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# Comparative technical analysis of anti-drone system technologies: kinetic, laser, and high-power microwave approaches

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**Abstract**. This paper examines three principal counter-drone technologies: kinetic projectiles, high-energy lasers (HEL), and high-power microwave (HPM) systems. The analysis considers operational performance, resilience in the operational environment, and economic efficiency. Kinetic solutions provide precise engagement with low collateral risk, but remain limited to single-target neutralization. Laser systems enable rapid interception at very low cost per shot, although their effectiveness is strongly affected by weather conditions. High-power microwave technologies offer a unique advantage against drone swarms through the simultaneous disabling of multiple targets at minimal operational cost. The study concludes that integrated, multi-layered defence architectures deliver superior effectiveness by compensating for the individual limitations of each system, addressing emerging autonomous threats, and reducing dependence on costly missile-based air-defence solutions.

**Keywords:** drones; laser; microwaves; kinetic; counter-UAS; directed energy.

## 1. Introduction

Unmanned aerial systems, commonly known as drones, have evolved from recreational instruments into ubiquitous tools of modern warfare, terrorism, and criminal activity. Low-cost commercial quadcopters, priced between $2,000 and $8,000, have become a genuine operational threat, executing precision strikes with success rates frequently reaching 70–80%. Terminal guidance is achieved autonomously, with artificial intelligence increasingly replacing direct human control, thereby reducing classical jamming vulnerabilities. The threat is amplified in swarm configurations: coordinated groups of 50 or more than 100 units can rapidly overwhelm traditional air defences, with cost and volume favoring the attacker.

The economic asymmetry is stark: a single Patriot PAC-3 missile, costing $3 million, cannot sustainably counter a $35,000 Shahed drone, creating cost ratios exceeding 100:1. The conflict in Ukraine has exposed this vulnerability, with Russian forces launching 574 drones in coordinated deep-strike attacks that saturated existing defences [1]. Critical infrastructure, military bases, urban centers, and naval vessels face existential threats from these inexpensive, rapidly proliferating systems [2].

Military responses have initially adapted legacy systems: electronic warfare jamming disrupts communications but fails against autonomous or fiber-optic-guided drones; net guns offer a local tactical solution but are not scalable; and traditional surface-to-air missiles prove economically disadvantageous [3].

This study systematically evaluates three counter-drone technologies, namely kinetic projectiles, high-energy lasers, and high-power microwave systems, with respect to operational performance, environmental resilience, economic efficiency, and swarm-defence capability. The analysis draws on specifications from leading manufacturers (EOS Slinger/Apollo, Epirus Leonidas, MBDA DragonFire), combat performance data from Ukraine deployments (2023–2025), and atmospheric physics modelling of directed-energy propagation [4, 5, 6]. Quantitative indicators include engagement range, neutralization capacity (targets/minute), cost per shot, meteorological performance-degradation matrices, and the feasibility of layered-architecture integration. Real-world validation incorporates 2025 field tests (Leonidas testing in the Philippines, UK RapidDestroyer evaluations) and doctrinal evolution documented in CSIS/KSE Institute reports [2, 1, 7].

## 2. Kinetic anti-drone projectile systems

Modern battlefields are witnessing a proliferation of small, inexpensive drones that conventional air defence struggles to counter. In response, militaries are repurposing autocannon and machine-gun weapons into dedicated counter-unmanned aerial system (C-UAS) platforms. The Australian Slinger system (EOS) is a prominent example: a fully stabilized 30×113 mm Bushmaster cannon firing RF proximity-fuze fragmentation projectiles. Unlike a direct-impact projectile, the Slinger round detonates at an optimal stand-off distance via an integrated sensor, dispersing fragments across a three-dimensional kill zone and considerably increasing the probability of destroying small, agile drones [8].

### *2.1. Components of a kinetic anti-drone system*

The Slinger system integrates three principal subsystems into a compact remote weapon station. First, a sensor suite and fire-control system includes an Echodyne ultra-low-SWaP Active Electronically Scanned Array (AESA) 4D radar and a four-axis electro-optical/infrared (EO/IR) tracker. The Echodyne radar provides rapid multi-dimensional tracking (range up to 1.4 km for small drones) and cues the electro-optical and thermal cameras. EO/IR sensors can identify targets at approximately 12 km by day and approximately 13.7 km via thermal imaging, enabling long-range acquisition and targeting. A fourth axis on the sighting turret allows the sensor package to move independently in azimuth and elevation, maintaining lock while the gun tracks the target [8].

