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DIRECTED ENERGY WEAPON SUPPLY CHAINS

SECURING THE PATH TO THE FUTURE

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Cover Photo: The 30 kilowatt Laser Weapon System (LaWS) was deployed and operated aboard the USS Ponce in 2014. LaWS was installed on the USS Ponce, which operated in the Persian Gulf, to evaluate shipboard lasers in an operational setting against swarming boats and UAVs.

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Executive Summary

Directed energy weapons (DEWs), including high energy lasers (HELs) and high power microwaves (HPMs), have emerged as potentially transformative weapons on the modern battlefield. Recent advancements have made DEWs more capable than ever, with many systems possessing the power and range necessary to engage a wide variety of threats, more affordably than current systems. Recent conflicts in the Middle East and Europe have highlighted the importance of munitions capacity as well as the need to both efficiently and effectively counter different kinetic threats. The ability of some DEW systems to engage many targets at once with an "unlimited" magazine could yield enormous economic and tactical benefits. However, the U.S. Department of Defense (DoD) has often wavered in its commitment to fielding DEWs at scale. As such, current DEW supply chains, including critical raw materials, the manufacturing base and workforce, and testing infrastructure are incapable of supporting DEW deployment at scale. The current DEW supply chains are only able to produce small quantities of systems with long lead times. Without a clear and sustained demand signal from DoD, and therefore a return on investment, industry is hesitant to make the investments necessary to have secure, healthy, and resilient DEW supply chains. While addressing these vulnerabilities is a formidable task, it is not insurmountable. To strengthen DEW supply chains and fulfill the potential of these cutting-edge technologies, a series of concrete steps by government, industry, and academia are necessary.

Key Findings & Recommendations

1. The most important step DoD can take to secure directed energy weapon supply chains for the future is to provide a consistent demand signal to industry and clearly articulate its strategic goals for DEWs. The lack of consistent demand signal was raised many times by industry leaders as negatively impacting all levels of the supply chain. Existing DEW supply chains can only produce small numbers of systems with long lead times. Once DoD's strategic goals are articulated, appropriate DEW systems should be transitioned to programs of record and multi-year contracts used to send an extended demand signal. A clear, sustained demand signal, accompanied by the overarching strategic vision, will provide industry with the assurance that they can begin to make the internal investments necessary to secure DEW supply chains for the future.

2. DEW supply chains have several vulnerabilities when it comes to critical raw materials and goods, notably the supply of germanium, gallium, and Rare Earth Elements (REE), all of which are largely dominated by China. In order to address these vulnerabilities, gallium should be added to the national defense stockpile, steps should be taken to develop domestic gallium nitride (GaN) production capabilities, and DoD should invest in synthetic alternatives to the most vulnerable DEW materials.

3. The current DEW manufacturing base can only produce small numbers of systems with long lead times and is insufficient to support fielding DEWs at scale. Efforts to scale up production would quickly run into issues including producing optical components (e.g., diffraction gratings, mirrors, and lenses), beam directors, batteries, and the regulatory regime governing above-the-horizon DEW testing. Key recommendations to address these issues include establishing DEW programs of record that provide clarity on future system demands, standardizing and clearly defining requirements for DEW systems, components, and testing, and harnessing technology from the commercial industry wherever possible.

4. The current DEW workforce is insufficient to support scaling up DEW production. Optical coatings, energy production, and optics are three specific areas highlighted by interviewees as facing the greatest shortage. As such, DoD should expand existing workforce development efforts by establishing a DEW University Consortium with the specific goal of creating a strong workforce to meet future DEW needs.

5. DEW supply chains face several key security issues and vulnerabilities. While the overall financial health of directed energy companies is relatively stable, the failure of even a single company could have severe repercussions due to limited supplier concerns. Limited suppliers exist throughout DEW supply chains but especially in beam directors, adaptive optics, optical coatings, specialty optical fiber, beam dumps, ceramic laser materials, and fused silica. DEW supply chains also face adversarial capital investments in DEW companies, and cybersecurity challenges. To mitigate these risks, DoD should consider using artificial intelligence to anticipate potential supply chain failure points, the development and prioritization of overlapping components for DEW systems between different programs, and conducting regular, in-depth analysis of the financial stability and security risks of companies involved in the DEW supply chain.

6. International partnerships and allied nearshoring present potential avenues for diversifying DEW critical material sources and enhancing testing capabilities. However, barriers including overclassification, and restrictive export controls often impede international collaboration. DoD should designate the Joint Directed Energy Transition Office (JDETO) as the office of primary responsibility for international collaboration on DEWs in order to streamline collaboration. At the same time, DoD should work with Australia, which has existing DEW testing infrastructure, to help increase U.S. DEW testing. Finally, given Israel's Iron Beam program, the JDETO should work with the Israeli Ministry of Defense to identify opportunities where the U.S. and Israel can combine demand for key DEW subsystems and components, while ensuring security measures to protect sensitive information.

It is important to note that this report is the second in ETI's supply chain series. While the first report focused on hypersonics, it also contained important recommendations that could also help secure DEW supply chains. If implemented, the recommendations in this report could help enhance the resilience, health, and security of directed energy weapon supply chains in the years to come.

Introduction

Over the past several years, the COVID-19 pandemic, subsequent economic challenges, the Russian invasion of Ukraine, and other world events have exposed the entangled and fragile nature of global supply chains. Nearly every sector has been affected, including defense and national security. The U.S. government recognized this compounding issue years ago. Multiple presidential administrations and Congresses have tried to address supply chain issues.[i] In early 2021, the House Armed Services Committee launched a bipartisan Defense Critical Supply Chain Task Force and subsequently published a report outlining key findings.[1] Many nonprofits have also contributed to the effort, including the Hudson Institute's Hamilton Commission on Securing America's National Security Innovation Base, the Reagan Institute's Task Force on National Security and U.S. Manufacturing Competitiveness, and the CNAS project on Securing America's Critical Supply Chains. This plethora of efforts – both inside government and outside – is indicative of the issue's importance. One area that has received significantly less attention outside of government, however, is the nascent supply chains that will support emerging technologies as outlined in the 2018 and 2022 National Defense Strategies.

As such, the National Defense Industrial Association's nonpartisan think tank, the Emerging Technologies Institute (ETI) launched an in-depth research study focused specifically on defense emerging technology supply chains. The study set out to assess the state of these supply chains and provide policy recommendations to advance their development, health, and resilience. The study is focused on key emerging technologies critical to the U.S. Department of Defense (DoD). The first report published as part of this study focused on hypersonics supply chains (published in May 2023). This second report focuses on directed energy weapon (DEW) supply chains, specifically focusing on high-energy lasers (HELs) and high power microwaves (HPMs). The report examines four aspects of the DEW supply chains: 1) Critical Raw Materials and Goods, 2) Manufacturing Base and Workforce, 3) Supply Chain Security and Vulnerabilities, and 4) International Partnerships and Allied Nearshoring. While this report focuses on DEW supply chains, some issues raised are relevant to many different emerging technology supply chains.

Methodology

The Emerging Technologies Institute (ETI) leveraged its unique position as part of the National Defense Industrial Association (NDIA) to conduct this emerging technologies supply chain study. This position provided access to companies and industry experts at all tiers of the defense industrial base, including academia, and allowed ETI to incorporate data and insight from those companies closest to the supply chain challenges. The methodology that ETI used is as follows:

First, ETI established a partnership with an NDIA academic member, the University of Maryland (UMD). This partnership culminated in a team of professors and graduate students from UMD's Supply Chain Management Center using open-source material to provide foundational research on directed energy weapon supply chains. UMD played a pivotal role in identifying key companies, sources of raw materials, and potential vulnerabilities that are analyzed throughout this report. Simultaneously, ETI convened four working groups composed of over 40 key stakeholders, and conducted over 25 interviews with subject matter experts. Each working group and interview focused on the four aspects of the supply chain listed above. The stakeholders were selected from industry, government, and academia based on their expertise in directed energy weapon technologies and subsystems. The ETI team also attended various DEW-related conferences and symposia including Directed Energy Professional Society (DEPS) events and the Society of Photo-Optical Instrumentation Engineers (SPIE) Photonics and Optics DC Summit. The working group and interview findings were compiled into this final report along with UMD research and internal research. Prior to publication, this report was submitted to several external reviewers with deep expertise in DEWs and a peer review committee, consisting of former senior government officials as well as former and current industry officials.

ETI decided to conduct the study at the publicly releasable level in order to reach the widest audience possible, and given that others have already conducted DEW supply chain reports and industrial base assessments at different classification levels. Additionally, publicly accessible analysis, findings, and recommendations were deemed important for the report to support continued dialogue between government, industry, and academia on critical DEW issues, potentially leading to programmatic and policy changes.

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i See Executive Order 13806 and subsequent DoD report "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States" (September 2018). See Executive Order 14017 and subsequent DoD report "Securing Defense-Critical Supply Chains" (February 2022)

Background

History of Directed Energy Weapons

Although often associated with groundbreaking technological advancement and science fiction, directed energy weapons have been considered for over two millennia. Many will recall apocryphal tales of the Greek mathematician and scientist, Archimedes, using sunlight amplified through an array of mirrors to set fire to an invading Roman fleet during the siege of Syracuse in 214 B.C.[2] The U.S., for its part, has been researching DEWs since the 1960s.[3] This early research originated from observations of the electromagnetic pulses (EMPs) triggered by atmospheric nuclear detonations and the potential to use high-power oscillating electric fields to damage enemy electronics.[4] While interest in DEWs grew over the ensuing years, the technology was slow to mature.

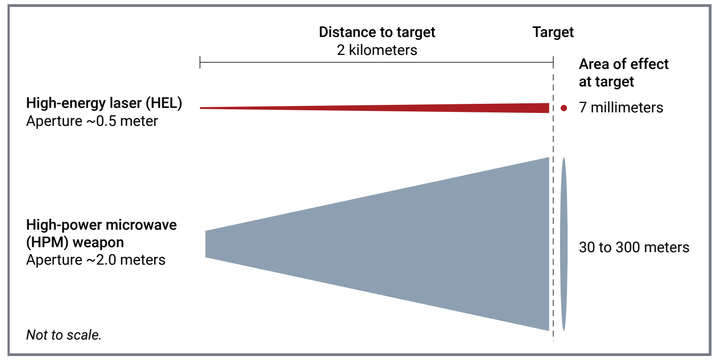
Despite substantial technological limitations, the 1980s saw greatly expanded interest and investment in DEW capabilities, particularly in the Reagan administration's Strategic Defense Initiative (SDI), or the "Star Wars" program.[5] While ultimately unsuccessful, this program represented a clear commitment to the pursuit of directed energy technology. The 1980s also saw some of the first uses of blinding laser systems to directly damage targets in the Falklands War (1982) and the Iran-Iraq War (1980-1988).[6, 7] Concerns about the potentially inhumane nature of blinding technology led to the 1995 Protocol on Blinding Laser Weapons (Protocol IV to the 1980 Convention on Certain Conventional Weapons) which "prohibits use of blinding laser weapons as a means or method of warfare as well as their transfer, to any state or non-state actor."[8]

Although few initiatives of the 1990s matched the stardom of SDI, promising programs such as Airborne Laser (ABL) and Advanced Tactical Laser (ATL) were developed using chemical oxygen iodine laser (COIL) technology.[9] Following the 9/11 attacks, there was speculation regarding the role DEWs would play in the Global War on Terror.[10] According to multiple interviewees, despite lofty expectations, DEW systems had not yet reached the level of cost efficiency or technological maturity necessary to enable their widespread deployment in either Iraq or Afghanistan. Some of the highest-profile programs of the time were ultimately canceled.[11] Testing continued, however, and some DEWs such as the Active Denial System (ADS) saw limited deployment before being removed from the field.[12] A landmark moment came in 2014, when the USS Ponce deployed with the first operational U.S. directed energy weapon.[13] Today, the U.S. is in an era of Great Power Competition and faces an increasingly contested security environment, with wars in the Middle East and Europe, and confrontations in the South and East China Seas. As will be discussed further in this report, directed energy weapons are poised to play an increasingly vital role in countering the threats posed by an increasingly belligerent China, Russia, and Iran.

What are Directed Energy Weapons and why are they critical to America's national security?

For the purposes of this report, directed energy weapons (DEWs) are defined as "electromagnetic systems capable of converting chemical or electrical energy to radiated energy and focusing it on a target, resulting in physical damage that degrades, neutralizes, defeats, or destroys an adversarial capability."[14] While there are a wide range of DEW technologies, this report will focus on high power microwave (HPM) and high energy laser (HEL) weapons.[15] Because of their potential advantages, discussed below, DoD identified directed energy as an emerging technology in the 2018 National Defense Strategy (NDS), and again as a critical technology area in the 2022 NDS.

Figure 0.1 Illustrative Effects of HELs Versus HPM Weapons[ii]



Note: *Units of measurement are illustrative*

High Energy Laser Weapons

While there are many types of high energy lasers (HELs), this report will focus primarily on solid state and fiber lasers given their predominance in current military technology. Chemical lasers have played an important role over the years in the development of DEW technology, but ultimately the focus has shifted to other promising laser technology, including solid-state lasers and fiber lasers.

Proponents of HELs have cited many potential benefits, including the potential for a large firing capacity, low cost-per-shot, and relatively low logistics requirements.[16] Additionally, HELs have unique characteristics that make them ideally suited for specific engagement scenarios. First, because they fire at the speed of light, HELs can rapidly engage high-speed targets, and with the use of beam directors and trackers, could potentially match the maneuvers of advanced weapon systems.[17] This speed of light capability also makes them uniquely suited for engagements in space, leading to significant potential for future warfare scenarios.[18] With no need to reload, HELs can immediately acquire and confront the next target with an unlimited magazine, assuming sufficient energy supply.[19] Finally, "HELs offer the potential for graduated responses that range from warning targets to reversibly jamming their systems," to causing damage to targets, the degree of which is tunable by system operators.[20] This graduated response capability allows the user to tailor HEL engagement to highly specific scenarios, avoiding unnecessary damage (given the extreme precision of the narrow and focused beam) and minimizing escalation.

HELs also face several challenges, especially when used at a significant range. According to interviewees, many of the following concerns are being addressed in various programs and may not prove detrimental to the effectiveness of future HEL systems. However, they

ii Sayler, Kelley M., Andrew Feickert, and Ronald O'Rourke. "Department of Defense Directed Energy Weapons: Background and Issues …" Accessed September 14, 2023. https://sgp.fas.org/crs/weapons/R46925.pdf.

are worth mentioning due to their historical impact on DEW development. First, since lasers propagate in a straight line, they are limited to line-of-sight engagements.[iii] Further, lasers are highly susceptible to atmospheric disruptions. Common airborne substances including smog, fog, smoke, and dust can absorb and scatter the beam, reducing the range of HELs. While not a major concern at close-range, long-range engagements that involve significant atmospheric exposure must employ adaptive optics to compensate for potential disruptions or wait for ideal conditions to engage.[21] As such, HELs may not yet be an all-weather solution, although DoD is actively working to address this challenge, according to interviewees.[22] Thermal blooming is another issue, which occurs when a laser is focused on a single point for an extended period of time. The laser will rapidly "heat up the air it is passing through, which can defocus the laser beam, reducing its ability to disable the intended target" and make "lasers less effective for countering targets that are coming straight at them, on a constant bearing."[23, 24] Next, because of constraints in HEL control systems, they are not always suited for area denial missions and can generally only engage one target at a time, reducing their ability to counter swarm attacks.[25] It is also possible to counter low-power HELs with shielding, reflective surfaces, or rotational attacks that prevent the laser from focusing on the target for the time necessary to cause sufficient damage.[26] Similarly, lasers must be powerful enough to disable or destroy a target, which requires a level of knowledge about target vulnerabilities. Finally, many experts acknowledge that HEL systems are still too heavy, too large, and do not possess enough power for widespread deployment.[27] Size, weight, and power (SWaP) constraints are one of the central obstacles to widespread adoption in the near term, especially in the air domain.[28] Interviewees also mentioned that the ability to address SWaP challenges is directly correlated with demand signal. Technological advancements are necessary for these issues to be addressed. However, according to interviewees, some advancements may have already occurred, and there is strong sentiment within DoD that DEWs will play a key role in the future.

Key Components of High Energy Lasers[29]

While HELs are highly complex systems that vary based on program and platform, there are several general components that are common amongst most systems. For the purposes of this report, these include:

Power Source: The power source, such as high-capacity batteries or generators, converts stored or generated energy into electrical power, supplying the laser system with the necessary electricity for sustained operation.

Laser Diode: The laser diode provides the initial light source that will be converted to a different wavelength and directed by subsequent components.

Lasing Medium/Gain Medium: The lasing medium, such as a solid crystal, optical fiber, liquid dye, or gas-filled chamber is responsible for amplifying the laser light through stimulated emission, producing a concentrated and powerful beam.

Doping materials: Doping materials, such as rare-earth elements or other chemical additives, are introduced into the lasing medium to alter its properties, enhance efficiency, alter the achievable wavelength range, or increase the power output of the laser system.

Optics: Optics in laser systems are instrumental in shaping and controlling laser light. They serve several crucial functions, including focusing laser beams, maintaining beam precision, and adjusting beam profiles for specific applications. Optics also contribute to the stability of laser output, ensuring controlled and consistent laser characteristics. Diffraction gratings are a critical optical component, which propagates light in the same direction to amplify effects.

Optical Coatings: Coatings, including anti-reflective, high-reflective, or protective coatings, are strategically applied to surfaces within the system to optimize light transmission, minimize losses from reflections, and safeguard sensitive components from damage caused by thermal or optical effects.

Beam Director: The beam director is the device responsible for precisely aiming and controlling the direction of the laser beam. Beam control and optical components manipulate the laser beam's trajectory, divergence, focus, or polarization, enabling precise targeting, adaptive optics correction, or beam shaping for specific operational requirements. DoD's research, development, testing and evaluation (RDT&E) funding priorities are shifting from laser sources to beam control due to the need for better technology in addition to the limited domestic expertise.[30 iv]

Tracking: The tracking system, often integrated into the beam director, employs various sensors and algorithms to continuously monitor and adjust the laser's aim, ensuring it remains accurately focused on a moving target. Fast steering mirrors, often made with high-quality reflective coatings, play a crucial role in reflecting, aligning, and steering the laser beam, maintaining beam integrity and precise propagation along the desired path, and are often used in conjunction with other optical elements to achieve the desired beam characteristics and control.

Cooling system: The cooling system employs various techniques, such as active liquid or gas circulation, to dissipate the significant heat generated during laser operation, preventing the degradation of components and maintaining stable performance.

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iii Typically defined as extending no more than 50 miles https://crsreports.congress.gov/product/pdf/R/R46564/9

iv There are two methods, which are both capable of combining large numbers of optical beams to enable high beam quality. First, there is spectral beam combining, where optical beams are directed at different angles, but made to overlap spatially on a diffraction grating, where the beams emerge on the opposite sides of the diffraction grating as a single beam. According to one industry interviewee, most of the HELs built for DoD are spectrally beam combined lasers. Second, coherent beam combining refers to a method of power scaling by positioning laser emitters side by side to form a single, spatially coherent larger aperture, which preserves the laser's spectral bandwidth. One industry interviewee noted that Israel's Iron Beam program uses coherent beam combining and said that the future of DEWs should employ this approach for beam combining. This is due to coherent beam combining's two primary benefits: 1) its ability to scale power and 2) enables the system to counteract atmospheric effects.

