitude, temperature, wind, payload and communications conditions.

Navigation illustrates the interaction. When global navigation satellite system signals are jammed or masked by terrain, systems may rely on inertial navigation, visual odometry, terrain matching, LiDAR or cooperative navigation. These alternatives improve resilience but increase processing and sensor loads. Similarly, autonomy at the edge requires on-board computing to reduce dependence on vulnerable links, but local inference consumes power and produces heat. The desired outcome is not maximum autonomy at any energy cost; it is mission-effective autonomy that understands its own energy state, adapts its behavior, and can return to or locate a charging point before becoming a recovery burden. Commanders should specify the required effect and endurance, not simply the maximum degree of autonomy.

[8] Cyber-physical threat model: spoofed state-of-charge, malicious BMS firmware, compromised smart chargers, hostile telemetry collection and firmware-update supply-chain risk. Require authentication, offline modes and graceful degradation.

4. Energy Resilience in Remote and Austere Environments

European Industrial Dependency and Strategic Exposure

European forces increasingly rely on commercial and dual-use energy technologies: lithium-ion cells, battery-management systems, photovoltaic modules, inverters, power semiconductors, fuel-cell components, rare-earth magnets, digital controllers and specialized connectors. These systems are often designed in Europe but depend on raw materials, processed inputs, cells, subcomponents, firmware or manufacturing capacity located outside the Alliance or concentrated in a small number of suppliers. This creates a strategic exposure that may remain invisible during peacetime procurement but become decisive during crisis or conflict.

The concentration is particularly pronounced in clean-energy supply chains. The International Energy Agency assessed in 2026 that China accounted for approximately 85 per cent of solar manufacturing capacity and 80 per cent of lithium-ion battery supply-chain capacity, with even higher shares in photovoltaic wafers and battery anode materials. The European Commission reported that the EU represented only 8 per cent of global lithium-ion battery production capacity in 2023 and still relied on imports for about half of its demand. These figures concern the wider civilian market, but the same cells, materials, electronics and production lines support military batteries, tactical charging systems, unmanned platforms and deployable microgrids.

The risk is broader than dependence on one country. It includes single-source materials; foreign-controlled intellectual property; opaque firmware and remote-update functions; long lead times for power electronics; limited European refining and recycling capacity; dependence on civilian transport and energy infrastructure; and competition between defense demand and much larger automotive, telecommunications and renewable-energy markets. A military customer may have priority politically but still lack leverage if its order volume is small, its technical specification is unique, or the upstream supplier is several tiers removed from the defense prime contractor.

NATO has identified twelve defense-critical raw materials, including cobalt, gallium, germanium, graphite, lithium, platinum, rare-earth elements, titanium and tungsten. The EU Critical Raw Materials Act similarly seeks to reduce strategic dependency by setting 2030 benchmarks for extraction, processing, recycling and supplier diversification. These initiatives are important, but operational energy resilience requires the same attention to manufactured components, software, test equipment, specialized tooling and repair capacity. A stockpile of lithium is of limited immediate value if Allied industry lacks qualified cell production, battery-management electronics, certified connectors or the capacity to assemble and test military packs at scale.

Principal Industrial Risks and Operational Consequences

	Industrial exposure	Operational consequence	Priority response
1.	Imported cells and processed battery materials	Replacement batteries and UAV power packs become unavailable during surge demand or export restriction.	Dual-source qualified cells; maintain strategic component reserves; invest in Allied assembly, testing and recycling.
2.	Concentrated solar, inverter and power-electronics production	Loss of a low-cost civilian component can disable an otherwise deployable charging node or microgrid.	Qualify NATO reference designs using interchangeable, trusted components and multiple suppliers.
3.	Proprietary connectors, protocols and firmware	Multinational units cannot exchange power; repair depends on the original vendor; cyber or remote-access risk increases.	Enforce open interfaces, common data protocols, software assurance and configuration control.
4.	Fragmented national demand and small defence orders	Industry lacks predictable volume to invest in ruggedized production, tooling, stock and workforce.	Aggregate demand, harmonize requirements and use multi-year multinational contracts.