Second, the kinetic effector consists of a fully stabilized M230LF 30×113 mm Bushmaster automatic cannon mounted on an EOS R400 remote weapon station. It fires RF proximity-fuze fragmentation rounds, with each projectile carrying an integrated RF sensor that initiates detonation as it approaches the drone. Slinger carries up to 150 rounds and can fire at a deliberate rate of 100 rounds per minute (for precision) or a burst mode of 200 rpm for rapid engagement. This hybrid mode allows operators to select carefully aimed single shots or a rapid burst against fast multiple targets. The autocannon and ammunition weigh approximately 355 kg. Full stabilization on all axes produces a very high first-shot hit probability even while moving, with firing dispersion below 1 milliradian [8].

Third, the stabilized platform and integration: the entire turret (gun, radar, sensors, ammunition) weighs under 400 kg and stands only 0.9 m tall. In practice it is mounted on light armored vehicles, armored personnel carriers, or utility vehicles. The Slinger's on-the-move capability is critical: it can detect, track, and engage drones without stopping. An operator inside the vehicle uses a joystick and

control unit to select targets, and the system can lock on and fire autonomously once threats are identified [8].



Figure 1. Example kinetic C-UAS turret (Rheinmetall Skynex with 35 mm autocannon).

*2.2. Comparison with other kinetic C-UAS systems*

Other kinetic counter-drone systems operate on similar principles with different calibers and form factors. Naval and land-based close-in weapon systems (CIWS), originally designed against missiles, have been adapted for C-UAS roles. The US Army's C-RAM Centurion uses a 20×102 mm M61A1 Vulcan Gatling gun (4,500 rpm) with radar guidance to intercept rockets and mortars, and can also intercept slow drones. The Rheinmetall Skyranger 30 is a 30×173 mm autocannon mounted on an armored vehicle, firing up to 1,200 rpm and carrying 252 rounds, engaging targets at approximately 4 km. Similarly, the Rheinmetall Skynex air-defence suite integrates a 35×228 mm revolver cannon (1,000 rpm nominal, 200 rpm single-shot) with a high-performance AESA radar, networked to a command node and capable of autonomously detecting, tracking, and engaging drones out to approximately 4,000 m [9].

**Table 1.** Kinetic C-UAS Platforms.

| System | Caliber & Ammo | Muzzle Velocity | Rate of Fire | Mag. Capacity | Range | Weight (system) | Notes / Cost |
|---|---|---|---|---|---|---|---|
| EOS Slinger | 30×113 mm RF-prox HE-Frag | ~1,040 m/s | 100/200 rpm | 150 rounds | ≈800 m | 355 kg (turret) | Unit ~$1.55M; ~$155–1,550/shot |
| C-RAM (Centurion) | 20×102 mm Vulcan (PD) | 1,050 m/s | 4,500 rpm | 2,000+ (truck) | ~2,000 m | 24 t (truck+gun) | $10M/unit |
| Skyranger 30 | 30×173 mm AHEAD (PD) | 1,075 m/s | 1,200 rpm | 252 rounds | ~4,000 m | ~2–3 t (turret) | Germany, ongoing programs |
| Skynex (Revolver) | 35×228 mm AHEAD (PD) | 1,250 m/s | 1,000 rpm | 252 rounds | ~4,000 m | Vehicle mount | 35 mm, networked defence |

Note: PD = proximity detonation. AHEAD rounds disperse tungsten sub-projectiles.

Table 1 compares selected kinetic C-UAS platforms. The Slinger's principal advantages are its compact size, moderate caliber, and specialized ammunition. Heavier systems such as C-RAM or Skyranger offer greater range and volume of fire, but at significantly greater weight and cost. The C-

RAM highlights the trade-off: nearly 1.2 km coverage with 24 tons of equipment, versus Slinger's mobility on a pickup truck. Skyranger/Skynex similarly provide a much greater range (~4 km) and automated tracking, at the expense of vehicle size and cost [9].

### *2.3. Performance and accuracy*

*Effective engagement range.* The Slinger is optimized for engagements at approximately 0.8 to 1 km. Its radar can detect small UAS at approximately 1.2 to 1.4 km, while the weapon itself maintains accurate fire beyond 800 m. Experimental evaluations have shown Slinger systems can successfully neutralize drones at approximately 500 m during on-the-move operations. Heavier kinetic C-UAS systems such as Skynex and Skyranger can engage targets at approximately 4 km, while close-in weapon systems such as Phalanx operate typically at approximately 2 km [8, 9]. This difference reflects the fundamental trade-off between mobility and range.