High Power Microwave Weapons

There are two primary types of HPM weapons being developed by DoD, continuous and pulsed wave.[31] Both versions deliver powerful microwaves in narrowband, wideband, or ultra-wideband, each of which have unique characteristics that make them suitable for specific operational scenarios.[32] Continuous-wave HPMs deliver a constant stream of microwave energy in a wide area and are best suited for area denial operations against personnel or small electronics, like unmanned aerial systems (UAS), whereas pulsed-wave HPMs deliver high power, short-duration pulses of microwave energy that provide high degrees of accuracy.[33] Overall, HPMs have the ability to "degrade or destroy" the electrical components of a target, and are well suited for both offensive and defensive operations.[34]

Like HELs, HPM weapons have the benefits of a large firing capacity, low cost per shot, rapid engagement times, and a graduated response capability.[35] HPMs can also destroy unshielded military and commercial electronic systems.[36] This makes them extremely effective at countering a major asymmetric threat: drone swarms. Additionally, some HPMs can produce wavelengths that target specific electronic systems, leaving others entirely unharmed.[37] This makes it possible to limit both physical and electronic collateral damage in highly populated urban environments.[38] These weapons are also far less vulnerable than HELs, to atmospheric disturbances, allowing them to be used in a wider array of environments.[39] Finally, HPMs provide a non-lethal option to deescalate potential threats, including people, before resorting to kinetic weapons and lethal force, potentially limiting unnecessary collateral damage.[40]

Despite their many advantages, HPMs also have unique limitations. For example, the wide HPM "cone" (See Figure 0.1 "Illustrative Effects of HEL vs. HPM Weapons") rapidly disperses and loses effectiveness over distance, making these weapons ill-suited for engaging targets such as hypersonic missiles or aircraft.[41] In some instances, HPMs can damage nearby friendly equipment, necessitating extra precautions to shield potentially vulnerable assets.[42] Substantial knowledge of the target is often necessary to apply an effective HPM solution.[43] This knowledge is essential given difficulties surrounding battle damage assessments (BDA) when using HPMs. The absence of visible damage to a targeted system may leave commanders unsure if a target's capabilities have been sufficiently degraded or destroyed, and this uncertainty may make officials reluctant to rely solely on HPMs until reliable BDAs can be ascertained.[44] Finally, like HELs, HPM weapons are still limited by SWaP constraints.[45]

Key Components in High Power Microwaves[46]

While HPMs are highly complex systems that vary based on program and platform, there are a number of general components that are common amongst most systems. For the purposes of this report, these include:

Prime Power: The prime power component provides the main electrical power required to operate the high power microwave system, typically sourced from batteries, generators, or power grids.

Pulsed Power Systems: Pulsed power systems are responsible for converting the continuous electrical power from the prime power source into high-voltage pulses, delivering short bursts of energy to the microwave components.

RF/Microwave Generators: The RF/Microwave generator generates and amplifies high-frequency electromagnetic waves, typically in the microwave range, which are essential for producing the high power microwave output.

Antenna: The antenna serves as the interface between the microwave system and the target. It radiates the high power microwave energy in a specific direction, allowing for the efficient transmission and focusing of the electromagnetic waves towards the intended target.

Tracking System: Similar to tracking in laser systems, tracking components in high power microwave systems employ sensors, detectors, and tracking algorithms to monitor the target's movement and maintain accurate alignment of the microwave beam. This enables effective tracking and engagement of moving targets.

U.S. Department of Defense Directed Energy Programs

Based on public sources, DoD has at least 31 unclassified DEW efforts underway across the various services, SOCOM, and DARPA.

Figure 0.2 Navy Initiatives

Program	Kilowatt	HEL/HPM	Description	Recent Activity
Laser Weapon System (LAWS)	30[47]	HEL	C-UAS[48]	Temporarily installed on the USS Ponce (2014)[49]
Optical Dazzling Interdictor, Navy (ODIN)[50]	Unknown	N/A (Dazzler)	C-UAS [51]	First installed on the USS Dewey (2020). There are eight total ODINs installed on eight DDG destroyers[52]
Solid-State Laser Technology Maturation (SSL-TM) Program[53]	150[54]	HEL	Produced Laser Weapons System Demonstrator: employed for C-UAS, Close-in defense and counter-ISR[55]	Laser transported from Redondo Beach, CA, to San Diego, CA, for installation on the USS Portland (2019). Operational Test occurred 2020, scheduled for de-installation in 2023[56]
Ruggedized High Energy Laser (RHEL)[57]	150[58]	HEL	Laser architecture to pursue incremental increased capability[59]	Initiative Complete[60]
Surface Naval Laser Weapon System (HELIOS project)[61]	60-150[62]	HEL + Dazzler	C-UAS, counter-ISR[63]	Expected sea trials Fall 2023, Expected operational FY 2023[64]
Layered Laser Defense[65] (LLD)	N/A	HEL	Close-in Defense, Counter-Cruise Missile (C-CM) C-UAS, C-ISR[66]	Successful test to defeat a target representing a subsonic cruise missile in flight occurred February 2022[67]
High Energy Laser Counter-Anti-Ship Cruise Missile Program (ASCM) (HELCAP)[68]	300+[69]	HEL	Anti-Ship Cruise Missile[70]	Currently underway; Testing in maritime environment (at Point Mugu and San Nicholas Island)'24-'25[71]
Bane[72]	N/A	HPM	No public information available	No public information available

Figure 0.3 USMC Initiatives

Program	Kilowatt	HEL/HPM	Description	Recent Activity
Compact Laser Weapon System (CLaWS)[73]	2, 5, 10[74]	HEL	C-sUAS[75]	Prototype testing reported 2019[76]

Figure 0.4 Army Initiatives

Program	Kilowatt	HEL/HPM	Description	Recent Activity
Mobile Expeditionary High Energy Laser (MEHEL)[77]	2, 5, 10[78]	HEL	C-UAS[79]	2.0 Version tested at White Sands Missile Range in 2017,[80] operational testing in 2018. Funding awarded to scale to 50 kw in 2019[81]
High Energy Laser Mobile Test Truck (HELMTT)[82]	10, 50-58[83]	HEL	C-UAS, M-SHORAD[84] Test for larger or smaller scaled system	Tested at White Sands Missile Range 2019[85]
High Energy Laser Test Vehicle Demonstrator (HELTVD)[86]	100[87], 300[88]	HEL	Air Defense, C-UAS[89]	Transition to Valkyrie program in 2022[90]
Directed Energy Maneuver Short Air Range Defense (DE M-SHORAD)[91]	50[92]	HEL	C-UAS, C-RAM[93]	Army Rapid Capabilities and Critical Technologies Office (RCCTO) recently delivered four DE M-SHORAD systems to the 4th Battalion, 60th Air Defense Artillery Regiment at Fort Sill.[94] Will transition to M-SHORAD Product Office in FY25[95]
Valkyrie Program[96] (IFPC-HEL)	250-300[97]	HEL	C-RAM/C-UAS[98]	Four prototypes due in FY 2024[99]
Palletized High Energy Laser (P-HEL)[100]	10, 20[101]	HEL	C-UAS[102]	Will integrate P-HEL into Infantry Squad Vehicles. First deployed operational HEL C-UAS capability[103]
Leonidas Program (IFPC-HPM)[104]	HPM[105]	HPM	C-UAS[106]	Ground-based Leonidas system unveiled in 2020; selected by RCCTO January 2023[107]
High Energy Laser Scaling Initiative (HELSI)[108]	300, 500 kw[109]	HEL	M-SHORAD[110] Counter-Cruise Missile Power scaling demonstrator	Delivered 300 KW laser to DoD for Indirect Fire Protection Capability High Energy Laser (IFPC-HEL), announced push for 500 kw in 2023[111] and 1 MW HELs in 2026[112]
Directed Energy Interceptor for Maneuver Short-Range Air Defense System (DEIMOS)[113]	50 kw[114]	HEL	M-SHORAD[115]	Successful laser demonstration (2023)[116]

Figure 0.5 Air Force Initiatives

Program	Kilowatt	HEL/HPM	Description	Recent Activity
Active Denial System (ADS)[117]	N/A	HPM	Anti-Personnel, Area Denial[118]	Operational systems developed.[119] Research continues[120]
Counter-Electronics High Power Microwave Advanced Missile Project (CHAMP)[121]	N/A	HPM	Electronic Warfare[122]	Unknown
High Power Joint Electromagnetic Non-Kinetic Strike (HiJENKS)[123]	N/A	HPM	Electronic Warfare[124]	Testing summer 2022[125]
Phaser High Power Microwave System [126]	N/A	HPM	C-UAS[127]	The Air Force purchased one prototype for $16.28M in 2019. Field testing announced to end by Dec. 20, 2020[128]
Tactical High Power Microwave Operational Responder (Mjölnir)[129]	N/A	HPM	C-UAS[130]	Contract for Mjolnir Awarded in February 2022.[131] Dynamic test of THOR occurred May 2023[132]
Counter-Electronic High Power Microwave Extended-Range Air Base Defense (CHIMERA)[133]	N/A	HPM	Extended-Range Air Base Defense (C-UAS)[134]	Contract awarded in 2020, further testing planned.[135] Dynamic testing may have occurred previously[136]
Self-Protect High-Energy Laser Demonstrator (ShiELD)[137]	50+[138]	HEL	Airborne C-RAM[139]	Prototype tested, first flight test expected in FY 2024[140]
Hybrid Aero-Effect Reducing Design with Realistic Optical Components (HARDROC)[141] (supports ShiELD)	N/A	HPM	Proof of Concept from Airborne HEL[142]	Flight test May 2023[143]
High-Energy Laser Weapon System (HELWS)[144]	10	HEL	C-UAS	Fourth system was delivered for field evaluation in June 2023

Figure 0.6 U.S. Special Operations Command Initiatives

Program	Kilowatt	HEL/HPM	Description	Recent Activity
Airborne High Energy Laser (A-HEL)[145]	60[146]	HEL	Offensive Electronic Warfare and Counter- Cruise Missile[147]	Will complete flight test activities and demonstration of a HEL system on the AC-130J in FY24[148]

Figure 0.7 DARPA Initiatives

Program	HEL/HPM	Description	Owner	Recent Activity
Modular Efficient Laser Technology (MELT)[149]	HEL	Improvement of beam quality, creating more scalable devices[150]	DARPA	Research, Testing and Evaluation in Progress, Completion expected October FY 2024[151]
Waveform Agile-Radio-frequency Directed Energy (WARDEN) [152]	HPM	Improvement of lethality and ranged attack[153]	DARPA	FY23 Plans: Develop high current electron gun and high power, broadband amplifier designs and verify them through 3D simulation[154]
Humboldt[155]	HPM	Counter Electronic[156]	DARPA	FY23 Plans: Develop initial designs of prototype proof-of-concept devices. Characterize the baseline performance of critical materials.[157] FY24 Plans: Demonstrate effectiveness of the proof-of-concept devices on electronic systems[158]

DEW FY24 Budget Information

DoD's FY24 President's Budget Request for directed energy weapons totals $917.2M, which includes S&T, system and defense technology development, industrial base efforts, and testing and evaluation investments.[159] This is divided across the military services, the Missile Defense Agency (MDA), the Joint Intermediate Force Capabilities Office, the Joint Directed Energy Transition Office, DARPA, Special Operations Command, and the Test Resource Management Center. While a full budget analysis of DoD spending on DEWs is beyond the scope of this paper, a few notable items are included below.

According to interviewees, the Army is the closest service to production and this is reflected in the budget request. It decreased its request for RDT&E money for the IFPC HEL ($85.852M in FY24 and $215.343M in FY23) and IFPC HPM ($11.166M in FY24 and $42.977M in FY23) programs due to the Army transitioning from engineering, long-lead purchases, and sub-system integration to prototype integration and delivery. It should be noted that the IFPC HPM system is common with other service efforts. The Army's DE M-SHORAD program ($110.625M in FY24 and $197.279M in FY23) is also beginning to transition from prototyping to production, with an anticipated transition to the M-SHORAD Product Office in FY25. The Army is also funding efforts to prepare the defense industrial base, which will be discussed in more detail in chapter 2.

The Navy's largest RDT&E request in the FY24 PB is $52.129M for its Directed Energy and Electric Weapon Systems technology Program Element, which states that it will transition from S&T research to the Technology Maturation and Risk Reduction Phase, leading to acquisition initiation. However, many of its projects are focused on assessing technical challenges, such as atmospheric propagation characterization and beam control, engagement modeling, lethality, and laser weapons concepts of operation (CONOPS). There is also funding to support operations and sustainment, which includes the procurement and/or production of repair parts as well as routine cybersecurity and software upgrade installments. One interviewee noted that integration for the Navy's HELIOS program is taking longer than expected due to the rushed integration of the Navy's SSL Technology Maturation program. Like the Army, the Navy has funding efforts to support the defense industrial base, which will be discussed in more detail later in chapter 2.

The Air Force is working to determine how directed energy weapons fit within Air Force operational concepts. This is reflected in the minimal prototyping funding ($1.246M) in the FY24 PB request. Air Force funding ($129.961M) is primarily focused on assessing how directed energy weapons meet Air Force needs as well as researching how to protect against directed energy weapons.

Special Operations Command requested $3M to complete flight test activities and demonstration of an HEL system on the AC-130J for special operations. DARPA's FY24 Presidential Budget Request is $37M, which includes funding for components with potential directed energy weapon applications. Currently, DARPA has two primary programs: Waveform Agile-Radio-frequency Directed Energy (WARDEN), which requested $20M for FY24, and Humboldt, which requested $17M.[160] DARPA's WARDEN program aims to extend the range and lethality of high power microwave (HPM) systems by developing and demonstrating the first broadband HPM amplifier among other novel waveform techniques. WARDEN's FY24 plans include demonstrating broadband amplifier power, bandwidth, and pulse duration performance at low repetition rates as well as disruptive agile waveform techniques on integration electronics. The Humboldt program builds on the WARDEN program and "seeks to develop directed energy devices to produce disruptive effects in electronic systems."[161]

While the MDA did not request RDT&E funding in its FY24 budget for directed energy weapons, there are several updates worth noting. MDA is completing its Directed Energy Demonstrator Development project. Its FY23 plans continue the transition of laser technology out of Lawrence Livermore National Laboratory to industry and the assessment of laser weapons to augment the layered defense capability of the Missile Defense System.[162] The project also includes the development and demonstration of a prototype with a direct diode laser in addition to a domestic battery-based power supply that can support all ground and ship DEW systems. Following the invasion of Israel by Hamas in October 2023, the Biden administration requested $1.2 billion in research, development, test and evaluation funding for Iron Beam which, if approved, would represent the most substantial U.S. investment in Israel's directed energy capabilities to date.[163]

While the above efforts by the U.S. government are a step in the right direction, there is still much work to be done. If the U.S. is committed to incorporating DEWs into its arsenal at scale, an important question that must be answered today is: what steps must be taken to ensure the DEW supply chains of the future are resilient and secure?

Foreign Directed Energy Programs

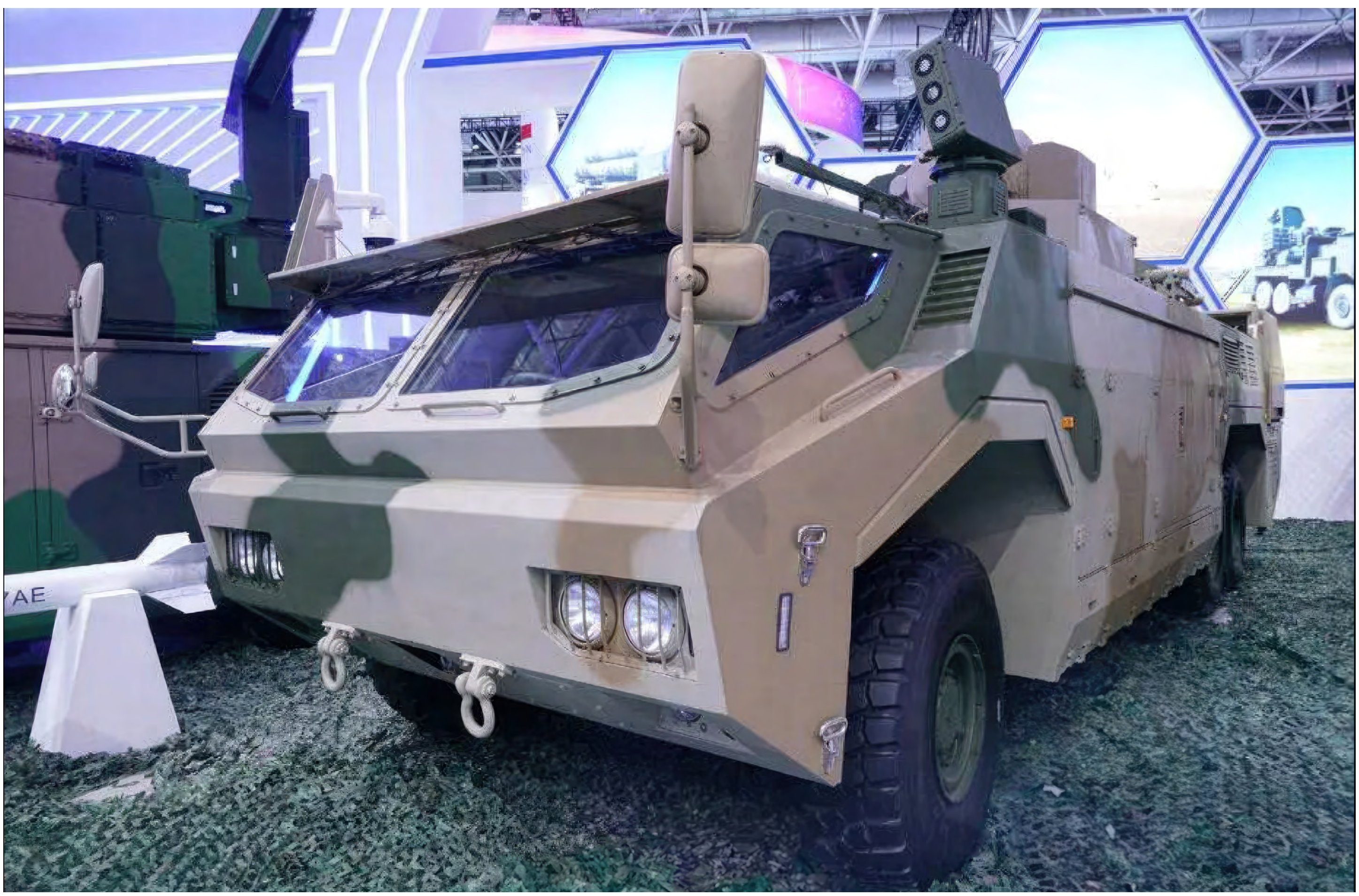
Chinese Directed Energy Programs

China has been developing DEWs since at least the 1980s and continues to make advancements.[164] While many reports regarding technical success are undoubtedly exaggerated and may simply be propaganda, it is unquestionable that China is undertaking serious efforts to expand and improve its directed energy capabilities. Some reports allegedly indicate that a Chinese research team developed a 1-megawatt pulse laser capable of being fielded on a small satellite.[165] Other reports indicate possible breakthroughs opening the door to lasers with "an output more than 10 times the capacity of the world's largest nuclear power plant."[166] China allegedly has both vehicle mounted and handheld DEWs.[167] One of its newest vehicle mounted systems, the LW-30, is a 30-kilowatt HEL weapon that "can strike unmanned systems below an altitude of one kilometer and speed of around 200 kilometers per hour. It can also neutralize drones with a radar cross-section smaller than one square meter."[168] Less powerful DEWs with a similar purpose have been tested in previous years, namely the Low Altitude Guardian system with a rating of 10 kilowatts and a maximum estimated range of 2 miles.[169] An additional truck mounted counter-UAS system, dubbed the Silent Hunter, is also reportedly under development, with a range of 4 kilometers at 30kWs.[170] One of China's first alleged developments in handheld DEWs was likely the now-banned ZM-87.[171] This weapon supposedly fires a 15-milliwatt neodymium laser and is allegedly capable of permanently damaging eyesight at ranges of up to 3 miles.[172] The Chinese military may also be in possession of handheld weapons designed to target electronic sensors, including the BBQ-905.[173] This weapon supposedly has a maximum strength of two hundred millijoules that can be fired in short bursts at a range of 1km.[174]

Along with HEL capabilities, China has also potentially made progress on HPM weapons. Reports indicate that China has developed the WB-1, an anti-personnel area-denial system similar to the U.S. Active Denial System (ADS).[175] Some news reporting indicates that this weapon might have been used against Indian troops in border disputes.[176] Other news reports allege that since 2018, Chinese destroyers have had operational DEW capabilities.[177] Future Chinese DEW development may be aimed at enhancing China's asymmetric ability to counter U.S. superiority in space.[178] While the deployment of space-based DEWs may still be limited, China's estimated $8.9 billion civil space budget could facilitate substantial progress in the miniaturization of DEWs and their energy sources, both of which are impediments to successful satellite installation.[179]

Russian Directed Energy Programs

Like the United States, Russia began researching DEW technology in the 1960s.[180] Despite this early investment, many of Russia's DEW projects did not materialize into deployable weapons, and others were paused after the fall of the Soviet Union.[181] Despite these setbacks, early developments provided foundational knowledge for Russia to potentially field several advanced DEW systems, with more planned. Some Russian DEWs are intended to counter U.S. space-based assets.