	Industrial exposure	Operational consequence	Priority response
5.	Limited visibility below prime-contractor level	Tier-two or tier-three bottlenecks remain unidentified until a crisis interrupts delivery.	Map supply chains to critical subcomponents; conduct N-1 stress tests and supplier-risk reviews.
6.	Dependence on civilian grids, transport and repair networks	A hybrid attack or infrastructure failure disrupts charging, maintenance and movement simultaneously.	Plan microgrids, mobile repair, protected stocks and alternative distribution routes.

Operational Architecture

A resilient architecture should be based on diversity, distribution, interoperability and prioritization. Diversity combines sources with different failure modes. Distribution avoids a single charging point whose destruction or technical failure disables the unit. Interoperability enables batteries, generators, vehicles and devices from different nations or manufacturers to exchange power. Prioritization ensures that command and control, medical equipment, navigation, critical sensors and force-protection systems remain available when total supply is insufficient.

The architecture should be layered. At soldier level, common rechargeable batteries and wearable power managers should reduce the number of separate battery formats. At team or squad level, a power manager should accept vehicle, generator, solar, fuel-cell and other locally available sources while charging multiple devices. At platoon or company level, deployable charging nodes should combine larger storage with generators and renewable sources. At temporary bases and logistics nodes, microgrids should balance generation, storage and demand. Each layer should exchange power without requiring a unique charger or vendor-specific interface at every step.

STANAG 4695 provides an important baseline for electrical connectivity between NATO power sources and dismounted-soldier systems. However, practical interoperability depends on adoption, not publication alone. NATO therefore requires agreed voltage ranges, connector families, cable discipline, quick-disconnect arrangements, data protocols, safety rules and test procedures. Interoperability should be demonstrated under field conditions and across national contingents before deployment. It should also include controlled use of civilian or locally sourced equipment without creating unacceptable safety, cyber or signature risks.

Environmental and Signature Resilience

Environmental management remains essential. Batteries and electronics may require insulated carriage, controlled warming and protected charging areas. Solar arrays must be sited with regard to slope, snow reflection, terrain shadow, icing and concealment. Wind devices require secure anchoring and must not create unacceptable acoustic or visual signatures. Hydro devices depend on suitable flow and protection from debris, freezing and detection. Fuel cells require safe fuel handling and ventilation. The optimum configuration will differ between a mobile patrol, observation post, relay site, fire-support position and valley logistics node; modularity is therefore preferable to a universal kit.

Signature is a central resilience issue. Combustion generators produce noise, heat and exhaust; solar panels may be visually conspicuous; wind devices move; battery banks and charging concentrations create thermal and electromagnetic patterns; and repeated resupply reveals routes and routines. Distributed hybrid systems can reduce some signatures but may also create many small electronic emitters. Energy planning should therefore include acoustic, thermal, visual and electromagnetic signature assessment, camouflage, emission control, deception and rapid displacement. Silent watch is not only a vehicle requirement; it applies to every position that must observe, communicate or control unmanned systems without being located.

The Ukrainian and Russian adaptation cycle provides a practical warning. Under persistent drone observation and strike pressure, forces have dispersed fuel and power assets, used smaller guarded convoys, concealed storage, created non-obvious charging locations and altered routes. Mountain forces should apply the same logic through dispersed energy caches, decoy charging sites, route deception and the ability to relocate power nodes quickly. The energy architecture must therefore be survivable as well as efficient.

Key NATO Challenges

First, NATO requirements remain fragmented across nations, services and procurement programmers. Different battery formats, connectors, safety standards and environmental specifications reduce interoperability and divide demand into volumes too small to justify resilient production. The European defense industrial base also remains fragmented and lacks scale in several sectors, while national procurement preferences limit the effective use of the European market.

Second, defense procurement cycles are slower than commercial technology cycles. By the time a military power system is fully qualified, its cells, semiconductors or control electronics may already be obsolete or discontinued. This creates dependence on lifetime buys, vendor-specific redesigns and difficult certification. NATO must preserve safety and reliability while enabling modular substitution of components without restarting the entire acquisition process.

Third, supply-chain visibility is insufficient. Prime contractors may know their direct suppliers but not the geopolitical, ownership, energy, transport and cyber risks affecting lower tiers. A single factory producing an inverter chip, battery separator, thermal-management component or connector insert can become a strategic bottleneck. The updated NATO Defense Production Action Plan calls for better visibility of industrial capacity, supply-chain challenges, surge options and long-term demand.[8] Operational energy systems should be explicitly included in this work rather than treated as generic commercial equipment.