*Hit probability.* A defining characteristic of modern kinetic UAS counter-systems is highly automated fire-control. Slinger employs a four-axis stabilized mount combined with an advanced fire-control architecture, resulting in a high first-shot hit probability during trials. According to EOS, the stabilization and pointing technology maintains accurate tracking even over rough terrain. Comparable trends are observed in Skynex, where radar and EO sensor integration enables automatic target tracking with limited operator intervention [8, 9].

Even so, projectile-based engagement remains constrained by ballistic geometry. The proximity fuze provides a significant operational advantage by detonating near the drone rather than on impact, reducing the precision burden on the fire-control solution. The resulting fragmentation pattern creates an area effect, specifically a sphere of lethal fragments, meaning the gunner does not need a perfect lead on an agile quadcopter [8].

*Rate of fire and ammunition capacity.* Slinger provides selectable rates of 100 or 200 rounds per minute, allowing operators to alternate between controlled precision fire and rapid short bursts. In many practical scenarios, a single 30 mm round is sufficient to disable a small drone, explaining the preference for single-shot or short-burst methods. The system carries a total of 150 rounds, imposing a clear limit on sustained defensive operations. At maximum rate of fire, continuous engagement lasts less than one minute [8].

By contrast, larger kinetic systems offer substantially greater magazine depth and, in some cases, higher rates of fire. Skyranger and Skynex carry approximately 252 rounds and can deliver high-volume salvoes exceeding 1,000 rounds per minute when required. C-RAM systems carry ammunition in the thousands. Nevertheless, even these systems remain subject to finite magazine capacity, reloading requirements, and the risk of mechanical stoppage. In swarm-defence scenarios, high volume of fire improves interception potential, but no kinetic system can sustain unlimited engagement without logistic support [9].

*Cost per engagement*. Cost per engagement remains one of the most important variables in counter-UAS operations. For the Slinger system, engagement cost is relatively low, ranging from approximately $155 to $1,550 depending on ammunition type and firing profile. By comparison, a single surface-to-air interceptor can cost tens of thousands to several million dollars: Patriot PAC-3 interceptors are typically valued at approximately $3.7 million per unit, Iron Dome interceptors are estimated between $20,000 and $100,000, and even short-range Stinger missiles remain significantly more expensive than gun-based interception [2, 10].

This cost asymmetry has important operational implications. As the EOS CEO Dr Schwer notes, "shooting down a $2,000 drone with a $500,000 missile makes no sense". Kinetic weapons offer a cost per shot that is orders of magnitude lower; US studies indicate a 20 mm gun system costs only a few thousand dollars per interception, permitting more appropriate use of fire against cheap threats [10].

### *2.4. Operational advantages of kinetic interceptors*

*Operational environment and weather.* Kinetic counter-UAS systems demonstrate strong resilience to environmental conditions. Unlike laser or HPM systems, projectile-based weapons are not materially

affected by atmospheric factors such as rain, fog, or cloud cover. Only extreme wind conditions have a measurable impact on projectile trajectory, primarily at extended ranges. This relative weather insensitivity ensures consistent operational performance across diverse climatic environments, in contrast to directed-energy systems, which frequently suffer significant degradation from atmospheric absorption, scattering, or thermal effects in wet or adverse meteorological conditions [11, 12].

*Lethality.* Physical fragments damage drones regardless of their technology. Electronic warfare systems may be rendered ineffective by autonomous navigation or hardened communication links, and directed-energy systems may be partially mitigated by reflective materials or thermal management. Fragmentation-based effects, by contrast, remain fundamentally difficult to counter. Proximity-fuze ammunition creates a lethal engagement volume, making kinetic systems highly reliable against both conventional and emerging drone architectures, including fiber-optic-guided and AI-controlled platforms [13].

*Reduced collateral effects*. Kinetic systems using proximity-fuze ammunition can achieve high precision with relatively limited collateral impact. Localized detonation of fragmentation rounds produces a confined engagement zone, typically within a few meters of the target. Compared to missile-based air-defence systems, which can generate wide debris fields or uncontrolled fragmentation, kinetic interceptors offer greater control over the engagement zone, making them particularly suited to deployment in urban environments or near critical infrastructure [10].

*Resilience and operational sustainability*. Kinetic systems offer a high degree of operational independence. Unlike directed-energy systems, they do not rely on high-capacity electricity generation or complex thermal management. Provided ammunition and platform fuel are available, kinetic interceptors can sustain continuous operation without recharge delays. Although ammunition resupply remains a limiting factor, logistic support for conventional ammunition is generally better established and more scalable than the infrastructure required for high-power energy systems [14].