LW-30 Chinese laser defense system. CASIC

This is often done using "dazzler" style laser weapons. For example, the Peresvet system is an ASAT (anti-satellite) directed energy weapon potentially deployed with five Russian strategic missile divisions, including possibly in Ukraine.[182, 183] The Peresvet is intended to blind the optical tracking systems of both drones and satellites, thereby obscuring the movements of strategic missiles.[184] The newer Kalina laser, part of the Krona space surveillance complex, also carries an ASAT function similar to that of Peresvet.[185] Along with ground-based ASAT DEWs, Russia is also developing airborne ASAT capabilities. For example, the Sokol-Echelon laser system would allegedly be mounted on an A-60 aircraft to target sensors on reconnaissance satellites, harnessing the 1LK222 laser.[186] Russia has also potentially made advances in HPM technology. Rumors of early HPM weapons began with the Moscow Signal, a suspected microwave weapon allegedly targeting U.S. embassy personnel from the 1950s to 1970s.[187] Some reports indicate Russia will attempt to arm sixth generation combat drones with microwave weapons.[188] While the deployment of some Russian DEWs has been confirmed, some weapons may reside in the realm of propaganda.[189] The Russian government has claimed the Zadira is active in Ukraine and "is capable of incinerating targets up to three miles away within five seconds."[190] Despite these claims, no evidence of the Zadira has been reported publicly by the U.S. or its allies.[191] Although Russian space initiatives receive only a fraction of the funding granted to U.S. and Chinese programs, a recent Defense Intelligence Agency report indicates that by the mid-to-late 2020s, Russia may field DEWs that are capable of damaging satellites.[192,193]

Figure 0.8 Chinese Programs

Program	Energy and Type	Description
LW-30[194]	30 KW HEL[195]	C-UAS weapon[196]
Low Altitude Guardian[197]	10 KW HEL[198]	C-UAS weapon, 1-2 mile range[199]
Silent Hunter[200]	30 KW HEL[201]	Truck-mounted C-UAS, 2½ mile range.[202]
ZM-87[203]	15 mW HEL[204]	Blinding device[205]
BBQ-905[206]	200 mJ HEL[207]	Handheld anti-ISR sensors[208]
WB-1[209]	HPM[210]	Anti-personnel Area Denial, up to 1km range[211]
Unknown name	1 MW Pulse Laser[212]	On-orbit ASAT

Figure 0.9 Russian Programs

Program	Energy and Type	Description
Peresvet[213]	HEL[214]	Ground-based blinding ASAT[215]
Kalina[216]	HEL[217]	Ground-based blinding ASAT[218]
Sokol-Echelon[219]	HEL[220]	Airborne ASAT[221]
Zadira[222]	HEL[223]	C-UAS, possible anti-personnel or counterbattery applications, claimed 3-mile range[224]

Chapter 1: Critical Raw Materials and Goods

Key Topics

- Critical Raw Materials for High Energy Lasers
- Critical Raw Materials for High Power Microwave Weapons
- Critical Raw Materials for Overlapping Components

Assessment of the Sector

The availability of critical raw materials and goods plays a vital role in numerous sectors but especially in the U.S. defense supply chains, and in the production of directed energy weapon systems. While the materials covered in this chapter have applications across many sectors and technologies, they are also critical for DEWs. Current HEL and HPM supply chains face multiple vulnerabilities, including foreign dependency, sole source dependencies, and capacity constraints. Although additional vulnerabilities may exist, this chapter will highlight those most pressing as well as provide recommended solutions to establish healthy and resilient DEW supply chains for the future.

Critical Raw Materials for High Energy Lasers

While HELs are highly complex systems with numerous components, this section will address a few critical materials for some of the general components that are relatively standard across systems. Overall, a number of vulnerabilities exist including Chinese dominance in the supply of rare earth elements, gallium, germanium (both of which are currently restricted by China), and other critical materials, as well as supply issues for materials needed for silica production.

Lasing Medium and Doping Materials

Rare Earth Elements

Rare earth elements are critical to a host of national security technologies, including directed energy. Solid-state and fiber lasers generally rely on crystalline or glass gain mediums to amplify light.[225] These mediums use doping materials which add impurities and thereby give the medium its desired properties and characteristics.[226] Advantages provided by these materials include stability, high optical quality, and excellent thermal conductivity.[227] The doping agents used in HELs are primarily rare earth elements, including neodymium (Nd), erbium (Er), thulium (Tm), and ytterbium (Yb).[228] Ytterbium is most commonly used in fiber lasers.[229] The U.S. is reliant on China for REE mining and processing, thus posing a direct vulnerability to numerous defense and non-defense applications, including directed energy weapons. According to the U.S. Geological Survey data, Chinese exports of refined rare-earth metals accounted for 74% of U.S. rare-earth imports from 2018-2021.[230] China not only mines the minerals, but also controls more than 85% the world's processing capacity, resulting in substantial power over materials that underpin a host of critical technologies.[231] Interviewees noted that the rare earth elements used in DEW systems represent a vulnerability in the supply chains. Generally, rare earth elements have repeatedly been identified as a major issue in both commercial and defense supply chains, including in the first iteration of ETI's supply chain study focusing on hypersonics. Since the publication of that report in May 2023, there have been notable changes in the U.S. rare earth supply chain.

First, MP Materials announced the first production of refined neodymium-praseodymium oxide from their newly commissioned rare earth separation plant in Mountain Pass, CA.[232] This plant, which has partial funding from DoD's Defense Production Act (DPA) Title III program, will allow MP Materials to produce separated and refined rare earth oxides without shipping material to China. Second, DoD's Office of the Assistant Secretary of Defense for Industrial Base Policy, through its Manufacturing Capability Expansion and Investment Prioritization (MCEIP) office, issued a $94.1 million award to E-VAC Magnetics to establish a domestic rare earth permanent magnet manufacturing capability.[233] As noted elsewhere in this report, specialized magnets are a critical component of numerous military systems including HPMs. Rare earth permanent magnets are the largest rare earth element application by market value-add, according to a subject matter expert. China currently dominates production of these magnets, which have critical electrification and national security applications. The U.S. was previously a global leader in rare earth permanent magnet production, but lost all capabilities as the rare earth market moved off-shore. E-VAC will join MP Materials, Noveon (another DoD DPA awardee), and other companies working to re-establish domestic production. Third, Australian firm, Lynas, signed an updated $258M contract with DoD to establish rare earth separation capacity in Seadrift, TX.[234] This facility will produce separated rare earth oxides for downstream customers in the commercial and national security sector. The capabilities will expand and complement Lynas's existing product line, which is currently produced in Malaysia.

As noted, some steps have been taken to address this vulnerability including activities aimed at increasing domestic mining and refinement.[235] While these recent developments are encouraging, mining and processing capabilities take time to reach full capacity and much more work remains.

Silicon

Silica glass, a derivative of silicon, is a key element in the construction of the optical fiber cable used as the gain medium in fiber lasers.[236] Notably, silicon is also used in laser optics, diffraction gratings, doping agents, laser diodes, coatings, and mirrors.[237] It can take the form of silicon carbide, fused silica, silicon nitride, or other silicon based materials, some of which occur naturally and some of which are synthetic.[238] Multiple working group participants and interviewees raised high purity fused silica as a concern since the DEW industry relies on a single company.[239] Silica originates from industrial sand and gravel, which is produced by 122 companies from 201 operations in 32 states as of 2023.[240] 87% of U.S. domestic consumption and sales originate from these companies, indicating a highly diverse supply chain.[241] Only 10% of this sand and gravel is used as glass-making sand, with the largest percentage being reserved for hydraulic fracturing.[242] Of the industrial sand and gravel that is imported, 87% currently comes from Canada.[243] Despite widespread domestic production and reliable imports from allied nations, a widespread shortage of industrial sand and gravel may become a vulnerability as global supplies of usable sand are depleted. While it is easy to think of sand as a limitless resource, it is the world's second most consumed raw material after water and is drawn from specific reserves such as riverbeds, coastlines, and quarries that are rapidly being depleted.[244] As this depletion accelerates, natural forces are unable to replenish the diminishing global supply.[245] Demonstrating the extent of the issue, the World Bank recently reported that the silica sand industry has been contracting for the last two years due to lack of industrial sand and gravel supply.[246] Substitutes for silica sand, such as quartzite rocks, exist but often come with trade-offs in the quality or expense involved with the final product.[247] Therefore, due to reliance on a single company and potential shortages in production materials, silicon and its derivative materials pose a significant vulnerability to DEW supply chains.

Optical Coatings

The primary function of lens and mirror coatings in HELs is to protect components from degradation and improve performance.[248] Some coatings, like hafnium oxide, have better resistance to damage, and may present more utility for HELs intended for deployments in harsh conditions.[249] Coatings are highly specific to their intended uses and there is currently little consensus on a particular coating for the broader HEL industry. Some current and potential coating materials include: silicon dioxide, aluminum oxide, hafnia, scandia, and ytterbium.[250, 251] This list is not comprehensive. Depending on their composition, some of these materials may experience greater supply chain vulnerabilities than others, but, until coatings become more standardized, it is beyond the scope of this paper to evaluate each one in turn. The manufacturing of these coatings is highly specialized and will be discussed more in chapter 2. Of note, one industry interviewee highlighted that there is only one commercial supplier developing optical coatings to improve laser damage threshold using higher bandgap materials in the coating design. Between this and the lack of standardization of coatings, much more work remains to secure this link in DEW supply chains.

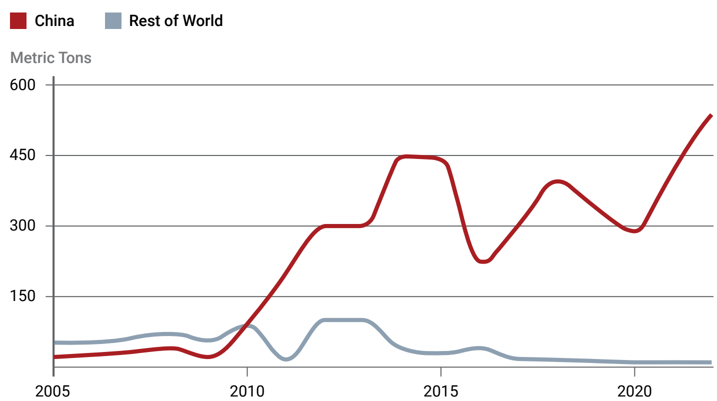
Laser Diode Pumps

Gallium

Gallium has many commercial and military uses but is commonly used in the construction of semiconductor lasers, also known as diode lasers.[252] The laser diode is often made of two doped gallium arsenide layers.[253] Of note, solid-state microwave emitters for HPMs are also most commonly made of gallium nitride (GaN).[254] Gallium arsenic (GaA) is also used in the process of tuning the HPM microwave emitter, as is barium titanate.[255] Gallium is recovered primarily as a byproduct of bauxite and zinc ores, with notable quantities produced during aluminum production.[256] As of 2023, the main domestic use (74%) of gallium is for integrated circuits, while optoelectronic devices, including the laser diodes used in HELs, are the second largest end use of this material, making up 25% of overall consumption.[257] Research and development projects make up the remaining 1% of usage. Alarmingly, "U.S. production of gallium metal is restricted to one New York company which processes a mix of scrap and imported low-grade primary feed," and there is currently no U.S. government stockpile of gallium.[258] The U.S. currently imports 53% of its gallium from China. China controls 98% of the global gallium market, producing 540,000 kilograms of unrefined gallium in 2022 compared to the rest of global production at 10,000 kilograms.[259]

In summer 2023, China announced export controls on gallium beginning on August 1, 2023. The export controls mean that gallium will be subject to "a license system for national security reasons,"[260] and the Chinese government will now have to approve the export of this critical materials. When China first made the announcement, the price of gallium jumped 20% in the U.S. and Europe.[261] Since the announcement, there has been much speculation on possible repercussions due to potential gallium shortages. Some interviewees confirmed a drastic price increase and expressed concern about being able to source gallium due to the controls. Others said the announcement was concerning but they still felt confident they could source gallium as long as they could plan far enough in advance.

Figure 1.1 Global Primary Gallium Production[iv]



While China dominates the gallium market, Japan is also a key player with existing facilities to refine, recycle, and produce gallium.[262] Japan does have some reliance on Chinese gallium exports, while other facilities are completely insulated from China. It is clear that in the short term, gallium prices will increase and it may be harder to source, thus negatively impacting DEWs. However, only time will tell the long-term impacts. On the one hand, the export controls may actually spur other countries to restart or begin production of gallium.[263] China's dominance in this market is recent, occurring due to a widespread gallium surplus in the 2010s which was caused by China's explosive growth in the industry and which forced international production to drastically decrease.[264] (See figure 1.1) In comparison, Germany, Canada, and Ukraine all produced similar quantities of gallium to China prior to 2010, indicating potential candidates for renewed gallium production[265] On the other hand, the export restrictions could act as an incentive for manufacturers requiring these materials to move their manufacturing facilities into China, as has happened in the past. According to one interviewee, this scenario unfolded following the 2010 Chinese Rare Earth export restrictions as Japanese rare earth magnet firms created joint ventures with Chinese manufacturers within China in order to gain access to low-cost raw materials and the large Chinese manufacturing sector.

v Data Source: U.S. Geological Survey. Graph Originally Produced by CSIS (https://features.csis.org/hiddenreach/china-critical-mineral-gallium/).

Further stressing already limited supply chains, sales of high-performance chips using gallium nitride are expected to climb from the current level of $2.47 billion to $19.3 billion by 2030, and those produced with gallium-arsenide are expected to grow from $1.4 billion to $3.4 billion in the same time frame due to rapidly increasing demand for AI, electric and autonomous vehicles, and other emerging technologies.[266] In sum, gallium is a significant vulnerability in the DEW supply chains.

Optics and Beam Control

HEL weapons require advanced optics to focus, shape, amplify, and manipulate the beams of energy they produce. Interviewees raised germanium, silicon, and some synthetic materials as common for advanced optics for HELs.

Germanium

Germanium is one of the primary materials used in infrared optics. Lasers working at wavelengths other than infrared use more conventional glass and tend to avoid many supply chain issues. Despite its importance, germanium is sourced primarily from China. As of 2023, 54% of imported germanium comes from China.[267] A primary source of domestic production is recycled germanium from decommissioned military equipment.[268, 269] Overall, 30% of current global germanium supply comes from recycled sources.[270] According to an expert in the optics industry, the supply chain of germanium also passes through Germany and Belgium, making the original source, often China, less obvious. In some cases, DoD issues waivers to approve the direct use of germanium sourced from China. China announced in summer 2023 new export controls on germanium beginning on August 1, 2023.[271] Similar to gallium, the Chinese government will now approve the exports of germanium "for national security reasons."[272] Reports indicate that the licenses necessary for exporters of germanium (and gallium) could take months to acquire, and it is unclear how many will be granted.[273] Again, only time will tell the impact of the export controls, but it is clear in the short term that prices will increase and customers will likely face long lead times.[274] Given the existing U.S. dependency on Chinese-sourced germanium, these export controls could damage the defense industry's ability to produce the optics for DEW systems, as well as other key defense components, including high-speed chips, night vision devices, satellite imagery sensors, and thermal sensing devices.[275,276,277] The United States does keep a reserve of germanium in the national defense stockpile, but these reserves are only meant to provide resources in the event of a national emergency and are not a long-term solution to addressing this DEW supply chain vulnerability.[278, 279]

Synthetics

Synthetic materials, often with proprietary formulas, were raised by interviews as an alternative option for HEL optics and several interviewed companies either fully or partially rely on synthetic materials for their optical production. According to one optical expert, these synthetics are often used in telescopes and other common consumer devices, in addition to defense applications. However, many of these materials are sourced from overseas. Even if onshoring production became a priority, it would likely take several years to complete this process, and both the business case and demand signal would have to be thoroughly established and communicated to justify doing so. Industry interviewees also said that it can be difficult for suppliers to convince manufacturers and the government to adopt a material that may be unknown or more expensive than overseas-sourced alternatives. However, the development of synthetics with superior characteristics that help achieve SWaP goals, and can also achieve similar performance and efficiency, may begin to accelerate the adoption of these materials in the future, all while reducing reliance on China. Overall, synthetics provide a potential alternative to reduce risk in optics for HELs, however, more work remains.

Adaptive Optics

The two key components in adaptive optics are the deformable mirrors and the wavefront sensor.[280] According to interviewees, the mirrors used in adaptive optics systems are predominantly made of materials like silicon, silicon nitride, or piezoelectric materials such as lead zirconate titanate or lead magnesium niobate-lead titanate. Silicon, discussed earlier in this chapter, is a key element in the construction of both deformable mirrors and wavefront sensors.[281] The wavefront sensor usually includes optical components made of glass or other materials, and a semiconductor that is likely silicon-based. The global market for wavefront sensors is expected to cross $4 billion by the end of 2031, indicating substantial growth over its 2020 value of $536 million.[282] Considering the diverse optics markets, including microscopy, astronomy, and ophthalmology, that take advantage of wavefront sensors, this market will have a reliable and expanding demand signal in the coming years that will not depend solely on the defense sector for its sustainment.[283] The adaptive optics market as a whole will likely see similar growth, expanding from a $281 million market value in 2021 to an estimated $3.24 billion by 2030.[284] The prevalence of this technology in a variety of fields should create a consistent commercial and defense demand signal, benefiting the maintenance of stable supply chains, including for DEWs.

Gimbal and Tracking System

The gimbal is the central component linking the weapon system to its platform, allowing it to move and engage targets. Gimbals are precision electromechanical devices, and also have to be large and move significant mass quickly and stably. Although there are a number of vendors who could produce them, the market for HEL beam director gimbals is so small and the precision required so high that only a few companies are willing to accept orders. The beam director, which is a combination of a mechanical metering structure and large precision optics with HEL coatings, presents another critical vulnerability which will be discussed in more depth in chapter 3. Tracking and software components of directed energy weapons rely on traditional electronic resources such as silicon-based semiconductors.[285] The vulnerabilities of these are addressed earlier in this chapter and in Chapter 2.