Fourth, Europe has strong research, engineering and system-integration capability but faces a gap between prototypes and mass production. SMEs and dual-use companies can innovate rapidly, yet they often lack access to long-term defense demand, test ranges, security accreditation, working capital and production finance. Conversely, major defense companies may offer assured integration but rely on slow, vertically specialized supply chains. NATO and the EU need mechanisms that connect both communities and move successful solutions from exercise trials to scalable production.

Fifth, energy systems introduce cyber and information-security risks. Digital power managers, smart batteries and microgrid controllers collect operational data, communicate with external devices and may depend on proprietary software. Compromised firmware could misreport energy status, disable charging, degrade battery life or reveal unit activity. Trusted hardware, secure boot, controlled updates, offline operation, data minimization and national authority over cryptographic functions should therefore form part of energy-system certification.

Priorities for NATO and Allies

NATO should not seek industrial autarky. The objective should be assured access through a balanced combination of Allied production, trusted partnerships, diversified suppliers, strategic stocks, repair capacity and substitution options. The Alliance should use its roles as requirements setter, standard setter, demand aggregator and convenor to shape a market that can deliver in peacetime, crisis and conflict.

- Treat operational energy resilience as a capability enabler within defence planning. Define minimum endurance, redundancy, interoperability, cyber-resilience and recovery requirements for relevant formations and deployable headquarters.
- Aggregate multinational demand for batteries, power managers, deployable microgrids and common connectors. Multi-year contracts and common technical profiles should provide industry with predictable volume and reduce national fragmentation, consistent with NATO and EU industrial-readiness objectives.
- Map critical supply chains beyond the prime contractor. Identify single-country, single-company and single-facility dependencies in cells, power electronics, semiconductors, catalysts, magnets, software and test equipment. Conduct periodic N-1 stress tests and tabletop exercises linking industrial disruption to operational plans.
- Establish a NATO-qualified family of open, modular reference architectures. Compliance should be demonstrated through plug-and-operate field trials, cold-weather testing, electromagnetic compatibility, cyber assessment, transport safety and signature evaluation.
- Create strategic reserves of high-leverage components, not only finished equipment or fuel. Stocks should include qualified cells, battery modules, inverters, controllers, connectors, cables, thermal-management parts, spares and repair tooling, with rotation policies that prevent obsolescence.
- Strengthen Allied repair, refurbishment and recycling. Regional repair hubs and deployable technical teams should be able to diagnose interfaces, replace modules and return systems to service without relying on the original manufacturer. Recycling should recover critical materials and reduce exposure to external supply shocks.

- Use operational experimentation to accelerate adoption. NATO exercises should include contested-energy scenarios, deliberate loss of suppliers or grid access, rapid relocation of microgrids, multinational exchange of batteries and power, and industry-supported repair under field conditions.
- Apply trusted-supplier and secure-by-design criteria to smart energy systems. Procurement should address firmware provenance, remote access, data ownership, software-update control, component traceability and the ability to operate safely in a disconnected mode.
- Coordinate NATO and EU action while preserving institutional roles. NATO should define military requirements, interoperability and readiness outcomes; the EU and national authorities should use industrial, trade, finance, raw-material and regulatory instruments to strengthen production and security of supply.

Commanders should understand energy as a finite combat resource and a source of both capability and vulnerability. Energy status should be included in estimates, orders, rehearsals and after-action reviews. Units require load inventories, realistic consumption forecasts, cold-weather battery drills, connector maintenance, fault isolation, disciplined charging plans and protected reserves. Commanders should identify which systems are mission-essential, establish shutdown priorities and specify the minimum energy reserve required for extraction, casualty care, command and control and force protection.

Commanders should also demand evidence that multinational energy systems function together before operations begin. A national contingent that arrives with technically advanced but incompatible batteries or proprietary charging equipment increases the logistic burden of the entire force. Conversely, common interfaces, shared spares and cross-trained technicians allow power to be redistributed as the tactical situation changes. Energy interoperability should therefore be treated in the same operational manner as communications interoperability, ammunition interchangeability and common medical procedures.