### *2.5. Constraints and operational challenges*

*Single-target engagement model.* Despite these strengths, kinetic defence has clear limits. The principal limitation is the single-target engagement model. Each projectile engages one drone, making exclusively kinetic defence inefficient against coordinated swarms. Documented swarm sizes of 10 to 50 drones, and mass attacks exceeding 500 units, exceed kinetic engagement capacity. In swarm attacks with dozens of drones, even a 200 rpm gun can be overwhelmed. Recent conflicts illustrate this: Ukraine faced coordinated strikes of 10–25 loitering munitions simultaneously, and Russia launched over 500 small drones in a single salvo. Researchers note that "exclusively kinetic defence is unsustainable" against large-scale swarm attacks [3, 1].

*Debris and collateral risks.* Although kinetic systems offer high precision, each successful interception may generate secondary hazards. Destroyed drones inevitably fall, and if equipped with explosive payloads, they may present risks at impact. In densely populated areas, even non-explosive debris can injure personnel or civilians. These considerations impose additional constraints on rules of engagement, requiring careful evaluation of engagement zones and potential impact areas [10].

*Logistics and sustainment.* Sustained kinetic defence requires the continuous production, transport, and storage of specialized ammunition, including proximity-fuze rounds. Maintaining these supply chains under combat conditions can become a significant logistic burden, particularly during high-intensity or prolonged operations. Directed-energy systems rely primarily on electrical power rather than consumable munitions, reducing logistic complexity and enabling a more sustained operational tempo, provided adequate power infrastructure is available [14].

*Operator requirements.* Despite increasing automation, kinetic systems continue to rely on trained operators for effective use. Target identification, prioritization, and engagement decisions remain cognitively demanding, particularly in complex environments with multiple airborne objects. Although modern fire-control systems assist with tracking and aiming, they do not entirely eliminate the need for human judgement [15].

## 3. High-energy laser systems

High-energy laser (HEL) counter-drone systems combine three main functions: (1) detection and tracking, typically via radar and EO/IR sensors; (2) a beam-pointing and -steering system that stabilizes and maintains the aimpoint; and (3) an energy-generation, storage, and thermal-management subsystem enabling repeated shots (an "energy magazine"). The Royal Australian Air Force Air Power Development Centre conceptualizes a generic directed-energy system as comprising four main subsystems: power generation, energy storage, beam control and direction, and thermal management, with energy storage explicitly defined as an "energy magazine" enabling repeated engagements without the constraints of conventional ammunition [11].

Apollo is a containerized high-energy laser intended for the neutralization of UAS and optical sensor denial, with a declared laser-power configuration of 50 to 150 kW. The technical specification states a typical hard-kill engagement range of 50 m to 3 km for UAS neutralization, optical sensor denial to 15 km, and continuous firing with external electrical power and cooling; when isolated, 200 stored engagements are stated. The same specification provides a detailed engagement timeline for a 60-degree slew: 700 ms to cue, 600 ms to lock, and 1.3 s to neutralize a Group 1 UAS at 50 kW (4.4 s for a Group 2 UAS at 50 kW) [5].

DragonFire is the United Kingdom's sovereign directed-energy laser weapon programme, developed under Ministry of Defence auspices in collaboration with MBDA, Leonardo, and QinetiQ. Official statements indicate the system has demonstrated high-power engagement capabilities against aerial targets, with emphasis on precision and cost-effectiveness. UK government reports describe the QinetiQ phase-combined laser demonstrator as producing approximately 50 kW, integrated into a complete architecture comprising a beam director, command-and-control (C2) systems, and an imagery processing chain [16, 17].

### *3.1. Operational characteristics*

HEL engagement is fundamentally constrained by line-of-sight conditions and the requirement to deliver continuous energy to achieve cumulative damage on the target. The Apollo system architecture illustrates this clearly: it incorporates radar and passive infrared detection, either as organic components or via third-party integration, alongside multiple C2 interfaces and rapid sub-second cue-to-lock timelines [4]. Similarly, the UK MoD describes DragonFire as a system that can engage any target it can directly see, although its exact range is not publicly disclosed [18].

Two further operational attributes follow from the energy-magazine concept. First, sustained firing capacity depends on platform power and cooling. Apollo explicitly claims a 100% duty cycle dependent on electrical power, and "unlimited" engagements with continuous power [5]. Second, set-up and mobility affect operational availability. Apollo is installed in a 20-foot ISO container and claims that experienced crews can make it operational in under two hours.