Thermal Management

HEL weapon systems require large amounts of power, and therefore generate substantial heat as a byproduct. If left unchecked, this heat could severely hamper or even damage the system. HEL solutions generally draw from common commercial and defense cooling applications, according to interviews with subject matter experts. Both the Army and Navy are continuing to conduct basic and applied research as well as technological development of thermal management systems for directed energy capabilities. Their research focuses on investigating new materials and methods for controlling thermal transients and improving thermal transfer characteristics to reduce the size and weight of thermal management components while increasing the energy magazine of DEW systems. For example, the Army received a Congressional addition of $12M in FY22 to improve laser diode fiber amplifier cooling among other things.[286] Existing thermal management solutions commonly use ammonia, aluminum, and copper (amongst others). Aluminum is discussed later in this chapter, so this section will focus on ammonia and copper.

Ammonia

Ammonia has a long and proven history as an effective industrial grade refrigerant, and, given its low cost and high efficiency, will likely serve as a primary coolant for DEW systems.[287] As of 2021, 88% of domestic ammonia consumption is for fertilizer use, and global demand for ammonia will likely continue to increase.[288] The U.S. has a substantial and well-established ammonia supply chain with production taking place at 35 plants in 16 different states.[289] Further, domestic ammonia production has been steadily increasing in the past decade, rising 46% from 11.6 million metric tons per year (mt/y) in 2015 to 17.0 million mt/y in 2020.[290] This has also led to a decrease in imported ammonia, dropping from 40% in 2010 to 13% in 2020.[291] Given current production capacity and the easily accessible inputs to ammonia production, there is little indication that ammonia will be a vulnerability in future DEW supply chains.

Copper

Copper is an excellent conductor of heat and has been used in various thermal management systems for years.[292] The U.S. is the fifth largest producer of copper in the world, with 1.3 million metric tons produced in 2023, a 6% increase over the previous year.[293, 294, 295] The U.S. is also a top ten exporter, shipping ores, concentrates, and refined copper around the globe. There are currently 25 domestic copper mines, 17 of which account for 99% of mining production.[296] The U.S. also imports large amounts of refined copper, 95% of which comes from Canada, Mexico, and Chile, representing fairly low geopolitical risk.[297] Despite this stable supply of copper, the process of turning ore into a refined and usable product is a major vulnerability. There are currently only 3 copper smelters in the United States, compared to 14 in China.[298] As of 2022, 41% of all refined copper originates in China.[299] The global demand for copper is expected to radically accelerate in the coming years due to both traditional and new sources of demand, including construction and renewable energy.[300] Within the U.S., copper demand is projected at three times the supply by 2035, and globally there is an expected 6.5 million ton shortage by 2030.[301, 302] Due to its ability to both mine and refine substantial amounts of ore, China will likely continue to grow as a major industry player, thus potentially introducing risk into the DEW supply chains. Another issue raised by an interviewee was the challenge in permitting domestic copper mines and smelters. While ETI's Hypersonics Supply Chain Report discusses the issue of permitting and regulations further, projects like Resolution Copper in Arizona, have been unable to move beyond permitting. With the potential for China to become a major industry player combined with the mining and smelting permitting challenges faced in the U.S., copper may introduce significant risk into DEW supply chains in the future.

Critical Raw Materials for High Power Microwave Weapons

While HPMs are also highly complex systems, this section will assess some of the most critical raw materials needed for relatively standard components.

Pulsed Power

According to interviewees, the pulsed power source in HPMs is generally derived from a variation of a Marx generator.[vi] The materials used in Marx generators need to withstand the high voltages involved, and generally include ceramics, particularly barium titanate, amongst others.

Barium Titanate

Barium titanate is a synthetic crystalline material created through the processing of barite and titanium. It has a variety of uses.[303] In HPMs it is used as a ceramic capacitor. Exact domestic production numbers are difficult to come by due to sensitivities around proprietary data. Of the imported barite in 2023, 39% came from China. India, Morocco, and Mexico make up the majority of the remaining supply.[304] While the U.S. has a domestic barite industry, reliance on China for some imports and significant demand from the hydrocarbon industry makes this resource a vulnerability in the HPM supply chain. Titanium has two notable supply chains: 1) titanium mineral concentrates and 2) titanium sponge.[305] ETI's previous supply chain report on hypersonics[306] included additional details on titanium and assessed that while titanium is a relatively stable component, limited domestic production and heavy foreign dependency brings potential vulnerabilities. In the long-term, the U.S. should consider the economic feasibility of restarting domestic production of titanium and expanding domestic production of barium to eliminate the potential for disruptions and ensure stable directed energy supply chains.

Antenna

Aluminum

According to interviewees, the dipole antenna is commonly featured in HPM applications. Aluminum is the primary material used in the construction of antennas due to its light weight, strength, conductivity, and resistance to corrosion.[307] However, the aluminum industry faces challenges, the majority of which were documented in ETI's hypersonics report.[308] An ongoing pandemic-fueled global aluminum shortage will likely affect aluminum supply chains for several years. Additionally, the U.S. aluminum industry experienced substantial decline in the previous decade, going from 23 operating smelters to only 1 in 2017.[309] Currently, there are six primary aluminum smelters spread over five states.[310] Despite this increase, there is likely still limited capability in the U.S. to produce the high-quality aluminum required for defense and aerospace applications. However, DoD announced in June 2023, an award to Arconic Corporation to increase their capacity of this critical material.[311] [312] Notably, during DEPS' 2023 Science and Technology Symposium, a service representative noted the need for improved materials for radomes, which are the dome-shaped structures connected to the antenna. Reliance on allies for a substantial portion of aluminum imports, well-developed recycling capabilities, and efforts to boost domestic production leave some room for optimism about long-term aluminum security, and their impact on HPM supply chains.

vi A Marx generator is a type of electrical circuit whose purpose is to generate a high-voltage pulse by a number of capacitors that are charged in parallel and then connected in series by spark gap switches.(https://www.idc-online.com/technical_references/pdfs/electronic_engineering/Marx_Generator.pdf)

Critical Raw Materials for Overlapping Components

Although HEL and HPM weapon systems require unique components tailored to their specific use case, some aspects of these weapons, especially power supply, have significant overlap and require similar input materials.

Power Source

Aside from systems that have unique energy density requirements, particularly those used by the Air and Space Force, DEWs are generally powered by off-the-shelf, commercially available lithium-ion batteries certified to meet defense requirements.[313] Critical raw materials used in these batteries include lithium, graphite, cobalt, nickel, and manganese, amongst others.[314] According to a battery expert, these batteries are primarily sourced from China, with many U.S. companies purchasing and repurposing them for use in DEWs. The same expert stated that the U.S. does possess some capability to manufacture these batteries domestically, however the cost per battery would likely increase by 2 to 3 times. The lack of demand for domestically-sourced batteries has led some domestic production facilities to only operate at 10% capacity. Further, DEWs compose a very small share of the overall market and are not drivers of overall battery demand compared to consumer electronics and electric vehicles. Because of this, any realistic scaling of DEW production in the foreseeable future is unlikely to drive the production of domestically sourced batteries on its own and will need to leverage investments made in domestic battery sources by other industries. As such, the DEW community will need to convey and coordinate power requirements for DEW applications across the services and interagency partners, especially the Department of Energy.

Lithium

The large power requirements of DEWs call for high efficiency power sources. DEWs experience drastic power fluctuations and must maintain a readily available source of stored energy to operate efficiently. This typically comes from a rechargeable lithium-ion battery. These high-density batteries are used in consumer electronics, electric vehicles, and aerospace and military applications, including directed energy, due to their longevity and relatively low maintenance requirements. As of 2023, only one commercial-scale production facility for lithium exists in the U.S. and the majority of lithium is supplied from foreign countries.[315] The growing demand for electric vehicles will also likely have a significant impact on global lithium consumption. DoD will also have to compete with the dominant consumer market which uses lithium for a wide variety of rechargeable electronics.[316] While 91% of U.S. lithium imports came from Argentina and Chile, from 2018-2021, U.S. companies continue to purchase a majority of their lithium-ion batteries from China, which dominates the global battery manufacturing market.[317] China currently produces 75% of all lithium-ion batteries and is home to 70% of production capacity for cathodes and 85% for anodes.[318] Over half of lithium, cobalt, and graphite processing and refining capacity is located in China.[319] However, DoD recently announced a $90M DPA agreement to Albemarle for the establishment of domestic lithium production.[320] This funding is an addition to a previous $150M award and will re-open a hard-rock deposit in Kings Mountain, North Carolina.[321] The Albemarle production facility is anticipated to begin production between 2025 and 2030.[322] While this development is a good step towards securing future supply chains, DEW supply chains still face significant risk due to current reliance on China.

Graphite

Graphite, a crystalline form of carbon, is a highly versatile mineral that exhibits both metallic and non-metallic properties. Graphite is known for its stability, high thermal and electrical conductivity, and ability to survive high temperature environments.[323] One of the primary applications of graphite is in energy storage systems, particularly in lithium-ion batteries.[324] While much attention is paid to the cathode materials - lithium, cobalt, manganese, and nickel - the vast majority of anodes are made using graphite material.[325] Its excellent conductivity properties enable higher capacity and longer-lasting battery performance, making it an essential component in portable electronics, electric vehicles, and renewable energy storage.[326] Because graphite is such a versatile material, it has a wide range of applications and can be found in nuclear reactors, batteries, and metal refineries due to its high thermal and electrical conductivity.[327] Global consumption is expected to increase largely due to the demand of the lithium-ion battery industry and the global push for renewable energy. U.S natural graphite imports increased by 55% in 2022 and predominantly came from China, which produced approximately 65% of the world's graphite in 2022.[328] China has also recently restricted the export of graphite, leading to increased risk.[329] U.S lithium-ion batteries generally contain synthetic graphite, a material derived from the high-temperature processing of carbon materials such as petroleum or coal.[330] The higher costs associated with synthetic graphite highlight the need for secure access to natural graphite supply chains. Some recent awards by the Department of Energy and DoD to U.S. industry to expand domestic graphite production are encouraging, but only time will tell their economic feasibility. Syrah Technologies LLC was awarded $220 million from the DoE to expand domestic refining, in Vidalia, Louisiana, for graphite mined in Mozambique.[331] DoD, under a $37.5 million DPA Title III program agreement, is working with Graphite One to potentially develop a graphite mine in Alaska.[332] As more lithium-ion batteries are produced, there is a potential opportunity to recover the graphite in them through recycling, if costs can be reduced to make these processes economically feasible. Overall, Chinese dominance in graphite introduces risk into DEW supply chains.

Nickel

Nickel plays an important role in battery technology and thus impacts DEW supply chains. It is a key component in rechargeable nickel-metal hydride (NiMH) batteries, offering efficient energy storage for defense and commercial products. Nickel is also important to the development of high-performance lithium-ion batteries, enabling higher energy density and increased reliability. Its use in EVs particularly indicate rapidly growing demand as the ongoing energy transition continues. Market vulnerabilities of nickel were covered extensively in ETI's hypersonics report.[333] In 2022, the U.S imported 45% of its supply from Canada and another 24% from allied countries like Norway and Australia, indicating a stable supply chain.[334] However, as of 2019, China was responsible for processing 35% of the world's nickel supply and China continues to invest in countries like Indonesia who are responsible for 33% of global extraction of nickel.[335] Overall, because the U.S. primarily imports nickel from a close ally, Canada, this link in the supply chain is relatively stable. However, with changing markets and Chinese dominated processing, future supply could require attention.

Manganese

Manganese, a versatile transition metal, has significant usage in battery technology. The unique properties exhibited by manganese dioxide make it an excellent choice for ensuring high capacity and high voltage energy solutions.[336] This mineral is found most often in the cathode component of lithium-ion batteries. Manganese-based lithium-ion batteries offer higher capacities and energy densities than traditional cathode materials, and the mineral itself is more abundant than minerals like cobalt and nickel.[337] Manganese-ore, the most common form of manganese, is most often used in steel production. Steelmaking accounts for most domestic manganese usage , presently in the range of 85% to 90% of the total demand.[338] As of 2023, the U.S currently relies on two African nations for 86% of its manganese supply: Gabon (67%) and South Africa (19%).[339] Manganese used for steelmaking purposes typically contains 44% or more manganese by weight and while there are known deposits of this grade in the U.S, they are in small quantities and not economically viable to mine.[340] Domestically, manganese ore containing 20% or more manganese has not been produced since 1970, so the U.S is 100% reliant on foreign countries for its manganese supply.[341] While manganese deposits are abundant and the mineral is widely available from a global perspective, these deposits are not evenly distributed and this could prove to be a concern to U.S. national security in the long term. Manganese production is generally tied to demand from the steel industry and a lack of steel production means a lack of manganese ore production. There is presently low risk to the supply of manganese and the existing supply chain is relatively stable due to strong demand signals from the steel industry. However, total reliance on foreign countries could be an issue in the future.

Figure 1.2 Critical Materials Risk Assessment[vii]

Materials	Top Producers	Vulnerability	Explanation
Rare Earth Elements	China, U.S., Australia		China dominates mining and processing.
Silicon	U.S., Norway, Brazil, Russia, China		This is a highly diverse supply chain with Canada and other friendly countries contributing to most U.S. imports.
Gallium	China, Canada,, Japan, Russia, South Korea, United States		The U.S. depends on China for a majority of imports, and China has added new export controls.
Germanium	China, Canada, Russia, Finland, United States		A large reliance on China for imports which may be affected by new export controls.
Barium Titanate	China, India, Morocco, United States		Reliance on Chinese imports and hydrocarbon industry demands increase vulnerability.
Aluminum	China, India, Russia, Canada		Half of U.S. imports are from an ally.
Ammonia	China, Russia, United States, India		U.S. industry is growing and decreasing import needs.
Copper	Chile, Peru, Democratic Republic of the Congo, China, United States		Domestic ore refining and processing difficulties and U.S. domestic permitting challenges may allow China to dominate the market.
Lithium	Australia, Chile, China, Argentina		Raw lithium is sourced from Argentina and Chile, but the majority of lithium-ion batteries are imported from China.
Graphite	China, Madagascar, Mozambique, Brazil		China dominates the industry with increasing growth in U.S. capabilities.
Nickel	Indonesia, Philippines, Russia, New Caledonia		U.S. imports from friendly nations, but China has the most processing capabilities.
Manganese	South Africa, Gabon, Australia, China		Current supply is stable due to strong demand in the steel industry.

vii This chart is a visual representation of the information and data in Chapter 1. Green generally represents a healthy mix of domestic producers and/or imports from allies and partners. Yellow represents some level of vulnerability due to factors such as limited suppliers, ongoing or anticipated supply disruptions, etc. Red represents clear, significant vulnerabilities. Vulnerability designation was determined based on the following factors: Does mining and/or processing occur in China (or under Chinese control)? (negative) Does mining and/or processing occur in Russia (or under Russian control)? (negative) Does mining and/or processing occur in a volatile region? (negative) Does mining and/or processing occur in a stable region and is controlled by a US ally or partner? (generally positive) Does the US import from a stable region? (positive) Does the US import from an ally or partner? (positive) Is the US the largest producer? (positive) If the US is not the largest producer, does the US produce enough domestically to meet demand? (positive) Are there significant market shifts occurring or are likely to occur? (negative or positive depending on context)

Figure 1.3 Critical Minerals Commodity Supply Risk Assessment[vii]

__Note:__ The disruption potential (horizontal axis), economic vulnerability (vertical axis), and trade exposure (point size) are the inputs used by the USGS to calculate the overall supply risk.

viii Graph Originally Produced by the U.S. Geological Survey (https://pubs.usgs.gov/of/2021/1045/ofr20211045.pdf) and adapted by CSIS (https://features.csis.org/hiddenreach/china-critical-mineral-gallium/).

Summary

This chapter illustrated a variety of critical materials and goods that are essential to components for laser and high power microwave systems, contributing to their efficiency, performance, and overall functionality. Ensuring a stable and reliable supply chain for these critical materials is crucial, as vulnerabilities or disruptions can significantly impact the development and deployment of DEWs. Supply chain disruptions may lead to production delays, increased costs, and potential limitations in the availability of necessary components. Foreign source reliance, shortages due to the pandemic, and other factors continue to impact U.S. supply chains, and these vulnerabilities are currently being exacerbated by China's limits on exports. Although some pandemic-era shortages appear to be nearing resolution, and there have been some steps to address existing supply chain vulnerabilities in several listed materials, substantial work remains to ensure the DIB's ability to effectively ramp up DEW production. The following recommendations should be implemented to ensure secure directed energy supply chains in the future.

Recommendations

In addition to the recommendations below, ETI's hypersonics supply chain report provided actionable recommendations that could also work to help secure directed energy supply chains.[342] These include DoD & Congress working together to reinforce the National Defense Stockpile, the U.S. government setting the regulatory environment to permit and incentivize more domestic rare earth mining and processing, and industry expanding partnerships with government and academia to incorporate new innovative rare earth extraction and processing methods.

1. The Department of Defense, working with Congress, should add gallium to the National Defense Stockpile. The current lack of a domestic stockpile of gallium in the U.S., combined with Chinese export restrictions on this critical material, highlight the need for gallium to be added to the national defense stockpile. As a key element in the fabrication of high-power semiconductor lasers and microwave devices, the availability of gallium is essential for maintaining a secure and reliable supply chain for these advanced directed energy technologies. By establishing a national stockpile of gallium, the U.S. can mitigate the risks posed by potential supply chain disruptions and reduce dependence on foreign sources, ensuring a consistent and sustainable supply of this critical material in the event of an emergency. This strategic move will bolster the U.S. defense readiness, protect its technological advantage, and reinforce its ability to maintain cutting-edge directed energy systems for safeguarding national security interests.

2. Industry, in collaboration with academia, as well as federal, state, and local government, should take steps to build a domestic gallium nitride (GaN) production capability. Creating a domestic gallium nitride production capability is a complex endeavor requiring collaboration between all levels of government, industry, research institutions, and other stakeholders. It will require planning, resource allocation, and a long-term commitment to establishing a resilient and self-sufficient gallium supply chain. Some U.S. allies, such as Canada and Germany, have already taken steps to ensure a domestic gallium production capability, and the U.S. should follow suit.[343] By developing a domestic GaN capability, the U.S. would reduce its dependence on foreign sources and mitigate potential supply chain vulnerabilities caused by geopolitical uncertainties or disruptions. A self-sufficient GaN supply chain would provide the necessary foundation for the production of GaN-based components, including integrated circuits, crucial to DEWs, such as high-power amplifiers and transmitters. By securing a stable and controlled source of GaN, the U.S. enhances its capability to produce and deploy effective DEWs while reducing vulnerability to external disruptions that could undermine national security.

3. The Department of Defense should invest in synthetic alternatives for DEW optics materials and other critical directed energy weapon materials. Although there are several promising instances of synthetic materials achieving high levels of performance and efficiency, especially for DEW optics materials, many synthetics are still in early stages of development and have not experienced widespread adoption within the directed energy community. Because of this, synthetics are not a short-term solution to many of the critical resource vulnerabilities that directed energy supply chains face. While finding immediate solutions is vital, DoD must also dedicate resources to long-term strategic resource planning. One part of this plan should be to invest a steady stream of funding to industry and academic partners for the development of synthetic materials to help alleviate foreign sourced resource dependency. For example, researchers at Northeastern University in Boston and Cambridge University recently manufactured a material that had previously only been found in meteorites.[344] The material, tetrataenite, has substantial potential to be used to produce the permanent magnets necessary for advanced machine technologies, which currently rely on the rare-earths elements neodymium and praseodymium.[345, 346] These rare earths are also heavily used in HELs. Once proven as a viable alternative for DEW applications, synthetics could be given the funding they need to become realistic alternatives to current critical resources.