Finally, commanders must incorporate the industrial dimension into readiness. Availability in a catalogue does not equal availability during war. Readiness reporting should distinguish between equipment on hand, replacement stocks, repair capacity, supplier lead time, foreign dependency and the ability to surge. A technologically advanced microgrid will not compensate for depleted reserve batteries, a discontinued semiconductor, an untrusted firmware update or operators who cannot diagnose a failed interface.

Energy resilience in remote and austere environments is a strategic-security requirement. Its operational expression is distributed, modular and signature-aware power at the tactical edge. Its industrial foundation is a secure and adaptable supply chain able to produce, repair and replenish systems under pressure. Europe possesses substantial engineering, research and integration strengths, but remains exposed to concentrated external supply chains, fragmented demand and insufficient production scale in several critical energy technologies.

NATO can reduce this vulnerability by aligning requirements, aggregating demand, enforcing interoperability, mapping dependencies, building trusted reserves, exercising industrial disruption and accelerating the transition from prototype to production. The desired outcome is not a single universal technology. It is an Allied energy ecosystem that can absorb loss, substitute components, operate without continuous external support and sustain commanders' freedom of action in the most demanding terrain and security conditions.

5. Capability Gaps Requiring Innovation

The first gap is **cold-tolerant, safe and high-specific-energy storage**. Existing batteries force trade-offs among energy density, power, cold performance, safety and cost. Mountain forces need storage that can be charged at low temperature, survives ballistic or mechanical damage without catastrophic propagation, and retains useful capacity after prolonged cold soak. Innovation should include chemistry, packaging, thermal management and accurate state-of-health estimation. Qualification criteria must reflect the actual mountain envelope rather than generic “outdoor” conditions.

The second gap is **energy generation under poor weather and during darkness**. Solar power is valuable but variable. Wind is abundant in many mountain areas but turbulent, destructive and difficult to harvest efficiently at backpack scale. Flowing water can offer persistent generation, yet suitable streams may be absent, frozen, environmentally sensitive or tactically exposed. Fuel cells offer quiet endurance but create a fuel chain. The requirement is therefore a portfolio of complementary sources, supported by tools that predict expected yield and recommend the lightest mission package for a specific route, season and duration.

The third gap is **interoperable energy management**. The attached concept notes highlights connectors as an overlooked issue and calls for a NATO approach comparable in effect to civilian USB-C standardization. STANAG 4695 provides a foundation, but forces still encounter different connectors, voltages, charge protocols and proprietary battery-management data. A future architecture needs standard physical interfaces, intelligent voltage conversion, device authentication, common state-of-charge reporting and safe “power scavenging” from available sources. Interoperability should include allied systems and commercially derived equipment likely to be introduced rapidly during operations.

The fourth gap is **autonomous replenishment**. UAS and UGVs require docking stations battery exchange, refueling and health checks that can function in snow, ice, wind and degraded navigation. A charging pad that works on a level test site may fail on a sloped, concealed or snow-covered position. Development should include self-aligning connectors, inductive or contactless charging where efficient, robotic battery swap, standardized fuel cartridges and autonomous route planning that accounts for energy and weather. The system must also prevent an adversary[9], from using the charging infrastructure as a cyber entry point or targeting cue.

The fifth gap is **mountain-representative testing and evidence**. Product specifications often state temperature and ingress-protection limits but do not reveal performance after repeated freezing, icing, condensation, altitude changes, vibration, pack carriage and gloved operation. NATO and nations need common reference missions and test profiles: a winter observation post, a high-altitude UAS relay, a dismounted patrol, an autonomous resupply route and a temporary command node. These profiles should specify loads, duration, weather, altitude, signature limits and acceptable resupply. Industry can then demonstrate performance against a common operational problem rather than present isolated technologies.

A final gap is **doctrine and organizational ownership**. Energy cuts across logistics, signals, engineering, infantry, aviation, medical support and capability development. Without a clear lead, each system optimizes its own battery and charger while the unit inherits the integration burden. Operational energy should be incorporated into capability requirements, experimentation, training and planning. The proposed cooperation among MWCOE, NATO DIANA, the NATO Energy Security Centre of Excellence, national test organizations and industry is therefore as important as any individual technology.