**Table 2.** Performance characteristics of the Apollo and DragonFire systems.

| Attribute | Apollo (EOS) | DragonFire (UK) |
|---|---|---|
| **Published power class** | 50 to 150 kW [5] | Order of 50 kW (phase-combined demonstrator) [16] |
| **Hard-kill range** | 50 m to 3 km (typical) [5] | Range classified; line-of-sight [18] |
| **Optical sensor denial** | 50 m to 15 km [5] | Unspecified [19] |
| **Slew to cue** | 700 ms for 60° [5] | Unspecified [18] |
| **Target lock time** | 600 ms [5] | Unspecified [18] |
| **Neutralization time** | Group 1: 1.3 s at 50 kW; Group 2: 4.4 s at 50 kW [5] | Unspecified; ~10 s cost example cited [18] |

| Attribute | Apollo (EOS) | DragonFire (UK) |
|---|---|---|
| **Engagement rate** | >20 Group 1 UAS/min (swarm ranges) [5] | Unspecified [17] |
| **Magazine / energy** | 200 stored; unlimited with continuous power [5] | Unspecified; low operating cost [18] |
| **Cost per shot (marginal)** | Unspecified in open sources [5] | Approx. £10 per shot [20] |
| **Demonstrated targets** | Group 1–3 UAS; integrates with NATO C2/IADS [4] | High-speed drones up to 650 km/h [17] |

### *3.2. Cost economics*

The economic arguments for HEL are explicitly articulated in UK government communications. DragonFire is described as costing "just £10 per shot", positioned as more cost-effective than missile-based solutions costing hundreds of thousands per shot [17]. A January 2024 UK press release states the operating cost as typically less than £10 per shot and explicitly argues this can reduce dependence on expensive ammunition while also reducing collateral risk [18]. At the strategic level, CSIS notes that a Patriot PAC-3 interceptor costs "over $3 million", providing further evidence of the cost-exchange pressure driving lower-cost effectors for drone defence [2].

### *3.3. Operational advantages*

HEL systems can offer (1) precision at line-of-sight ranges, as underlined by DragonFire's claimed coin-sized precision at 1 km; (2) low marginal cost, governed primarily by energy consumption; and (3) reduced explosive fragmentation risk compared to kinetic munitions or proximity-fuze rockets [20]. Apollo adds the further operational advantage of published sub-second cue-to-lock and short dwell requirements against small UAS, sustaining a high engagement tempo against sequential targets [5].

### *3.4. Limitations and constraints*

Atmospheric and environmental effects remain the dominant physical constraint. The RAAF Air Power Development Centre states directly that atmospheric conditions such as clouds, rain, and fog can attenuate directed-energy transmissions and that directed-energy weapons are not all-weather weapons, and will likely need to be complemented by weapons that work in adverse weather [11]. The US Government Accountability Office similarly notes that fog and storms can reduce laser range and beam quality [21].

A second constraint is energy and thermal management. Directed-energy system design requires power, energy storage, and cooling subsystems. The RAAF document discusses cooling techniques and the need to manage the impact on platform performance during directed-energy operation [22]. Apollo's 100% duty-cycle claim is explicitly conditional on electrical availability, reinforcing that sustained operation is as much an infrastructure and sustainment challenge as a beam-control problem [5].

A third constraint is safety and collateral management. The RAAF document highlights risk of beam spillover, reflections, and accidental illumination of unintended objects beyond the target line, requiring mission planning and operator awareness [23]. Although HEL can reduce fragmentation, it does not eliminate collateral risk; rather, it shifts the risk towards optical-line management, beam interactions, and deconfliction with friendly sensors [24].

## 4. High-power microwave systems

High-power microwave (HPM) systems defeat drones by producing counter-electronic effects across a beam footprint, rather than requiring focused laser dwell on a single point. ITU literature on line-of-sight propagation provides a useful physics analogue: microwave signals are subject to absorption and scattering by hydrometeors such as rain, snow, hail, and fog, with attenuation increasing rapidly at

higher frequencies [25, 26]. While this does not directly specify weapon effectiveness, it explains why HPM performance can be environment-dependent, even if generally less sensitive than optical lasers in fog or cloud.

The most clearly documented and mature HPM reference point is THOR, developed by the US Air Force Research Laboratory. THOR is described as an electromagnetic "counter-swarm" weapon that installs in a 20-foot ISO container, operates from a wall plug, sets up in three hours, and requires minimal user training [27]. Its defeat mechanism is described as a nanosecond discharge with instantaneous effect [28].

The UK's RFDEW demonstrator under Project Ealing, delivered by a Thales-led consortium, represents another significant HPM approach. UK Defence Equipment and Support reports that RFDEW can detect, track, and engage targets on land, in the air, and at sea; neutralize aerial targets at up to 1 km with near-instantaneous effect; and achieve an estimated energy cost of less than 10 pence per shot [29]. Its high automation is described as enabling single-operator use [29].