4. The U.S. Department of Defense and Industry should work together to develop a method to increase government visibility of the origin of raw materials for directed energy weapons. Many of the most vital military systems are dependent on materials sourced from foreign powers, including adversaries. Unfortunately, it can be challenging for both contractors and DoD to have full visibility throughout the supply chains. While reports like this provide some awareness, much more work remains. To combat the inadvertent use of potentially vulnerable raw materials in American military equipment, DoD and Industry should work to develop a method to increase visibility of the origin of raw materials for directed energy weapons, while balancing proprietary information with national security needs. This transparency will ensure that both industry and government are aware of any potential vulnerabilities in core elements of the supply chain and will make risk analysis a more efficient and effective process.

5. The U.S. government should incentivize the use of domestically produced batteries in DEW systems by DoD entering into long term contracts with domestic battery manufacturers, where fiscally prudent, providing financial incentives to promote domestic competitiveness with the long-term goal of reducing current reliance on China. There are many ways the U.S. government can incentivize the use of domestically sourced batteries in critical defense technologies in order to reduce current reliance on China. For example, DoD can enter into long-term contracts with domestic battery manufacturers, offering them guaranteed demand and stable revenue, once deemed fiscally prudent. This is especially vital considering some domestic facilities are operating at 10% capacity, indicating substantial gaps in demand and capacity. By providing assurances of consistent business over an extended period, domestic suppliers can invest in research, development, and scale up production, potentially leading to cost reductions over time. The U.S. government could also offer financial incentives, such as tax breaks, to domestic battery manufacturers to help bridge the price gap and make their products more competitive with Chinese alternatives. DoD acquisition program offices could also offer considerations in proposal evaluations including cost considerations and preferential weighting for use of U.S. or allied suppliers. These incentives should be tied to specific performance benchmarks, ensuring that the batteries meet DoD's stringent requirements. Further, DoD should continue to invest in research and development collaborating with industry and academia to develop advanced battery technologies with the goal of fostering innovation in the domestic market to make domestically-sourced batteries more cost-competitive.

6. The Department of Defense and the Department of Energy should coordinate efforts focused on ensuring the security and resilience of critical resource supply chains for emerging technologies, including directed energy technology. The DoE and DoD should use existing collaborative frameworks (where possible) to ensure the security of critical resources fundamental to DEW development. To operationalize this collaborative effort, the DoE and DoD should take two initial strategic steps : 1) identify and deconflict existing efforts to reduce risk in emerging technology supply chains; and 2) leverage the combined research capacities of DoD and DoE laboratories to initiate joint research programs on priority items such as synthetic alternatives to high-risk materials. By anticipating potential disruptions and devising joint strategies to respond, the DoE and DoD can enhance the resilience of DEW supply chains against unforeseen challenges.

U.S. Rare Earth Mining, Photo provided by Stew Magnuson, *National Defense Magazine.*

Chapter 2: Manufacturing Base and Workforce

Key Topics

Manufacturing Base

- Insufficient Manufacturing Base Due to the Absence of a Clear DEW Strategic Vision and Inconsistent Demand Signal
- Long Lead Times & Limited Suppliers
- Challenges with Particular Components
- Active DoD and Industrial Base Efforts
- MOSA, Advanced Manufacturing, and Digital Engineering

Testing Infrastructure

Directed Energy Workforce

- Larger Workforce Shortages and Competition
- DEW Workforce Challenges
- Relevant Workforce Partnerships and Initiatives

Assessment of the Sector

The U.S. manufacturing base and workforce is essential to the defense industrial base's ability to develop and deliver directed energy weapons, at scale. During the ETI-led working groups, participants assessed the health of the current DEW manufacturing base and workforce. Overall, the directed energy weapons manufacturing base and workforce is insufficient to meet the needs of the future. When asked about their ability to ramp up production, industry interviewees generally responded in the affirmative. However, they highlighted a number of challenges that must be overcome first. Those manufacturing base challenges include long lead-times, limited suppliers, the highly complex manufacturing process for mirrors and lenses, foreign reliance for battery supply, semiconductor supply, and a lack of standardization. The DEW workforce and testing capabilities also face significant issues that must be addressed in order to secure the supply chains of the future. These issues along with actionable policy recommendations to begin to remedy them are discussed in this chapter. Finally, several participants noted the importance of developing a clear DOTMLPF-P (Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities – Policy) Framework for DEWs. While outside the scope of this paper, additional information about the DEW DOTMLPF-P Framework can be found in Annex 2.

Manufacturing Base

Insufficient Manufacturing Base Due to the Absence of a Clear DEW Strategic Vision and Inconsistent Demand Signal

A common theme throughout all the working groups and interviews was the impact of inconsistent DoD demand for DEWs on the supply chains. Overall, DoD lacks a clearly defined and articulated strategic vision for directed energy weapons and has therefore been inconsistent in its demand signal to industry for DEWs. As such, the manufacturing base is only able to produce small quantities of DEWs with long lead times. Without a consistent demand signal, provided via a clearly articulated vision from senior leadership and transitioning appropriate DEWs to programs of record, the business case does not exist for companies to make the necessary investments to expand production and the necessary workforce.

Long Lead Times & Limited Suppliers

Multiple industry participants throughout the DEW supply chains cited long lead times as a significant supply chain challenge for DEW components. For example, one company cited lead times of up to a year for integrated circuits. The same participant also quoted long lead times for raw materials. Both the heat exchangers in thermal management systems and optics can also face significant delays, with some optics manufacturers experiencing lead times of 12-18 months for a 30+ centimeter optic, according to working group participants. While the impacts of COVID-19 still cause the delays in some instances, limited purchase orders due to the absence of programs of record are also a factor. Multiple industry participants noted that DEWs are a small piece of the market and lack "bulk buys'', preventing many companies from producing the necessary components and materials on schedule and at scale. These delays are often amplified by the highly customized nature of many DEW components. While purchase orders remain small, lead times will continue to be an issue within DEW supply chains.

Another area where a lack of demand signal has impacted the DEW manufacturing base is the scarcity of suppliers for certain components. As will be discussed in chapter 3, some components of DEWs have commercial applications and can therefore leverage existing commercial supply chains. However, for components specific to DEW applications, the supplier base is often small and highly specialized. Given that it is a severe vulnerability, this topic will be covered in Chapter 3.

Challenges with Particular Components

Mirrors and Lenses

According to working group participants and interviewees, both the mirrors and lenses used in the optical elements of laser weapon systems require highly precise grinding and polishing to meet specific tolerances and specifications, sometimes resulting in lead times of 12-18 months.[347] The complexity and precision required in the manufacturing process of these mirrors can lead to potential supply chain delays. According to multiple industry participants, a shortage of specialized manufacturing facilities with the necessary equipment and expertise can limit production capacity. Additionally, any issues during the grinding, polishing, coating, or testing stages may result in rejected mirrors, further delaying the supply chain. Furthermore, in a global supply chain, delays in the procurement of raw materials or shipping disruptions also impact the timely delivery of these critical components to the final assembly stage. Due to the critical nature of these mirrors and the highly complex manufacturing process, any supply chain delays can have cascading effects on the entire production schedule and deployment timelines.

Battery Supply

The supply of batteries for directed energy weapons faces challenges across the board. While raw materials are covered in chapter 1, there are additional supply chain issues with this critical component of DEWs, including cost competition from Chinese manufacturers and limited domestic production volume. Because China dominates the international battery market, domestic manufacturers are unable to compete with the lower-priced Chinese commercial lithium-ion batteries.[348] Because of this, interviewees stated that most DEWs and many DoD systems in general, buy commercially-sourced batteries from China. Similar to semiconductors, DoD comprises an extremely small piece of a largely commercial battery market, and DEWs are an even smaller slice of the market. While there has been discussion in recent years about domestically sourcing batteries, including the acknowledgement that battery reliance on China could be eliminated, customers have yet to express a willingness to pay the higher costs associated with domestic sourcing. To mitigate battery-associated DEW supply chain risk, one industry participant discussed efforts to stockpile material powders and cells domestically. This would establish a 24-month reserve – if efforts to ramp up domestic battery production take place. Overall, U.S. reliance on China for batteries is a significant vulnerability in the DEW supply chains.

Semiconductors

Another issue raised by multiple working group participants was the supply of semiconductors. The semiconductor industry plays a critical role in modern technology, spanning various sectors, including directed energy weapon systems. Semiconductors play a particularly vital role in the generation and amplification of high power microwave signals, targeting systems, laser diodes, laser gain media, and many other components.[349] Semiconductors have been the topic of numerous reports over the past few years, including an extensive report by ETI published in 2023.[350] As such this section will only touch on a few key points. Notably, there are ongoing DoD plans to invest in next generation semiconductor technology to enable high power operation while providing longer ranges for sensing and effect-on-target under adverse conditions and improved size, weight, and power.[351] However, this vital industry faces ongoing vulnerabilities and challenges that have far-reaching implications.

One of the most significant vulnerabilities in the semiconductor industry is the heavy reliance on a few key players and manufacturing facilities. The majority of the world's semiconductor manufacturing is concentrated in just a handful of countries, such as Taiwan, South Korea, and China.[352] This geographical concentration creates a potential single point of failure, as disruptions in any of these regions, whether due to natural disasters, geopolitical tensions, military operations, or pandemics, could severely impact the global supply of semiconductors. In recent years, the United States has experienced the consequences of such vulnerabilities firsthand. The global shortage of semiconductors, which began in 2020 and persisted into 2023, significantly affected various industries, including automotive, consumer electronics, and defense.[353] The shortage disrupted production lines, delayed product launches, and hindered the development of cutting-edge technologies.[354] Moreover, geopolitical tensions between the United States and China raise concerns about the availability and security of semiconductor supply.[355]

Another challenge facing the semiconductor supply chain is the rapid growth of the commercial tech industry. The tech industry – fueled by the rise of artificial intelligence (AI), advanced computation and data storage, and wireless technologies – has resulted in a demand surge for semiconductors.[356] Alongside increased demand, there is also the escalating cost of research and development. As chip designs become increasingly complex and demand increases for more powerful and energy-efficient devices, companies must invest significant resources in innovation.[357]

Lack of Standardization

One particular challenge highlighted by several interviewees is the lack of standardization across DEW systems. This lack often makes it difficult for industry to see a return on investment due to very small production runs that are often highly specific to individual systems. Simply, certain components are critical to the system's effectiveness, but are necessary only in small numbers and require a highly specialized process. As such, this leads to higher unit cost and manufacturing challenges.

This is especially true for coatings, according to multiple working group participants. To date, production of coatings has been largely heterogeneous, with many diverse and proprietary approaches to coating formulas. Because of this, there has been little standardization or consensus on preferred coating materials in order to build robust supply chains. Additionally, because of intellectual property concerns, systems integrators often have little visibility into the specific coating materials used by their subcontractors, resulting in potential lack of awareness of supply chain vulnerabilities.

Much of the current conversation at the S&T level is focused on DEW design simplification. During the DEPS 2023 S&T Symposium, DoD and industry alike agreed that DEW designs need to be tailored towards volume, with a goal of pushing common architecture and components. Each component needs to be improved or optimized to reduce costs and increase overall system effectiveness. Multiple presentations noted that the application for DEWs needs to be captured in system requirements as S&T choices can affect functionality in different domains. Several presenters also noted the need for standardizing interfaces. Ultimately, DoD will need to work with industry to determine how to balance component performance, availability, and costs, potentially through standardization, when manufacturing DEWs at scale.

Active DoD and Industrial Base Efforts

Batteries

DoD and other government entities have begun to take some steps to mitigate the vulnerabilities in battery supply chains. While all of the following may not be directly relevant to DEWs in the near term, according to interviewees, many advancements in the field may ultimately prove beneficial to directed energy weapon systems in the future. A full analysis of government efforts related to batteries is beyond the scope of this paper. However, this section attempts to highlight a few that could potentially help mitigate DEW supply chain vulnerabilities. In 2022, DoD and other interagency partners established a Federal Consortium on Advanced Batteries and the Defense Advanced Batteries Working Group with the goal to "explore how to leverage new technology improvements and battery science to achieve increased battery performance and capabilities." [358] In FY23, DoD invested $43 million in efforts in support of the Under Secretary of Defense for Acquisition and Sustaintment's Lithium Battery Strategy for 2023-2030.[359] This includes investment in test and evaluation infrastructure, analytics, and battery standardization. The strategy evaluates DoD policy changes to "improve its buying power, incentivize allied and domestic markets, and allow DoD to be a better customer to the Defense Industrial Base." [360] Alongside this strategy, the Department of Energy (DoE) has its own National Blueprint for Lithium Batteries 2021-2030.[361] In September 2023, DOD announced the launch of an "energy storage systems campus," led by the University of Texas at Dallas, to "accelerate transition and scaling of next generation batteries, while reducing dependence on scarce critical materials."[362] This initiative is part of DoD's SCALE (Scaling Capacity and Accelerating Local Enterprises) initiative with the goal of stimulating commercial investment and building robust markets in technologies critical to national security.[363] The project has three goals: 1) optimize current lithium ion-based battery performance, 2) accelerate development and production of next generation batteries, and 3) ensure the availability of raw materials needed for these batteries.

The Defense Innovation Unit (DIU) has also contributed to battery technology development and strengthening manufacturing capabilities. The DIU and Industrial Base Policy office are partnering to tap into the knowledge of the growing allied and domestic battery market, where the DIU will leverage "significant private sector investments in battery development in order to learn from the most knowledgeable players in the field, then use that expertise to make scalable products with traditional and non-traditional industry partners."[364]

The Army is also conducting a battery/electrification initiative through its Platform Electrification and Mobility (PEM) project, which seeks to mature, integrate, and demonstrate technologies to electrify both manned and unmanned next generation vehicle platforms.[365] One notable effort within PEM is a supply chain assessment for battery technologies, which received $8.647M in FY23 and requested $16.656M in the FY24 PBR. The FY23 plans include providing an assessment of industrial base risk in battery component technologies critical for military ground vehicle electrification and other Army battery applications.[366] This assessment will inform follow on research into batteries and battery chemistries and materials that can be domestically sourced. Part of its FY24 plans include leveraging the industrial base assessment's findings to design and develop Li-ion 6T battery technologies with higher percentages of domestically sourced cells and materials.[367]

In FY23, the Navy received roughly $14 million to support Industrial Base Analysis and Sustainment (IBAS) program efforts to improve the production capability of the industrial base for laser weapon beam director components and subsystems; reduce production lead times of laser weapon system optics; and improve quality and reduce production times of fast steering and deformable mirrors.[368] In FY24, the Navy requested $4.825M; the decrease in funding is due to the completion of the production enhancements developed in FY23.

Finally, there are ongoing efforts in academia to research alternatives to lithium-ion batteries. For example, the MIT Technology Review recently documented industry and academic efforts to develop innovative new battery technologies, including but not limited to solid-state, sodium ion, and iron air batteries.[369, 370, 371] The University of Central Florida recently developed a seawater-based battery that offers improved safety.[372] Other organizations are simultaneously working to improve anode and cathode designs.[373] The University of Maryland is also developing cutting-edge battery technology utilizing natural materials like crab-shells and wood.[374] If successful, these innovations could potentially reduce reliance on China in the long-term thus improving supply chain security including for DEWs. While these efforts reach far beyond the needs of directed energy weapons, battery innovations in other fields could benefit DEW supply chains.[375]

Semiconductors

The semiconductor industry's vulnerabilities and challenges have prompted the U.S. to take actions to enhance its supply chain. Companies are stockpiling critical resources to prepare for a potential shortage, and government initiatives such as the CHIPS and Science Act and the National Semiconductor Technology Center aim to strengthen U.S supply chains and invest in domestic production of semiconductors.[376] The U.S. government has also been collaborating with allies to strengthen supply chain resilience and reduce dependency on a few key regions.[377] DARPA also completed a project on ultra-wide bandgap semiconductors in FY23, which sought to develop an entirely new class of semiconductor materials with applications for DEW and other emerging high power technologies.[378] While these steps are promising, addressing these vulnerabilities will require even greater strategic planning, further international cooperation, and sustained investments to ensure a resilient and robust semiconductor supply chain for the future. More information on DoD efforts related to semiconductors, please reference ETI's Microelectronics Report.[379]

MOSA, Advanced Manufacturing, and Digital Engineering

Modular Open Systems Approach (MOSA)

Given the challenges highlighted above with a lack of standardization, Modular Open Systems Approach (MOSA) could benefit DEW production in several ways, if implemented. MOSA promotes the use of standardized interfaces and protocols, allowing different modules and components to seamlessly work together.[380] In directed energy weapon systems, this enables the integration of various subsystems, such as power sources and control units, from different vendors. This interoperability simplifies system integration and upgrades, enhancing flexibility and reducing both development time and cost.[381] MOSA's modular nature enables swapping of components or subsystems without requiring major overhauls to the system, resulting in potentially easier repair, and ensuring that systems remain viable and maintainable over their operational lifetimes, even as individual components become obsolete.[382] This flexibility is particularly advantageous in directed energy systems, as new technologies emerge and operational requirements evolve. Additionally, MOSA-designed systems can be easily expanded or scaled down based on mission requirements.[383] In DEW systems, this scalability ensures that the weapon can be tailored to various operational scenarios, from shipboard defense to ground-based deployment. Further, MOSA fosters a competitive marketplace by enabling multiple vendors to offer interchangeable modules and components.[384] This competition can drive innovation and improve overall system performance, as vendors strive to provide the most capable and cost-effective solutions. However, a key consideration for the success of MOSA is service support. The Principal Director for Directed Energy noted during SPIE's 2023 Optics & Photonics Summit that a particular challenge is getting the services to support and implement the architecture. In December 2022, OUSD R&E published a "Directed Energy Weapon System Modular Open System Approach Reference Architecture," in response to Congressional and DoD Service Leadership mandates for the use of MOSA.[385] This is an important step in a MOSA for DEWs, but it must be implemented.

Advanced Manufacturing

Like other advanced manufacturing processes, additive manufacturing (AM) can play an important role in the development of directed energy systems. One industry representative noted that there are benefits from new advancements made in AM methods, such as directed energy deposition, that could be leveraged for future DEWs. Specifically, developments seen in the commercial sector in the laser source, which is used for melting materials, could lead to more efficient DEW systems. According to working group participants, as DEW systems have become more complex, traditional manufacturers often struggle to produce the highly customized and intricate components that are critical to the functioning of modern DEWs. Further, the slightest changes in system requirements can result in the need for completely new custom parts with high costs. Even when production is possible using traditional methods, additive manufacturing could allow for more rapid production by several orders of magnitude as well as reduced costs, provided that the necessary infrastructure is in place to do so, according to working group participants. However, as demand for DEWs continues to ramp up, subject matter experts noted that existing additive manufacturing benefits may not transfer to production at scale, as discussed below.

During ETI interviews, working group participants highlighted several limitations for current DEW additive manufacturing capabilities. First, existing additive manufacturing is primarily used to produce prototype, limited production components. If these components were needed at volume, additive manufacturing would be insufficient to meet demand due to the limits of existing 3D printers and capabilities. Current 3D printers are also unable to efficiently produce many of the large components found in DEW systems. If AM is to be used for anything beyond prototyping or the production of extremely intricate, custom parts, substantial investments are needed to expand the availability and capability of 3D printers. In the current 3D printing market, other methods of manufacturing, including casting and forging, would be required once production of a component or system eclipsed existing capacity. While additive manufacturing is useful for many applications, this method may produce lesser quality surface finishes than would be necessary for DEW systems, and traditional methods may be required. Lastly, an expansion of 3D printing would also require increased and reliable production of powders and other inputs that are necessary for the manufacturing process. However, there is currently a lack of consensus on powder type for a variety of applications. If there were one or two agreed upon powders to use, it may be easier to anticipate demand for the material and ramp up production.