Important to emphasize: “Sustainment in today’s war is conducted under constant drone ISR and strike threat, making traditional logistics convoys highly vulnerable. As seen in Ukraine, sustainment must shift toward dispersed, low-signature, and unmanned solutions, with UGVs supporting supply delivery and CASEVAC while reducing risk to personnel. **Sustainment is also becoming energy-centric due to reliance on batteries and charging systems**, **which must be treated as critical supplies.** In addition, countering low-cost drones with expensive air-defense missiles is unsustainable, driving the need for cost-effective C-UAS solutions such as electronic warfare (EW) and drone-based interceptors.

[9] To consider: docking under degraded navigation: snow-covered pads, slope, camouflage, UWB/visual fiducials, GNSS-denied return-to-charge, robotic battery swap and authentication to prevent adversary use of charging infrastructure.

6. Current Market Solutions and Direction of Development

The market already offers components that can improve mountain endurance, but no commercial catalogue provides a complete solution. The most mature products fall into four groups: standardized storage, intelligent power management, portable generation and hybrid systems. Their value depends on integration and realistic employment. Table 1 provides illustrative examples; **it is not a procurement recommendation.**

Table 1. Illustrative current market landscape

Solution class	Illustrative example	Operational relevance and principal limitation
Power management	Galvion NERV CENTR Squad Power Manager	Accepts and converts multiple sources, charges and powers diverse equipment, and can reduce charger/battery proliferation. Effectiveness still depends on cables, supported profiles and operator training.
Portable solar	PowerFilm man-portable and foldable systems	Low-noise replenishment for batteries and remote sensors; packable and rapidly deployed. Output is weather-, orientation- and shadow-dependent and requires storage for night operations.
Tactical fuel cell	SFC JENNY direct-methanol systems	Quiet, high-endurance charging with fewer spare batteries; the manufacturer states substantial weight savings for multi-day deployment. Requires methanol cartridges, ventilation and fuel logistics.
UAS propulsion	Intelligent Energy IE-SOAR hydrogen modules	Commercial modules from 800 W to 2.4 kW target fixed-wing, rotary-wing and VTOL UAS and can extend endurance beyond batteries. Hydrogen storage, refueling and cold-weather support remain constraints.
Micro wind / hydro	Primo FORCE; Flowtric wind/water generator	Potential persistent low-power generation at selected exposed ridges or flowing-water sites. Site dependence, icing, anchoring, debris, signature and limited military qualification constrain broad use.
Base-scale future power	Project Pele transportable microreactor	Potential megawatt-scale resilient power for enduring sites. It remains a prototype demonstration transported in several containers, not a man-portable or maneuver solution.

Note: Product and company references are illustrative examples of the current market landscape and do not constitute NATO or national endorsement.

Several trends are visible across these examples. First, the market is moving from isolated chargers toward **universal power management** that can scavenge, convert and allocate energy. Galvion's Squad Power Manager is representative: it is designed to accept multiple sources and run or charge varied equipment, addressing the integration burden at team level. This function may be more immediately valuable than a marginal increase in battery energy density because it reduces unused residual energy, duplicate chargers and planning complexity.

Second, **hybrid systems are replacing technology competition**. Solar, batteries, fuel cells and generators should not be assessed as mutually exclusive. Foldable solar is mature enough for battery replenishment and persistent low-power loads, but mountain shadow, cloud and winter daylight make it unreliable as a sole source. Direct-methanol fuel cells provide quiet generation and high fuel energy density for multi-day missions; SFC markets the JENNY family specifically for reducing carried spare-battery mass. The most useful configuration may be a small battery for peaks and silent operation, a fuel cell for steady charging, and solar for opportunistic replenishment.

Third, **power is becoming platform-specific and software-aware**. Hydrogen fuel-cell modules for UAS are commercially available and target power levels from hundreds of watts to multiple kilowatts. These solutions may increase endurance for relay, mapping and surveillance missions, but only if the hydrogen chain is operationally supportable. Future UAS and UGV procurement should therefore evaluate the complete energy ecosystem—fuel or battery transport, charging time, weather performance, maintenance and recovery—not simply advertised endurance.