The US Army's IFPC-HPM programme represents a step towards operational field deployment: the Army states that IFPC-HPM emits a microwave energy beam that can disrupt, disable, or destroy UAS and describes it as the first "material-release" directed-energy system specifically designed to counter groups and swarms of drones; it was fielded with the 1st Multi-Domain Task Force in February 2024 and tested in a tropical environment during Exercise Balikatan in the Philippines [30, 7].

Finally, Epirus Leonidas press releases provide open-source performance claims: a live-fire demonstration reportedly disabled 61 of 61 drones, culminating in the defeat of a 49-drone swarm with a single pulse, and a separate release claims a successful December 2025 demonstration defeating fiber-optic-guided FPV drones, a class said to be immune to traditional jamming because it lacks an RF command link [6, 31].

### *4.1. Operational characteristics*

HPM counter-drone operations are defined by beam footprint, pulse sequencing, and the ability to apply effects across multiple targets in a single engagement window. The THOR fact sheet explicitly highlights multi-target defeat, nanosecond discharge, and instantaneous effect [28]. UK RFDEW communications similarly emphasize "multiple targets simultaneously" with near-instantaneous effect, integrating the system into a detect-to-engage chain that includes automation for single-operator use [32].

HPM systems also present a distinct sustainment logic: they reduce physical ammunition consumption, but create dependencies on power generation, cooling, and electromagnetic deconfliction. The British Army report notes that RFDEW requires less power to operate than laser weapons, but also describes the technology as expensive to procure and highlights ongoing experimentation to extend range and power [33].

**Table 3.** Performance characteristics of the Apollo and DragonFire systems.

| Attribute | THOR (AFRL) | RFDEW (UK) | IFPC-HPM (US Army) | Leonidas (Epirus) |
|---|---|---|---|---|
| **Effect mechanism** | HPM counter-electronics [28] | High-freq. radio waves disrupting electronics [29] | Microwave beam disrupts/disables UAS [7] | Weaponized EM interference [6] |
| **Neutralization timing** | Discharges in nanosecond; instantaneous [28] | Near-instant (qualitative) [34] | Unspecified [7] | Instant pulses (qualitative) [6] |
| **Engagement range** | Unspecified [28] | Up to 1 km [35] | Unspecified [7] | Unspecified [6] |

| Attribute | THOR (AFRL) | RFDEW (UK) | IFPC-HPM (US Army) | Leonidas (Epirus) |
|---|---|---|---|---|
| **Setup and mobility** | 20-ft container; 3 h setup [28] | Vehicle-mount potential; automation [29] | Fielded; live-fire exercise [7] | Unspecified [36] |
| **Power and magazine** | Wall plug power [28] | <10 pence/shot; magazine unspecified [29] | Not specified [7] | Software-defined arrays [31] |
| **Operator and training** | Minimal training [28] | High automation; single operator [35] | Used with EO/IR in layered concept [7] | Unspecified [36] |
| **Swarm relevance** | Multi-target defeat [28] | >100 drones immobilised in trials [37] | Groups and swarms; multiple environments [7] | 49-drone swarm defeat; 61/61 disabled [36] |
| **Fiber-optic drone** | Unspecified [28] | Unspecified [29] | Unspecified [7] | Claimed defeat of fiber-optic FPV drones [31] |

### *4.2. Cost economics*

UK official statements quantify a defining advantage: RFDEW energy cost is described as less than 10 pence per shot, implying an extremely favorable cost exchange against drones and complementing costly missile-based air defence [35]. UK government announcements and Army reports also underline that RFDEW could complement missile systems and is intended to address evolving threats, including those that cannot be jammed by electronic warfare [38].

### *4.3. Operational advantages*

HPM systems offer (1) one-to-many engagement potential; (2) extremely low marginal engagement costs when electrical power is available; and (3) effectiveness against targets where mere disruption of RF links is insufficient, because hard electronic-kill effects do not depend on blocking communications [39]. These characteristics align with the US Army operational framework for IFPC-HPM as a system intended for groups and swarms, and with UK study reporting emphasizing simultaneous neutralization [40].

### *4.4. Limitations and constraints*

HPM introduces area effects and electromagnetic compatibility (EMC) challenges. The US Government Accountability Office warns that broader-beam directed-energy systems such as HPM affect all assets in a zone, whether friendly or hostile, making engagement doctrine, EMC, and sensor-based positive identification essential for safe and effective operation [21]. This is particularly relevant in environments dense with friendly electronics, such as airfields, ports, urban infrastructure, and command posts.