Manufacturers must also be aware of system operational requirements when selecting materials used with 3D printing processes. Because DEW systems have a broad array of applications, it is highly likely that 3D printed components will need to survive in high stress environments, including on high-G aircraft and in corrosive environments such as the western Pacific. While 3D printed components may work well in a lab setting, these components must also survive the harshest operational environments. Specific qualification of AM parts must be developed to ensure all components repeatedly meet safety and performance specifications, according to working group participants. Once advanced manufacturing demonstrates repeatability in structural properties and the material make-up of critical components, adoption at scale will likely meet fewer obstacles. Overall, additive manufacturing provides several benefits to DEW systems, particularly when manufacturing complex components at reduced cost and lead times. However, much work remains if additive manufacturing is to be used for DEW systems at scale.

Digital Engineering

According to working group participants and interviewees, although it is gaining more traction with time and is used by some organizations to varying degrees, digital engineering (especially digital twins) for DEWs is still largely in the early stages of adoption. Model-based system engineering used for initial requirement identification and development is likely the most common use of digital engineering techniques. Further, some organizations are using virtual reality (VR) to help systems stay within required dimensions and specifications of their intended use-case, according to interviewees. If adopted, digital engineering methodologies have the potential to improve the design, development, testing, manufacturing, and sustainment processes for DEW systems.

Testing Infrastructure

Adequate testing infrastructure, though not traditionally considered part of the supply chain, is an important component in the development and fielding of directed energy weapons. As such, it was deemed within the purview of this study. While a detailed study of DEW testing infrastructure is beyond the scope of this report, this section will focus on a few key issues.

Throughout the working groups and interviews, a common theme was the lack of DEW testing capabilities. The actual number of DEW testing facilities is not the central concern, according to working group discussions. Instead, testing regulations, especially Federal Aviation Administration regulations, play a far more substantial role. Since most DEW systems in development are meant for integrated air and missile defense, a majority of DEW testing requires a discharge of high-powered energy into the air.[386] This requirement leads to significant challenges due to heavy restrictions on testing "above the horizon" in order to safeguard air and space assets from potential damage. A method of predictive avoidance has been used in the past to grant very limited windows of safe testing, but these windows are often so small that any delays in any aspect of the test would result in the cancellation of the entire endeavor. One working group participant explained that an 8-hour testing window would result in less than 15 minutes of actual testing time. There are also very few active testing facilities that permit air testing of DEW weapons with relative ease (referred to as special use space ranges) (See figure 2.1). These restrictions severely limit the number of systems that can be tested and the frequency at which tests can occur, affecting the amount and quality of feedback for different DEW systems. In comparison, allied and partner nations such as Israel are often able to test several times a day with systems developed on site,

Figure 2.1 U.S. Directed Energy Weapons Test Ranges[ix]

Facility	Location	Type[x]	Ownership	Above or Below Horizon
High Energy Laser Systems Test Facility, etc.[387 388]	White Sands Missile Range, NM[389]	Static and Dynamic[390]	Army[391]	Above[392]
Energetics Research and Testing Center[393 394]	Playas, NM[395]	Static[396]	New Mexico Tech (NMT)[397]	Below[398]
Directed Energy Directorate[399]	Kirtland AF Base, NM[400]	Unknown	Air Force[401]	Below[402]
DESIL (Army)[403]	Redstone Arsenal, AL[404]	Static[405]	Army[406]	Below[407]
DESIL (Navy)[408]	Point Mugu, CA[409]	Static and Dynamic[410]	Navy[411]	Below[412]
Utah Test Training Range[413]	Hill AF Base, UT[414]	Dynamic[415]	Air Force[416]	Below[417]
Cuddeback Range[418]	China Lake Navy Air Weapons Station, CA[419]	Dynamic[420]	Navy[421]	Above[422]
KOFA Range & Cibola Range[423]	Yuma Proving Ground, AZ[424,425]	Dynamic	Army	Unknown
Bush Combat Development Complex[426]	Bryan, Texas	Static	Texas A&M	Below
Townes Laser Institute[427]	Cape Canaveral[428]	Static[429]	University of Central Florida[430]	Below[431]
Falcon Range[432]	Fort Sill, OK	Dynamic[433]	Army[434]	Below
Joint Pacific Alaska Range[435]	Fairbanks, AK[436]	Dynamic[437]	Department of Defense[438]	Below
Directed Energy Center[439]	Tucson, AZ[440]	Unknown	University of Arizona[441]	Below[442]
Surface Combat Systems Center[443]	Wallops Island, VA[444]	Dynamic[445]	Navy[446]	Primarily Below[447] Above-the-horizon testing has occurred once but faces tremendous challenges[448]
NSWC Crane[449]	Odon, IN[450]	Dynamic[451]	Navy[452]	Below[453]
NBVC San Nicolas Island[454]	San Nicolas Island, CA	Unknown	Navy	Previously conducted above the horizon engagements. Current level of testing unknown.[455]
Letterkenny Army Depot[456] (NOTE: Testing facility is still in the planning stage)	Letterkenny, PA[457]	Dynamic[458]	Army	Below

ix Table is meant to provide a sample of existing DEW testing ranges rather than an exhaustive list.
x Static implies fixed, known targeting scenarios. Dynamic implies less predictable, often moving targeting scenarios that may involve above the horizon engagements

the results of which can be seen in advanced DEW systems such as Iron Beam, according to interviewees. Because development and testing often take place at the same facilities, thereby ensuring integration and rapid feedback, the testing rate is drastically improved. At the same time, modeling and simulation may present an opportunity to address some of the existing challenges for DEW testing, though it is contingent on the type of intended testing.

According to working group participants, a second impediment to adequate DEW testing is the existing testing workforce. Testing directed energy weapons requires substantially different processes than those of kinetic munitions. This is particularly true of HPM systems due to the risk of collateral damage to nearby systems. DEW systems often do not fit within normal safety parameters of ranges, so additional education, training, and facility modification are required before tests can be conducted. Staff must understand the dynamics of speed-of-light engagement as well as foundational DEW testing knowledge. The existing workforce is older and well-educated, but it is necessary to bring in the next generation to bolster workforce numbers and replace those who are reaching retirement age. Facility sharing with other weapons programs also poses unique challenges, as much of the range must be shut down during the DEW test in order to not damage other systems.

There have been some efforts to mitigate these testing limitations. For example, since 2005, Test Resource Management Center's Directed Energy Test (DET) multi-year effort has had a mission to

> **"address test technology shortfalls in HEL and HPM domains by maturing and transitioning high-risk, high-payoff directed energy test technologies for both the laboratory environment and DoD test ranges to enable capability development for full-spectrum test and evaluation for DEW systems and U.S. systems' vulnerability to DEW threats."[459]**

Currently, DET is in its third phase, manages 8-10 ongoing projects, and has transitioned over 65 projects to DoD test facilities, including an array of sensors and various modeling and simulation tools.[460] Further, in the FY22 Consolidated Appropriations Act, Congress provided $34 million to improve the DEW T&E capabilities, including investments focused on delivering ground- and air-based detection/tracking and lethality assessments as well as upgrading the current mobile diagnostics suite to improve characterization of performance.[461] These investments are an encouraging start to rectify ongoing testing shortfalls. Similarly, initiatives such as the Directed Energy T&E Investment Roadmap, which outlines 40 HPM projects and 51 HEL projects required to reduce shortfalls in the DEW testing infrastructure through FY2030, are also promising.[462] However, work remains to continue developing a robust directed energy weapon testing infrastructure.

Directed Energy Workforce

The current DEW workforce faces many of the challenges as the rest of DoD STEM workforce and is insufficient to support large-scale deployment of DEW weapons in the future. Interviewees from larger companies generally expressed limited concern with hiring the necessary DEW workforce, however, interviewees from sub-tier suppliers expressed serious workforce concerns in a few specific areas that will be discussed in this section. While the situation is concerning, some small-scale partnerships are underway to begin to address the issues.

Larger Workforce Shortages and Competition

According to several working group participants and interviewees, the current DEW workforce faces similar challenges to the larger DoD STEM workforce overall. STEM (Science, Technology, Engineering, and Mathematics) talent is very important in the development of directed energy weapon systems. Advanced HEL and HPM technologies heavily rely on cutting-edge scientific research, sophisticated engineering, and innovative solutions, all of which necessitate a highly skilled and knowledgeable workforce. Developing and refining these systems requires a multidisciplinary approach, with experts in physics, chemistry, optics, electrical engineering, materials science, and computer science collaborating to achieve breakthroughs in directed energy capabilities. However, the current U.S. workforce is experiencing a shortage of STEM talent and increased competition for existing talent, thus posing significant challenges to the advancement of directed energy systems. A recent study published by the Semiconductor Industry Association (SIA), in partnership with Oxford Economics, determined that

> **"the United States faces a significant shortage of technicians, computer scientists, and engineers, with a projected shortfall of 67,000 of these workers in the semiconductor industry by 2030 and a gap of 1.4 million such workers throughout the broader U.S. economy."[463]**

The shortage can be attributed to various factors, including an aging STEM workforce and insufficient interest and participation in STEM education, according to interviewees.[464] Alongside this shortage, many STEM workers are choosing to take their talents to the commercial tech sector. As a result, the pool of skilled professionals available to work on defense projects becomes limited, making it harder for defense contractors, government agencies, and research institutions to recruit top talent for these critical roles.

The term "aging workforce" can be slightly misleading when it comes to the STEM field. Usually, aging workforce issues arise when older, experienced veterans of a field begin to retire, leaving substantial gaps in knowledge and capability in their wake. The STEM workforce has the opposite issue. [465] In part due to a 1994 rule change that eliminated mandatory retirement at universities, older scientists are remaining employed longer than they would have under the previous system, resulting in fewer vacancies to be filled with new PhD candidates.[466] An absence of academic job opportunities may discourage those considering advanced STEM degrees, and could prevent those with creative, new ideas from contributing to the workforce.[467]

While a large talent pool in the commercial sector does provide a greater opportunity for DoD to recruit for its DEW programs, the growing appeal of a commercial sector career is a challenge for defense-related STEM employment and may prove to be a major obstacle to the development of directed energy weapon technologies. Salaries for scientists and engineers in the defense and aerospace industries lag considerably behind salaries in the fastest-growing commercial high-tech companies, and the ecosystem of software service companies. According to a report by the Ronald Reagan Institute, "private-sector companies attract American students graduating from bachelor's programs with lucrative salaries and immediate offers of employment following graduation, causing them to forgo graduate degrees."[468] The barriers to entry are often far lower in the private sector, compared to the defense industrial base which often requires time-consuming security clearance processes. Further, the private sector often offers appealing hybrid or remote work opportunities, which are a highly desired benefit in the post-pandemic world.[469] Alongside these salary and benefit-related preferences, there are also more fundamental problems with the attractiveness of working on defense projects for the defense industry. An interviewee from academia suggested that many young students are disinterested in working on DoD-related STEM projects. Given this loss of interest, a potential increased number of STEM graduates does not necessarily correlate with an equally increased number of candidates applying for directed energy-related positions.

In some cases, the DEW community can attempt to pull from existing commercial talent where there is overlap between DEW components and commercial laser components. For example, HELs often use many components, such as optics and laser diodes, that are also necessary for industrial or medical laser applications. Because of the dual-use nature of these components, according to interviewees, there is generally a well-developed commercial workforce that DoD can pull from to work on its DEW programs. While many HEL components are dual-use in nature, there are some, such as coatings, that are specific to DEW applications and require a highly specialized workforce. Where HELs have some commercial application, HPMs have little direct use in the commercial sector and many of their components draw from far smaller fields, such as the plasma physics and pulse power communities. This smaller pool of talent may present recruiting difficulties if DoD drastically scales up orders for HPM systems. However, according to multiple subject matter experts, the skills needed for HPMs are comparable to those that are needed for radar and electronic warfare technologies, thus providing an existing pool of talent that could potentially be leveraged.

An overall lack of talent could directly impact the development and manufacturing of directed energy systems both in the present and the future. In the short term, it can slow down research and development initiatives, leading to delays in deploying advanced directed energy technologies. The scarcity of qualified personnel can hinder the optimization and integration of complex systems into the armed forces, limiting the effectiveness and efficiency of directed energy solutions in defense applications. In the long term, the shortage of STEM talent may impede the United States' ability to maintain a competitive edge in directed energy systems on the global stage. Other countries, particularly China, that are investing heavily in STEM education and research could surpass the U.S. in developing cutting-edge directed energy technologies.[470] This could have serious national security implications, as directed energy systems will play a crucial role in modernizing defense capabilities, countering emerging threats, and ensuring military superiority.

DEW Workforce Challenges

Interviewees from larger companies generally expressed limited concern with hiring the necessary DEW workforce, however interviewees from sub-tier suppliers expressed serious workforce concerns in the following areas:

Coatings

Working group participants identified coatings as an area of concern for the DEW workforce, given the significant expertise necessary to construct and apply these coatings. Industry participants often refer to coating construction and application as an “artform,” and something that takes extensive time and skill to master, presenting a potential workforce vulnerability if demand were to rapidly expand. While there is a significant coatings workforce in the U.S., there are only a small number of professionals devoted to the defense industry. According to interviewees, if demand were to rapidly expand, there would likely be difficulties in finding reputable coaters with reasonable lead times and pricing. The substantial barrier to entry for producing high-quality, specialized coatings puts further strain on the industry and creates a bottleneck in the DEW supply chain.

Energy Production

Another DEW workforce issue identified by an industry member relates to energy production. According to multiple interviewees, software engineers, electrical engineers, and power electronics engineers with the necessary experience in design for power switches and electronics switches for power conversion and charging are becoming more challenging to find. With larger trends in electrification leading to increased demand for talent, the related DEW companies are struggling to find individuals with the necessary experience.

Optics

Optics, where opto-mechanical engineers are responsible for the design and integration of optical systems, play a pivotal role and are another area of concern for the DEW workforce. These engineers bridge the gap between theoretical optics and practical applications, ensuring optical systems function optimally in real-world scenarios. According to an interviewee, there are only a handful of schools (both 2-and 4-year) with optics programs in the U.S., which leads to a limited supply of optics graduates. This leads to an even smaller pool of optics professionals that work in the defense industrial base or DoD, due to competition with the non-defense commercial sector (e.g., health industry, etc.).

Mission & Systems Engineering

The need for both mission and systems engineers for DEWs was raised in ETI-convened discussions as well as open forum events. The OUSD R&E Principal Director for Directed Energy publicly stated that DoD needs help in mission engineering and operational analysis. At the DEPS 2023 S&T Symposium, a representative from AFRL noted the need for machine learning tools for battle management. There was also attention drawn to the challenges of integration. Ultimately, a focus on hiring a workforce that can address these issues will progress both the technical advancement and acceptance of DEW systems.

Relevant Workforce Partnerships and Initiatives

Given the DEW workforce challenges identified above, multiple partnerships and initiatives have been established to address these issues. While many more successful partnerships likely exist at a plethora of universities and companies across the country, a few notable instances were raised during the working groups and interviews.

Letterkenny Army Depot

In an effort to connect with the local Pennsylvania community and enhance STEM opportunities for students, Letterkenny Army Depot (LEAD) co-developed a STEM pilot program to provide high school students the opportunity to learn about directed energy.[471] LEAD partnered with the Directed Energy Professional Society (DEPS) to create a curriculum and hands-on competency laser light kits for Shippensburg High School’s STEM club. While the effort is still new, if successful, this could be a model to replicate in order to increase interest at the high school-level in DEW careers.

An Indirect Fire Protection Capability – High Power Microwave (IFPC-HPM) prototype system developed by defense technology firm Epirus featured at a fall 2023 testing event.

University of Central Florida, Center for Directed Energy Systems, Science, and Technology

In August 2020, the University of Central Florida launched the first university-based Center for Directed Energy Systems, Science, and Technology.[472] The goal of the center is threefold: 1) better understand how DEWs work, 2) develop innovative solutions to present and future challenges, and 3) train the workforce necessary for the private and public sectors.[473] The center conducts numerous activities including managing the Townes Institute for Science, Technology, and Experimentation Facility (TISTEF) with funding from the Naval Research Laboratory, LP Photonics, and Booz Allen Hamilton.[474] UCF graduate students working in the field of DEW have also received scholarships from DEPS, indicating successful engagement between these communities.[475]

Department of Defense Manufacturing Technology Program

OSD ManTech has multiple efforts focused on DEWs, which will influence its manufacturing base as well as workforce. On the workforce side, OSD ManTech Manufacturing Education and Workforce Development (M-EWD) works with DoD Manufacturing Innovation Institutes (MIIs) – a network of public-private partnerships within Manufacturing USA – that are designed to overcome manufacturing and workforce challenges in a variety of technology areas. Two relevant MIIs include: 1) Power America, which works to accelerate the adoption of next generation silicon carbide (SiC) and GaN, and 2) AIM Photonics, which seeks to advance integrated photonic circuit manufacturing technology development.[xi] DoD's MIIs offer the federal government, industry, and academia access to information, people, and infrastructure which helps provide cost-sharing opportunities to stakeholders interested in advancing DoD's critical technology areas.

Optimax[476]

Optimax, a domestic precision optics manufacturer, runs a Precision Optics Manufacturing (POM) Apprenticeship program.[477] The program is focused on developing new precision optics technicians, offering a fully-covered program consisting of a three year and 6000-hour on-the-job rotation in different departments at Optimax, where participants learn crucial skills that are applicable to both defense and nondefense projects. Through their program, Optimax also partners with community colleges as their POM program requires individuals to simultaneously enroll in two community college courses each year that relate to optics manufacturing. As such, their programs primarily focus on individuals with high school diplomas/GEDs.

Directed Energy Professional Society

The Directed Energy Professional Society (DEPS) is a professional organization focused on multiple missions across the DEW community. For example, DEPS holds annual conferences and workshops across the country, where the DEW community can present their latest technology advancements. These events allow the DEW community to review their colleagues' work and expose the newer members of the workforce to activities beyond their laborator or industry focus. DEPS fosters a collaborative culture within the DEW community by convening representatives from the services, OSD, and industry. DEPS also plays a significant role in educational outreach and workforce development efforts by providing educational short courses for the newer members of the community, as part of a continuing education program. It also awards yearly grants to students who want to research directed energy, ranging in value from $2,500-$10,000. DEPS is unique in that its conferences allow for presentations and discussions at higher classification levels than just those in the public domain.

LaserNetUS

Established by the Department of Energy's Fusion Energy Sciences program in 2018, LaserNetUS is a high intensity laser research network of facilities at universities and national laboratories located throughout the U.S. and Canada.[478] Its scientific ecosystem – consisting of ten facilities – is designed to provide access to facilities for researchers and students from the U.S. and abroad. LaserNetUS fosters collaboration among varying levels of education; for example, postdocs and undergraduates routinely work together. Notably, U.S. citizenship is not required to perform research at one of their facilities.

University of Alabama at Huntsville[479]

For over a decade, the University of Alabama at Huntsville's (UAH) Center for Applied Optics (CAO) has partnered with the U.S. Army Space and Missile Defense Command (SMDC) in an effort to conduct R&D, experimentation, and evaluation of HEL component subsystems, and the like.[480] An important element of the partnership is the co-location of SMDC researchers with UAH researchers, faculty, and graduate students, emulating similar research efforts focused on space. One of the goals is to "excite, attract, and educate UAH students into the field of high-energy lasers." UAH has also started holding Optics Metrology Workshops[481] to bring optics vendors, academia, and DoD together to look for ways to standardize optical metrology and thin-film coatings.