Fourth, **renewables at personal scale remain supplementary**. Compact wind and hydro products demonstrate that local energy can be harvested outside daylight, **but power is generally modest and highly site-specific**. Their strongest mountain use may be at semi-static relay, observation or sensor sites where a few watts delivered continuously over many hours have high value. They are less convincing for rapidly moving forces if deployment, anchoring and retrieval cost more time and mass than additional batteries. Military experimentation should identify the narrow conditions where these systems outperform storage.

The direction of development should therefore prioritize integration rather than collecting gadgets. A credible mountain energy kit would be modular by mission: a standard storage layer; a common power and data interface; a power manager; optional solar, fuel-cell, wind or hydro modules; thermal protection; and software that recommends configuration and monitors consumption. At higher echelons, deployable microgrids should use the same principles at greater scale. DIANA's recent challenge programmed reinforce this direction by seeking location-independent, reliable and resilient power, adaptive microgrids, autonomous systems and solutions[10] for extreme environments.

[10] Experimentation idea: include red-team trials using cheap adversary-like systems - fiber-optic FPV, spoofed BMS telemetry, counterfeit batteries, jammed GNSS, COTS chargers and observed thermal signatures of charging nodes.

Conclusion and Priorities for Experimentation

Operational energy will increasingly determine the reach, endurance and tempo of mountain forces. Digitalization and autonomy can overcome terrain, reduce exposure and improve decision-making, but only when their energy chain survives cold, altitude, weather, movement and enemy action. The correct objective is not a fully renewable force or a single revolutionary battery. It is a resilient architecture that reduces demand, combines complementary sources, standardizes interfaces, manages power intelligently and preserves essential functions under disruption.

The next phase should convert this discussion into evidence. The Mountain Warfare Community should define representative mission profiles and measure actual loads; test hybrid soldier-, team- and node-level architectures in summer and winter conditions; validate cold performance, signature and interoperability; and assess autonomous charging and energy-aware navigation. A common experimentation framework would allow nations and industry to compare[11] solutions against the same mountain problems. It would also provide a practical foundation for the proposed congress panel and workshop, enabling participants to move from broad technology presentations toward prioritized capability gaps, standards, trials and a shared roadmap.

Recommended immediate priorities

- Define standard mountain energy reference missions and load profiles.
- Conduct seasonal field trials of hybrid generation, storage and power-management systems.
- Accelerate adoption of common connectors, charging protocols and energy-status data.
- Integrate energy state, signature and resupply risk into operational planning and autonomy algorithms.
- Create a cooperative experimentation network linking MWCOE, ENSEC COE, DIANA, national test centers and industry.

[11] Priority addition: create an operational-energy intelligence loop. Review global market releases, Chinese dual-use production, Russian battlefield adaptation, sanctions-driven substitution and NATO interoperability gaps every six months.

Acronyms

AI	Artificial Intelligence
BMS	Battery Management System
C-UAS	Counter-Uncrewed Aircraft System(s)
C5ISR	Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance and Reconnaissance
CASEVAC	Casualty Evacuation
COE	Centre of Excellence
COTS	Commercial Off-the-Shelf
DEVCOM	U.S. Army Combat Capabilities Development Command
DIANA	Defense Innovation Accelerator for the North Atlantic
DoD	United States Department of Defense
EDSTAR	European Defense Standards Reference System
EM	Electromagnetic
ENSEC COE	NATO Energy Security Centre of Excellence
EU	European Union
EW	Electronic Warfare
FPV	First-Person View
GNSS	Global Navigation Satellite System
ISR	Intelligence, Surveillance and Reconnaissance
LiDAR	Light Detection and Ranging
Li-ion	Lithium-ion
LiPo	Lithium-polymer
LTC	Lieutenant Colonel
MW COE / MWCOE	NATO Mountain Warfare Centre of Excellence
NATO	North Atlantic Treaty Organization
SME(s)	Small and Medium-sized Enterprise(s)
STANAG	Standardization Agreement
UAS	Uncrewed Aircraft System(s)
UAV	Uncrewed Aerial Vehicle(s)
UGS	Uncrewed Ground System(s)
UGV	Uncrewed Ground Vehicle(s)
USB-C	Universal Serial Bus Type-C
UWB	Ultra-Wideband
VTOL	Vertical Take-Off and Landing

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