The environment also matters. ITU guidance on line-of-sight propagation indicates that hydrometeors such as rain and fog introduce attenuation through absorption and scattering, increasing rapidly at higher frequencies [26]. Although weapons are not communication links, this physical constraint supports the cautious conclusion that heavy precipitation can reduce the range and reliability of microwave beams under certain conditions, even if generally less severely than for optical lasers.

Finally, capability maturity and disclosed performance remain uneven. THOR and RFDEW have clear public statements on set-up, operator training, and qualitative engagement effects, but do not provide a fully open performance envelope (e.g., THOR's published maximum range or beam width, or RFDEW's sustained duty-cycle limits) [41]. This uncertainty reflects the reality that many HPM

parameters are operationally sensitive and vary with target electronics, waveform, and engagement geometry [42].

## 5. Discussion

Table 4 aggregates qualitative environmental sensitivity based on government assessments and physics-based propagation references. Ratings are relative and intended for planning, not as guaranteed performance.

**Table 4.** Environmental Performance Matrix.

| Condition | HEL (laser) | HPM (microwave) | Kinetic (projectile) |
|---|---|---|---|
| **Clear, stable atmosphere** | High effectiveness [43] | High effectiveness [44] | High effectiveness [45] |
| **Fog, cloud, heavy haze** | High degradation (not all-weather) [12] | Potential degradation via scattering; magnitude depends on frequency [46] | Low degradation (visibility and fire control, not projectile physics) [45] |
| **Rain and storms** | High degradation (attenuation and beam quality) [47] | Degradation possible; attenuation increases at higher frequencies [26] | Low degradation (wind and ballistic dispersion dominate) [45] |
| **Strong turbulence / thermal gradients** | Degrades beam control; adaptive optics mitigate partially [48] | Likely scenario-dependent (open sources unspecified) [42] | Moderate impact via aiming stability and dispersion [45] |
| **Obstructed line-of-sight (urban, terrain)** | Fundamental constraint [49] | Fundamental constraint for directed beams and sensor confirmation [46] | Less constrained with radar cueing and ballistic arcs; still sensor-limited [45] |

Costs are presented as reported in cited sources (a combination of GBP and USD). Currency differences do not affect order-of-magnitude conclusions.

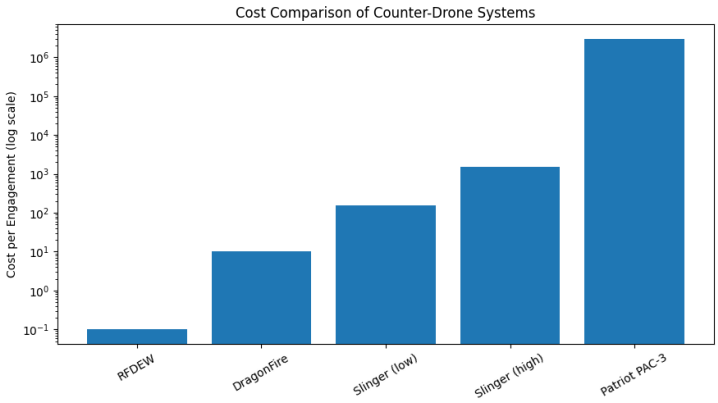



Figure 2. Example kinetic C-UAS turret (Rheinmetall Skynex with 35 mm autocannon).

UK DE&S states RFDEW is "less than 10 pence per shot" [29]. The UK Government states DragonFire is "£10 per shot" [17]. Slinger cost-per-interception values are reported by EOS-associated reports [50]. Patriot PAC-3 cost is cited by CSIS as over $3 million per interceptor [2].

Sensor integration and C2 play an essential role in determining the effectiveness of both HEL and HPM systems. In practice, overall performance depends less on the effector itself and more on how

rapidly and accurately information flows from detection to engagement. The Apollo system illustrates this approach by combining radar and passive infrared sensors, either as integrated components or via third-party interfaces, with multiple C2 layers and rapid sub-second cue-to-lock timelines [4]. Similarly, the DragonFire programme distributes key functions across the engagement chain: MBDA handles imagery processing and C2, Leonardo supplies the beam director, and QinetiQ provides the phase-combined laser source, all coordinated under UK defence research oversight [16].

HPM systems place particular emphasis on precise target identification and engagement deconfliction to minimize unintended effects on friendly systems or surrounding infrastructure. US Army field reports from Balikatan exercises indicate that IFPC-HPM systems were operated alongside FS-LIDS, with EO/IR sensors supporting a layered approach to UAS detection, tracking, and neutralization [7]. UK RFDEW programme reports similarly highlight that experimentation focuses not only on the microwave emission itself, but also on system integration and operational challenges associated with effective deployment within a broader counter-UAS architecture [51].