The Missouri Institute for Defense & Energy[482]

The Missouri Institute for Defense & Energy (MIDE) was established in 2021 with a focus on combining fundamental physics and applied engineering to address challenges in defense, energy, and related commercial sectors. While MIDE conducts research and development in several different areas, one of the primary points of emphasis is

xi For more information on Manufacturing USA's Innovation Institutes, visit: https://www.manufacturingusa.com/institutes directed energy, specifically compact directed energy systems, novel sensors, automated waveform selection, and immersive systems. MIDE was highlighted by working group participants as a public-private partnership where students are provided government clearances which not only allows them to work on government programs while still in school but also makes the transition to full-time employment (requiring a clearance) faster and more seamless.

Summary

Overall, the DEW manufacturing base and workforce face a number of challenges. First, a lack of clear and consistent demand signal from DoD negatively impacts the manufacturing base by causing longer lead times, increasing costs, and creating hesitancy by industry to invest in manufacturing capabilities. At the component level, mirrors, lenses, batteries, and semiconductors all face supply chain issues. The inability to regularly test directed energy weapons due to regulatory challenges and other factors, slows the process of fielding the weapons. Finally, the directed energy workforce, as a subset of the larger DoD STEM workforce, faces challenges such as an aging workforce and competition with more lucrative non-defense commercial jobs. However, there are also some encouraging developments that are starting to address these challenges. Opportunities for advanced manufacturing, as well as potential impacts of MOSA and digital engineering could address these manufacturing base challenges. At the same time, companies and universities across the country have begun establishing initiatives and partnerships to address workforce challenges. While these have the potential to help, work must continue to strengthen the directed energy industrial base and its workforce.

Manufacturing Base Recommendations

1. The Department of Defense should clearly articulate its strategic goals for DEWs and provide a clear demand signal to industry by designating appropriate DEW systems as programs of record. Securing the supply chain for directed energy systems is a critical concern, but it is contingent upon having a well-defined development and deployment strategy. Interviewees cited OUSD R&E's Directed Energy Roadmap as articulating a gradual technology development timeline for specific tactical missions. However, industry working group participants and multiple interviewees noted unclear DoD procurement goals. Without specifying target goals for the number of DEW systems, industry cannot confidently make investments in manufacturing needs or new capabilities. This particularly affects smaller companies. If the vision for DEW deployment includes a larger number - in the hundreds - the current manufacturing base would be unable to support. Setting clear target goals for DEW system deployment not only provides a focused demand signal to industry, but also allows for better planning, investment, and risk mitigation in the supply chain. Developing an overarching deployment strategy is equally vital. It ensures that DEW systems are not only produced but also integrated effectively into the military's operational framework. This strategy should consider various factors, including the types of DEW systems required, their intended applications, geographical deployment areas, and the associated logistics and sustainability requirements.

Once strategic goals are outlined, DoD should provide a clear demand signal to industry by designating appropriate HEL and HPM systems, as programs of record and utilizing multi-year contracts to send an extended demand signal.

In nearly every interview and working group, participants cited the lack of DEW programs of record as a major impediment to secure, resilient, healthy, supply chains. Without a clear and consistent demand signal, many in industry feel there is little to justify the investments that could yield secure supply chains. The procurement of HEL and HPM systems with established technology, likely consisting of low-power C-UAS variants at first, could provide a pivotal step in conveying a clear demand signal to private industry. By acquiring and deploying low-power DEW systems, DoD gains the invaluable opportunity to assess how these systems perform in real-world scenarios. Such practical experience is vital for refining DEW technology and optimizing its design for future iterations. Moreover, procuring and deploying DEW systems, even at lower power levels, sends a resounding message to the private industry. It signals DoD's commitment to DEW technology and its willingness to invest in practical solutions. This, in turn, instills confidence within the industry, encouraging sustained and long-term investment in DEW technology development. Initiating procurement with low-power systems does not preclude future advancements. In fact, it lays the foundation for gradual improvement. The knowledge gained from deploying these systems informs the design of more potent iterations, ensuring that future DEW systems align closely with operational needs and are more likely to succeed.

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2. The Offices of the Under Secretaries of Defense for Acquisition & Sustainment and for Research & Engineering, partnering with the Joint Staff and a technical or industrial association, should collaborate with industry and academia on requirements definition of future directed energy systems. One challenge expressed by the industry working group participants is the effective communication of DEW requirements from DoD to Industry. OUSD R&E, OUSD A&S, and the Joint Staff should partner with a technical or industrial association to host a workshop where government representatives can discuss desired DEW requirements with industry and academic participants at the appropriate classification level. For example, one of the requirements could be that the services use MOSA for all DEW programs of record. OUSD(R&E) should coordinate all the services' technical requirements to maximize use of common designs, common components, and common interfaces. This would allow industry, from all levels of the supply chain, to better prepare to meet future DEW demands, make appropriate investments, and prepare to scale up to ensure a secure, healthy DEW manufacturing base for the future. At the same time, this would allow the government to better understand from industry where supply chain issues may arise in the future.

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3. The Department of Defense should create a centralized data system under the Joint Directed Energy Transition Office for the services and relevant agencies to compile lessons learned from various DEW research, experimentation, and testing, and, where appropriate, share key takeaways with industry. Currently, most knowledge gained from DEW testing and development that is conducted by the services is contained strictly within the services themselves and is only spread to other institutions in an anecdotal manner, according to interviewees. As the field of DEW technology continues to advance and evolve, accumulating and disseminating valuable insights garnered from diverse activities becomes essential to enhance efficiency, streamline innovation, and foster a culture of continuous improvement. One of the primary advantages of establishing such a centralized data system is the systematic capture and documentation of best practices, challenges, successes, and failures encountered throughout the DEW development lifecycle. The Joint Directed Energy Transition Office is already developing a lethality database, which integrates data from service-sponsored field-tests into a systems-level architecture plan. While this is a step in the right direction, it will require acceptance and information sharing from the services to be successful. At the same time, where appropriate, DoD should share key takeaways with industry in order to inform future DEW systems.

4. Through the Department of Defense Manufacturing Technology Program (ManTech), the DoD should invest in the domestic DEW coatings manufacturing base to expand both the capacity and quality of available coatings. The current DEW coatings manufacturing base includes a handful of specialized companies with tightly guarded intellectual property. Recognized as the gold standard, these entities exhibit significant expertise, rendering replication by others challenging. Furthermore, the intricate nature of DEW coatings imposes a significant barrier to entry. To strengthen future DEW supply chains, DoD Manufacturing Technology Program should engage in a series of strategic investments aimed at diversifying and improving the coating manufacturing base. These investments should focus on expanding both the capacity and quality of available coatings, addressing scarcity issues while fostering critical innovation. Simultaneously, efforts should be directed towards enhancing the reliability of these coatings in varied operational environments.

5. Industry and the Department of Defense should work together to identify and leverage commercial technology for DEW components to facilitate a more efficient production process and secure supply chains. While the United States possesses impressive directed energy technology, the production of this technology can be hampered by stringent quality standards regarding military grade DEW components. According to working group participants, pricing for compliant components can be five times that of similar parts. Further, these components are often extremely unique, custom parts that provide little return on investment for industry. While it is important that weapons systems are of the highest quality and security, DoD should work with industry to identify and adjust requirements to incorporate more commercial-standard parts and components wherever possible. By doing so, DEWs could be produced faster and cheaper. Part complexity could be reduced, allowing for the use of more readily available production methods. Some potential areas for exploration discussed by industry participants include solid state electronics, beamforming technology, semiconductors, and power industry components in general. Another area where DoD could look to leverage commercial industry technology is in recent development in power system technology used in motor sports. Some work has already been done jointly between the U.S. and U.K. in this regard.

6. The Department of Defense should work with industry to publish testing and measurement standards to clearly identify necessary specifications for DEW components and standardize parts between systems where possible. Although DoD has made MOSA a priority in recent years, the absence of well-defined and universally accepted standards for key DEW components, such as optical lenses or coatings, poses challenges in achieving consistent and predictable performance across various DEW applications. According to industry and government participants, the lack of standardized benchmarks for parameters like glass purity and other critical characteristics hampers the assurance of desired outcomes in DEW operations. The development and deployment of directed energy systems demands an exceptional level of precision and reliability. By introducing standardized testing protocols, DoD can provide a common reference point for manufacturers, researchers, and developers, ensuring that DEW components meet rigorous but realistic quality benchmarks. These standards will facilitate a consistent and uniform evaluation of components, preventing discrepancies that may arise due to variations in manufacturing practices or materials. For instance, when dealing with optical lenses, well-defined testing standards would specify parameters such as glass purity, refractive indices, and transmittance characteristics. These standards would be tailored to the specific requirements of DEW applications, enabling manufacturers to produce lenses that consistently achieve desired results. Such standards-based testing not only guarantees optimal component performance but also supports efficient troubleshooting, system integration, and interoperability. At the same time, standardization of select components between DEW systems would benefit industry through economies of scale, and government through cost-savings and a stronger industrial base. Beam control and power designs were identified by working group participants as initial places to begin standardization efforts.

7. The Department of Defense should reassess specification requirements for new DEW capabilities to incorporate greater input from the warfighter and technical subject matter experts. DoD should proactively reassess the specification requirements for new directed energy weapons capabilities by incorporating more robust and comprehensive input from the warfighter community. According to working group participants, in the early stages of DEW technological development and integration, there is often a tendency for requirements to be driven predominantly by technologists, potentially sidelining the insights and priorities of those who will ultimately deploy and operate the systems in real-world combat scenarios. As a result, the emphasis on technical specifications can sometimes overshadow other critical factors such as maintainability, affordability, and reliability, leading to unintended consequences where minor improvements in power and efficiency inadvertently compromise the overall feasibility and operational effectiveness of the DEW system. Incorporating warfighter input throughout the DEW development process ensures that the systems are purpose-built to address real operational needs and constraints. By soliciting feedback from those who will use and maintain the technology, DoD can align DEW capability requirements with practical operational demands, focusing on creating predictable, reliable, and easily maintainable systems.

Testing and Workforce Recommendations

1. The Department of Defense should designate more existing testing sites as "Special Use Space Ranges" to permit expanded testing of DEWs. By establishing additional testing sites categorized as Special Use Space Ranges, which are "a specified three dimensional region defined in earth coordinates during a specified time period in which DoD laser operations will occur," DoD could increase the pace of testing and fielding DEWs while still maintaining stringent safety protocols and coordination with relevant aviation and space agencies.[483] Expanding above-the-horizon testing through Special Use Space Ranges offers a controlled yet dynamic environment that closely mimics real-world conditions. These ranges can accommodate a variety of scenarios, including atmospheric conditions, target distances, and engagement scenarios that DEWs may encounter in operational settings. Expanded testing sites can also accommodate larger-scale testing, allowing for multiple DEWs to engage multiple targets simultaneously, which is crucial for evaluating the effectiveness of networked or multi-system operations. This accelerated testing cycle facilitates quicker iteration, refinement, and advancement of DEW technologies, ultimately expediting their transition from development to deployment.

2. The Department of Defense should ensure that workforces at DEW testing facilities are adequately trained to test both HPM and HEL capabilities. DEWs, owing to their advanced technology and capabilities, present distinct safety considerations that demand specialized training and education for testing personnel. As these weapons deviate from traditional ordnance and ammunition, testing personnel must have comprehensive knowledge about the operational nuances, potential risks, and mitigation strategies associated with DEW systems. Additionally, given the hazards DEW testing can pose to nearby systems, well-structured training programs are essential to ensure the safety of testing personnel and nearby infrastructure. Standardized training ensures that testing personnel are adequately equipped to handle the unique challenges of DEW testing and safeguard the integrity of both the testing process and surrounding infrastructure. This training, combined with modernized diagnostics technology, empowers accurate performance evaluation, accelerates testing cycles, and enables the validation of DEW systems in controlled environments.

3. The Department of Defense should establish a Directed Energy University Consortium with the clearly defined goal of creating a strong workforce to meet future directed energy weapon needs. DoD should establish a Directed Energy University Consortium, with funding from Congress, focused specifically on creating a strong workforce to meet future directed energy needs. This consortium should build off of the successful efforts currently underway. Since its creation in 2001, the Joint Directed Energy Transition Office (JDETO), formerly the HEL-JTO, has focused on basic research with universities through grants and education outreach with the Directed Energy Professional Society (DEPS). This relationship with DEPS has resulted in many students going to work for the DEW industry and/or working in DoD labs on DEWs. This workforce development effort should continue but should also be expanded, given anticipated future workforce challenges if DoD demand for DEWs increases. The consortium should be used to expand the future DEW workforce through multiple efforts but especially connecting students with DEW opportunities in both industry and DoD, including providing students with clearances and hands-on experience prior to graduation. In addition to a focus on producing new graduates, the consortium should also look for opportunities to upskill the existing commercial workforce through educational short courses, building off of current proven efforts including those by DEPS. If federal funding is provided, criteria should be established for determining how or when government funding should end for the consortium.

4. OUSD A&S should conduct a DEW workforce study to understand the future needs of its planned programs and industry partners. A DEW workforce study would involve a systematic analysis of the current and projected workforce landscape, encompassing various aspects such as skills, expertise, training, and capacity. This evaluation would extend to both DoD and its collaborating industry partners, ensuring a holistic view of the talent pool supporting DEW technology development, production, integration, and maintenance. Insights should be drawn from relevant DoD entities such as OUSD Personnel and Readiness (P&R), the armed services, and programs such as the Defense Civilian Training Corps (DCTC), to better understand workforce challenges and needs. By assessing the future needs of the DEW sector, DoD can tailor its workforce development strategies to align with emerging trends and technological requirements. This includes identifying the types of specialized skills and knowledge that will be in demand, such as expertise in high power microwave systems, high-energy lasers, materials science, optics, electronics, power generation, cooling, and systems integration. Furthermore, understanding the capabilities and potential gaps within the industry partner workforce is crucial for effective collaboration and streamlined progress. The insights from the workforce study can inform targeted training programs, educational initiatives, and talent acquisition efforts. Such proactive measures will be pivotal in preparing a skilled workforce capable of tackling the challenges posed by DEW technologies, ensuring the development of mission-ready systems.

5. The Department of Defense should invest in artificial intelligence and machine learning (AI/ML) software techniques to improve DEW testing capabilities during the early stages of R&D, thereby reducing the need for above-the-horizon DEW testing and limiting the impact of current testing challenges and restrictions. The current inadequacies in DEW testing infrastructure, exacerbated by stringent Federal Aviation Administration regulations, hinder technological maturation, and impose significant delays on critical programs. Additionally, the limitations on testing "above the horizon" due to concerns about potential damage to air and space assets restrict the frequency and scope of DEW testing. Through the use of new AI/ML techniques, the defense modeling and simulation community could contribute by improving digital testing capabilities for DEWs, offering an alternative avenue for experimentation. Emphasis should be placed on the early stages of development, where AI/ML can help to streamline many basic testing requirements that are needed to develop prototype DEW systems.

Chapter 3: Supply Chain Security and Vulnerabilities

Key Topics

- Financial Health Assessment of Directed Energy Companies
- Foreign Influence and Adversarial Capital
- Key Supply Chain Vulnerabilities
- Cybersecurity Risks
- Counterintelligence & Economic Espionage Risks

Assessment of the Sector

Directed energy weapon supply chains face a range of security risks and threats related to cybersecurity, counterintelligence, and economic espionage. While DEW-specific examples can be challenging to find at an unclassified level, several related cases in addition to insights from working group participants and interviewees are analyzed in this section. ETI also partnered with RapidRatings, a NDIA member company that provides information on the financial health of public and private companies around the world, in order to analyze the financial health of companies within the directed energy industrial base. RapidRatings determined that the sample of DEW companies fared well in comparison to other similar companies. However, data from Govini, a commercial data company who also publishes a "National Security Scorecard" on critical technologies, indicates concerning trends in the DEW supply chain regarding foreign influence and adversarial capital. Finally, significant supply chain vulnerabilities exist for numerous DEW components due to a limited supply base, including specialized magnets, beam dumps for testing, adaptive optics, optical coatings, optical fibers, and crystalline materials.

Financial Health of Directed Energy Companies

In partnership with ETI, RapidRatings analyzed the financial health of a group of private and public companies within the directed energy industrial base. Using its analytical methodology, which is detailed below, RapidRatings determined that the sample of DEW companies fared well in comparison to averages across related industries and a broader database of U.S and Canadian-based companies. The failure of a single company occupying a critical space in the DEW supply chain could have severe repercussions because of a limited pool of potential suppliers. These concerns will be discussed further in the Single Source, Sole Source, or Limited Suppliers section of this chapter.

Methodology

Initial analysis was done using 82 companies identified by ETI as representative of central elements within the DEW supply chain. These companies were evaluated using RapidRatings' financial risk assessment tools Financial Health Ratings (FHR) and HealthMark. Of the 82 companies identified by ETI, 16 companies were evaluated using FHR, and 66 using HealthMark.

Financial Health Ratings (FHR) was developed by RapidRatings to evaluate public and private companies where financial data is available. FHR measures the short-term (1-year) default risk using company-specific balance sheets, income statements, and cash flow data. Overall, the FHR provides forward-looking visibility into operational resilience and indicates a company's ability to weather disruption and continue business operations. A company's assessment is delivered on a scale of 0-100, with five color-coded risk categories.

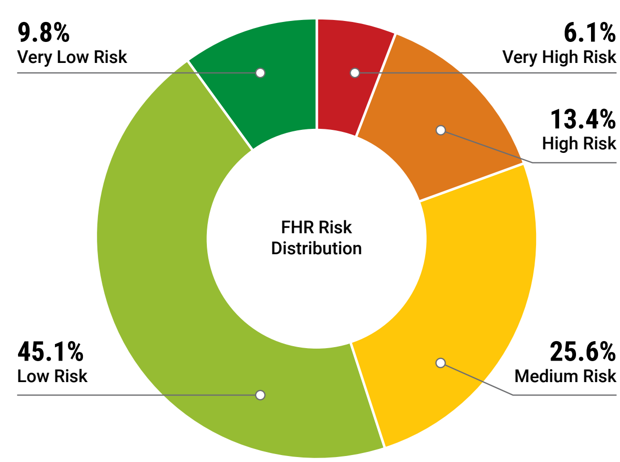
HealthMark (HM) is RapidRatings' alternate tool used to measure financial risk for private companies where data is not widely available. HM provides an instantaneous score for private company financial risk based on trade payment data, firmographic information, and aggregated FHR information. HM assessments are delivered on the same color-coded risk categories as FHR.

Findings

Of the directed energy companies analyzed, 54.9% were rated as either very low risk or low risk, with only 19.5% being labeled as high or very high risk, as seen in the chart below.

To provide additional context for these ratings, RapidRatings also conducted a comparative analysis between the financial health of the DEW companies and companies in related industry sectors.[484] The risk assessments of the DEW companies were benchmarked against a sampling of those related industry sector companies in RapidRatings' U.S. and Canada general database (see figure 3.1). The DEW companies generally fared better than the related public and private companies. While 19.5% of the DEW companies were assessed as high or very high risk, 34.4% of the public companies were rated as high or very high risk. Private companies fared slightly better with 25.7% assessed as high or very high risk.