Production, scaling, and sustainment represent critical constraints for directed-energy systems. While these technologies offer a very low marginal cost per engagement, large-scale deployment is often limited by industrial capacity, component availability, and specialized workforce requirements. The National Defense Industrial Association's Emerging Technologies Institute highlights that the current production base for directed-energy systems is insufficient to meet future demand, citing long lead times, a limited supplier base, and the complexity of producing key components such as precision optics, mirrors, lenses, and advanced semiconductor and battery technologies [52]. These limitations have direct operational implications: if HEL and HPM systems are expected to replace a significant share of missile-based interceptions, the supporting supply chains for beam directors, power electronics, and thermal management systems must expand at a pace comparable to acquisition efforts.

## 6. Conclusions

The principal conclusion of this study is that HEL and HPM systems offer significant advantages in terms of cost per engagement and sustained engagement capacity, but neither technology can independently substitute for kinetic or missile-based systems in all operational environments and against all threat types.

HEL system performance is directly limited by physical constraints, particularly atmospheric propagation and the requirement for an unobstructed line of sight. Both the RAAF Development Centre and the GAO underline that directed-energy systems cannot operate effectively in all weather conditions, being affected by phenomena such as fog, precipitation, or cloud cover, which can attenuate or distort the beam [47]. Even in favorable meteorological conditions, operating HEL systems entails high energy supply and storage requirements, integration of advanced cooling solutions, additional beam-safety considerations, and collateral risks associated with reflections or energy dispersion, all of which require rigorous operational planning and adequate personnel training [53].

Unlike HEL, HPM systems offer a distinct operational advantage in swarm scenarios: a single emission can simultaneously affect multiple drones within the coverage area, enabling a "one-to-many" defensive approach. Systems such as THOR, RFDEW, IFPC-HPM, and Leonidas consistently highlight simultaneous multi-target neutralization capacity and near-instantaneous electromagnetic pulse effects [54]. Nevertheless, HPM use introduces additional deconfliction requirements not present with narrow-beam HEL systems. The GAO underlines that broad-beam systems can affect all equipment in the action zone, whether friendly or hostile, making rules of engagement, EMC, and sensor-based positive identification essential for safe and effective operation [21].

Kinetic projectile systems remain an indispensable element of a realistic defence architecture. Systems such as the EOS Slinger and Rheinmetall Skyranger 30 provide hard-kill capability less sensitive to fog, cloud, and precipitation, and can neutralize drones regardless of their autonomy or communication method, at the expense of finite magazines and ammunition logistics [55]. Close-in systems such as the US Navy's Mk 15 Phalanx demonstrate large kinetic magazines and high rates of fire for terminal defence (1,550 rounds; up to 4,500 rounds per minute depending on mode), but still

rely on finite ammunition and are not optimized economically or logistically for prolonged mass drone attacks [56, 57].

Emerging threats reinforce the need for a layered defence architecture. Increasing drone autonomy reduces the effectiveness of purely RF-jamming solutions by diminishing dependence on external command-and-control links. Fiber-optic-guided drones, described in the literature including Epirus reports as immune to jamming and spoofing, are highlighted in CSIS and other security organization analyses as a major evolving factor in the Ukraine conflict [58]. In this context, hard-kill neutralization mechanisms, both physical (kinetic) and based on effects on electronic components (HPM), become essential complements to HEL capabilities. This combination ensures the maintenance of defensive effectiveness even in adverse conditions such as bad weather, terrain masking, or the use of jamming-resistant control schemes [59].

The study therefore concludes that integrated, multi-layered defence architectures combining kinetic interceptors, HEL systems, and HPM systems offer superior effectiveness and resilience. The empirical logic is explicit in several sources: the US Army describes layered effects using IFPC-HPM and FS-LIDS in live-fire tests; the RAAF document states that directed-energy systems will likely be complemented by all-weather weapons; and the UK positions both DragonFire and RFDEW as cost-effective complements to expensive missile-based air defence [60]. Within this architecture, HEL provides precise defeat and optical blinding in favorable line-of-sight conditions, HPM provides wide-area effects and low marginal cost where deconfliction is manageable, and kinetic guns provide robust all-weather hard-kill coverage and protection against evolving autonomy and guidance schemes. This layered approach reduces dependence on costly missile interceptors while improving both operational resilience and economic sustainability during extended drone campaigns [61].

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