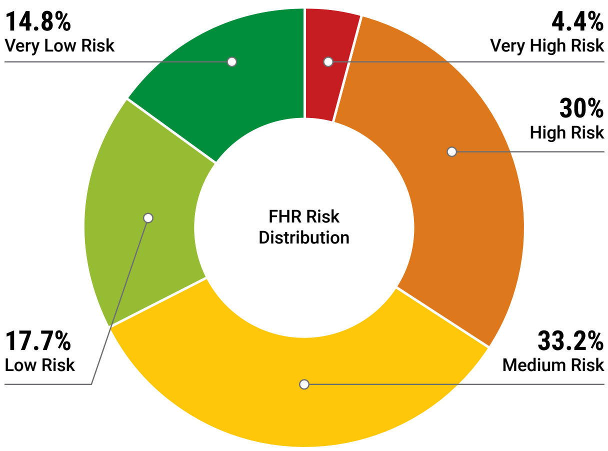
Figure 3.1 NDIA Directed Energy Companies



FHR & HM	Short Term Default Risk					Total Companies
	Very High	High	Medium	Low	Very Low	
NDIA Directed	5	11	21	37	8	82
Energy Companies	6.1%	13.4%	25.6%	45.1%	9.8%	100.0%

Chart reproduced by ETI, data provided by RapidRatings

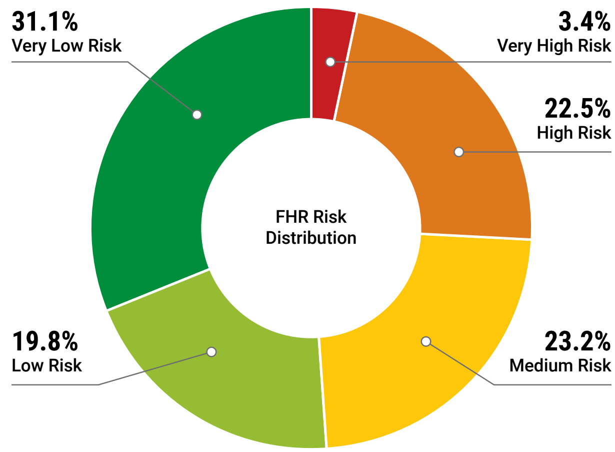
Figure 3.2 Public Companies



FHR	Short Term Default Risk					Total
	Very High	High	Medium	Low	Very Low	Companies
US and Canadian	18	124	137	73	61	413
Public Companies	4.4%	30.0%	33.2%	17.7%	14.8%	100.0%

Chart reproduced by ETI, data provided by RapidRatings

Figure 3.3 Private Companies



FHR	Short Term Default Risk					Total
	Very High	High	Medium	Low	Very Low	Companies
US and Canadian	84	557	574	490	771	2476
Private Companies	3.4%	22.5%	23.2%	19.8%	31.1%	100.0%

Chart reproduced by ETI, data provided by RapidRatings

RapidRatings also provided a general sense of trends for public and private companies in the related industry sectors. Notably, although privately-held companies generally had better ratings than their public counterparts, the financial health of private companies was deteriorating into the medium and high-risk categories at a faster rate. This trend can be seen in the graphs below. Many variables influenced this deterioration including rising raw material and labor costs, diminishing liquidity, and rising interest rates. These factors will likely continue to be a burden on the DEW supply chain for the foreseeable future, although long-term effects are difficult to discern.

Figure 3.4 Financial Health Trends for Public Sector Companies

Sector Risk-Publics	2019	2020	YoY % CHG 2019-20	2021	YoY % CHG 2020-21	2022	YoY % CHG 2021-2022	2023	YoY % CHG 2022-23
Aerospace & Defense	49.1	51.7	5.30%	52.8	2.00%	48.5	-8.20%	49.4	2.00%
Computer Serv. and Techn.	56.5	56.5	0.00%	57.9	2.50%	56.8	-2.00%	58.3	2.70%
Electronics and Semicon.	54.4	51.6	-5.10%	54.3	5.20%	52.8	-2.80%	51.7	-2.10%
Equipment & Mach.	51.8	53.1	2.40%	55.3	4.20%	52.2	-5.60%	52.2	-0.10%
Health Products	48.3	50.2	4.00%	54.4	8.40%	48.2	-11.40%	48	-0.40%

Data provided by RapidRatings

Figure 3.5 Financial Health Trends for Private Sector Companies

Sector Risk-Privates	2019	2020	YoY % CHG 2019-20	2021	YoY % CHG 2020-21	2022	YoY % CHG 2021-2022	2023	YoY % CHG 2022-23
Aerospace & Defense	64	60.2	-6.00%	58.9	-2.20%	53.6	-8.90%	47.3	-11.70%
Computer Serv. and Techn.	57.2	59.5	4.00%	59.5	0.00%	56.8	-4.60%	53.2	-6.30%
Electronics and Semicon.	65.3	64.8	-0.80%	65.7	1.40%	65.3	-0.70%	62.2	-4.70%
Equipment & Mach.	63.1	65	3.00%	66.1	1.80%	66	-0.20%	64.2	-2.70%
Health Products	61.8	62.2	0.60%	63.4	2.00%	60.3	-5.00%	48.4	-19.70%

Data provided by RapidRatings

Foreign Influence and Adversarial Capital

Govini, a commercial data company, published a National Security Scorecard in 2023 with a focus on critical technologies, including directed energy.[485] Govini's AI platform, Ark.ai, helped provide analysis which uses "data-at-scale with advanced ML techniques to generate a quantitative understanding of the state of the U.S.-China competition in emerging technologies, as well as innovation trends in the U.S. industrial base more broadly."[486]

Govini's analysis indicates concerning trends in the DEW supply chain regarding foreign influence and adversarial capital. From FY18-22, there were 379 unique Chinese tier 1 and 2 suppliers in the DEW supply chain, four of which were classified as prohibited. Chinese investors such as Yonjin Venture, Huami, Amperex Technologies, Sig China (Sig Asia Investments), and Chengwei Capital have been identified as notable investors in several U.S. directed energy startup companies and have contributed to these companies throughout multiple rounds of funding. Additionally, many companies that play an important role in the directed energy supply chain have been assigned risk scores from 23.1 to 38.6, indicating moderately high levels of risk. All have significantly high levels of foreign revenue, moderate levels of Chinese revenue, and all but one have confirmed Chinese suppliers. See the chart below for more details. Overall, this information on directed energy supply chains illustrates a concerning amount of foreign influence for a technology that has been deemed critical to U.S. national security.

Figure 3.6 Top Ten Vendors By Risk Score

Rank	Vendor	Risk Score	Foreign Influence		Chinese Influence	
FY23	Name	0-100	% of Foreign Revenue	Count of Foreign Suppliers	% of Chinese Revenue	Count of Chinese Suppliers
1	TTM Technologies Inc. (TTMI)	38.6	50.70%	4	10.80%	3
2	Schneider Electric SE (SBGSY)	35.3	72.00%	80	14.80%	28
3	Cummins Inc. (CMI)	33.7	44.30%	57	8.30%	23
4	Lumentum Holdings Inc. (LITE)	30	89.50%	5	9.80%	1
5	Coherent Corp. (COHR)	29.1	54.50%	9	18.20%	2
6	MKS Instruments Inc. (MKSI)	27.8	58.30%	5	13.70%	2
7	Sanken Electric Co. Ltd.	27.1	94.90%	5	26.30%	0
8	General Electric Co. (GE)	26.1	56.70%	195	7.80%	45
9	Jeol Ltd.	24.2	91.70%	3	12.70%	0
10	AMETEK Inc. (AME)	23.1	48.40%	3	3.20%	1

Chart reproduced by ETI, data provided by Govini

Key Supply Chain Vulnerabilities

Throughout the ETI-led working groups and interviews, participants highlighted key vulnerabilities in directed energy supply chains. Given how complicated and opaque DEW supply chains are, this is not a comprehensive list but instead is intended to provide general insights into specific areas of vulnerability. The majority of vulnerabilities were HEL-specific, while the ones raised by HPM industry participants were generally applicable to many different emerging technologies. Addressing these vulnerabilities will require action now to ensure DEW supply chains remain resilient and secure for the future.

High Power Microwaves Supply Chain Vulnerabilities

The majority of vulnerabilities raised by HPM industry participants are applicable to many different commercial and defense emerging technologies in addition to HPMs. Electronic components including semiconductors, integrated circuits and others have been a challenge in recent years due to long lead times. While the COVID-19 pandemic caused some delays, interviewees cited general global capacity as another limiting factor. Similarly, interviewees cited gallium nitride (GaN) devices that provide for high power amplification in solid state HPMs, as another area of concern for many of the reasons discussed in chapter 1. Finally, high power microwave weapons rely on specialized magnets, but the limited supplier base makes HPM systems vulnerable to supply disruptions.

High Energy Lasers Supply Chain Vulnerabilities

During the working groups and interviews, participants raised numerous HEL-specific examples of significant supply chain vulnerabilities. These vulnerabilities can be grouped into sole source, single source and limited suppliers.

Sole Source

According to interviewees, beam dumps,[xii] a critical component in high energy laser testing, are only produced by a single company located in Israel. Currently, there is not enough demand for more companies to exist. This sole source has already caused production delays, with some companies reporting lead times of up to 12 months to obtain these components. The interviewee cited that it can take nearly a year to fix damaged beam dumps due to lengthy shipping and receiving processes and limited production capacity.

Single Source

Working group participants and interviewees raised a few vulnerabilities that could be characterized as single source. First, ceramic laser materials for HELs are sourced only from one company in Japan. Diffraction gratings, a critical optical component, which propagates light in the same direction to amplify effects, are also sourced from a single industry supplier, who is on contract from a national laboratory to manufacture these components. Given the limited market and number of DEW prototypes, there is little incentive to explore improvements, reducing the probability of higher functionality, and a decrease in cost. Moreover, according to the interviewee, the providers bring in limited revenue from these inexpensive one-off components, suggesting that it may make more sense for the government lab to manufacture and stockpile this component due to the small profit margins as well as minimal incentive for technical progress. Finally, as discussed in chapter 1, multiple participants noted that fused silica is sourced from a single German supplier.

Limited Suppliers

Throughout the HEL supply chains, there are multiple instances of limited suppliers. Given the lack of consistent DoD demand signal for DEWs over the years, this is unsurprising but will pose a tremendous challenge to scaling up DEWs in the future.

Beam directors suffer from extremely limited suppliers. According to interviewees, there are only 2-3 companies in the U.S. that can make these advanced devices and the lead times are often 2+ years. Further, beam directors use large primary mirrors which can only be produced by a few optics manufacturers, and many will not interrupt their non-DoD manufacturing line for commercial/academic telescopes to expedite a DoD order. This is a critical supply chain bottleneck and weakness. Similarly, as previously mentioned in Chapter 1, gimbals face potentially limited suppliers. Although there are a number of vendors who could produce them, the market for HEL beam director gimbals is so small and the precision so high, that only a few companies are willing to accept orders, introducing another potential vulnerability into the supply chain.

Other working group participants noted that DEW adaptive optics have a limited number of suppliers, specifically because they do not have many commercial applications. While adaptive optics for ophthalmology is a lucrative and growing market, the adaptive optics market for non-medical applications, including DEWs, is small, especially for actuators, with only 2-3 companies providing the majority of production. Working group participants cited that this limited production can result in lead times of 18-24 months, introducing potentially severe production delays.

Coatings for high-energy laser optics, designed to withstand extreme conditions, are highly specialized and sourced from a limited number of suppliers, increasing the risk of delays and shortages.

According to industry interviewees, the specialty optical fiber base, essential for efficient energy transmission in DEW systems, has limited suppliers in the United States. While the optical fiber supply base overall is large due to the demand from the telecommunications industry, DEW systems use highly specialized optical fibers requiring unique chemistry. Interviewees cited low levels of demand and therefore a lack of business case for optical fiber producers to specialize in products for DEWs. One interviewee mentioned a Scandinavian-based company as one of the few suppliers that come close to specializing in fibers for HELs.

Finally, according to one external reviewer, there are very few crystal growers within the U.S. and many who provide crystalline material, use foreign produced material. Crystal growth technology impacts several areas of DEWs, including gain material development and optical substrates for mirrors, filters, and devices.

Cybersecurity Risks

Open-source information on cybersecurity risks specific to directed energy weapons is limited, but a brief analysis of related industries and technologies along with insights from the ETI-led working groups and interviews can provide an overview of the threats. ETI's previous report on hypersonics supply chains provided an overview of cyberattacks targeting the lower levels of emerging technology supply chains, including areas relevant to DEWs.[487] Most importantly, this included examples of rare earth mining companies from Australia to Canada to the United States, who have been the targets of information operations and espionage.[488] Moving up the DEW supply chain, there were reports in 2020 and 2023, respectively, of at least two laser manufacturing companies, IPG Photonics and MKS Instruments, facing ransomware attacks. [489] During the attack, IPG's IT systems were reportedly shut down worldwide, resulting in manufacturing parts and shipping becoming unavailable.[490] MKS Instruments was reportedly going to lose $200 million in revenue due to the attack which "encrypted business and manufacturing systems and may have stolen personal data."[491] Medium and large defense companies involved in DEW programs also face cyber-attacks. Recent reports indicate that Leonardo faced malware attacks in which individuals sought to steal "confidential data and military secrets."[492] Raytheon's CEO claimed in a 2022 interview that his company was confronted with "millions" of cyberattacks per week.[493] There have been claims that both Lockheed Martin and L3Harris face regular cyberattacks as well.[494] While unable to speak to specific incidents, working group participants and interviewees also confirmed that directed energy supply chains face similar cybersecurity threats as other emerging technologies.

Challenges of Cybersecurity Compliance

Another issue raised by industry participants is the fact that many companies at the lower tiers of DEW supply chains are less likely to have the capital needed for investments in cybersecurity. While this is certainly a significant issue, it must be balanced with the knowledge that general good cybersecurity practices are not difficult (e.g., multi-factor authentication, updating passwords, etc.). These are simple steps that

xii Laser beam dumps absorb incident light and are used to capture unwanted beams. In the laboratory, they are used to stop stray laser beams. Beam dumps can also be used to contain a laser beam within a portion of an instrument. "Laser Beam Dumps." MKS. Accessed October 17, 2023. https://www.newport.com/f/laser-beam-dumps-and-traps.

can have a notable impact in limiting cyberattacks. However, at the same time many small businesses often struggle to implement the necessary cyber infrastructure to work on DoD projects or are hesitant to even get involved with these projects due to complex cyber requirements. This issue is particularly pronounced when these businesses are tasked with producing components that have very low production volumes and no long-term contracts. Small businesses often operate with limited resources, both in terms of finances and personnel. When faced with the prospect of investing in extensive cybersecurity measures, especially for low-volume, short-term contracts, the cost-benefit analysis can be challenging. Cybersecurity implementation typically demands a substantial allocation of financial and human resources, including the establishment of secure networks, monitoring systems, and compliance checks. For many small enterprises, these demands can strain their capacity, diverting valuable resources away from core operations and impacting their competitiveness. The consequence is that potentially capable and innovative small businesses, which could diversify the DEW supply chain and provide alternative sources for critical components, are deterred from participation. This results in a supply chain that remains overly reliant on a limited number of suppliers for these vital components, introducing potential supply chain disruptions and increased costs or, at the very least, limiting competition and innovation throughout the sector. Finally, DoD's self-assessment model when it comes to cybersecurity, has the potential for inconsistency and lack of objectivity.[495] This model means that the assessments could vary significantly depending on the ability of a contractor to understand the standards, their perception of the evaluation process and its stringency, or even a willingness to self-correct.[496] Overall, cybersecurity compliance is a significant challenge for many small companies across DoD supply chains, including in directed energy.

Counterintelligence and Economic Espionage Risks

Other security risks to DEW supply chains include counterintelligence and economic espionage. Similar to cybersecurity risks, DEW-specific examples can be difficult to find in open-source information. However, important insights can be drawn from points raised during the ETI-led working groups and interviews, as well as publicly available documents. Working group participants and interviewees noted that directed energy weapon conferences and sites continue to be appealing targets to foreign adversaries. Some interviewees shared anecdotes including foreign nationals posing as students or being arrested after setting up front companies near DEW-related sites. According to a NATO Industrial Advisory Group report on emerging technologies, there are multiple Chinese organizations involved in directed energy projects that U.S. companies and government officials should be aware of. Within China's military-civil fusion ecosystem, named institutions include: 1028th Research Institute, China Academy of Engineering Physics, Northwest Institute of Nuclear Technology, and Naval University of Engineering.[497] The report also names Chinese companies to be aware of, including: NORINCO and Jiuyuan Hi-Tech Equipment Corporation. An interviewee remarked that the China Aerospace Science and Industry Corporation (CASIC) is a key manufacturer in China's directed energy weapons programs as CASIC produces the LW-30 laser weapon described earlier in this report. According to an interviewee, Wuhan Raycus Fiber Laser Technologies Co. is the laser supplier for CASIC's DEWs. Notably, Wuhan Raycus Fiber Laser Technologies Co. was put on a U.S. economic blacklist in 2021,[498] yet an industry representative explained American businesses still work with Raycus due to the dual-use nature of their portfolio.

Summary

Directed Energy Weapon supply chains face a number of security challenges and vulnerabilities. While the financial health of DEW companies is generally good, the significant number of single, sole, and limited suppliers means that the failure of a single company occupying a critical space in the DEW supply chain could have severe repercussions. At the same time, DEW supply chains face significant cybersecurity, counterintelligence, and economic espionage risks.

Recommendations

In addition to the recommendations below, ETI's hypersonics supply chain report provided actionable recommendations that could also work to help secure directed energy supply chains.[499] Among others, these include a potential bug-bounty program to strengthen cybersecurity at the lower levels of the supply chains, and restructuring the Committee on Foreign Investment in the United States to make it more efficient and better able to limit the flow of adversarial capital.

1. Following the example of the common-hypersonic glide body, the military services should collaborate on the development of overlapping components and subsystems of DEW systems in order to simplify weapon designs and secure DEW supply chains. This approach aims to eliminate redundancy in research, development, and production efforts while enhancing resource utilization and supply chain efficiency. Just as the common-hypersonic glide body initiative brought together the Army and Navy to collaborate on a single critical system, the same principles can be applied to DEW components.[500] By fostering collaboration and standardization among the armed services, the U.S. can significantly reduce the complexity of DEW supply chains. Overlapping components, such as power sources, beam control systems, thermal management solutions, and targeting systems, can be jointly developed, and manufactured, ensuring a consistent and reliable supply of key DEW system elements. This approach not only streamlines production but also reduces the risk of supply chain disruptions due to component shortages or vulnerabilities. Due to increased production numbers for shared components, industry will receive a stronger demand signal, increasing their ability to create robust supply chains for specific components, as well as to invest in expanded R&D for DEW system improvements. Furthermore, a joint approach to DEW components aligns with the broader goal of joint operations and interoperability among U.S. military branches, and also helps control sustainment costs. It promotes a unified vision for DEW technology while maximizing the use of expertise and resources across the armed services.

2. Industry and the Department of Defense should use AI-driven predictive analysis to anticipate failure points in both DEW supply chains and individual DEW systems. By harnessing AI-driven predictive analysis, the U.S. government and industry could gain valuable foresight into potential failure points across the DEW supply chain while also creating a valuable starting point for a more effective industrial base analytical framework. Although this initiative would require a change to government policies for managing contractor data and would require greatly expanded data-sharing efforts to give AI the necessary information to conduct analysis, it has many potential benefits. The AI system could analyze both the quantities and source of critical resources needed for each DEW program using historical data, real-time operational information, and external factors to identify patterns indicative of impending failures. This predictive capability enables stakeholders to take preemptive measures, such as sourcing alternative suppliers, increasing stockpiles of key components, or adjusting production schedules to mitigate the impact of potential supply chain interruptions. Within DEW systems themselves, AI analysis could play a pivotal role in predicting failure points and maintenance needs. By analyzing sensor data, performance metrics, and operational conditions, AI could forecast component wear, degradation, or malfunctions. This enables proactive maintenance planning, reducing downtime and enhancing the overall reliability of DEW systems. Additionally, the AI system could highlight which specific components are likely to experience higher demand for repairs, guiding efforts to prioritize production and distribution of these critical parts.

3. Industry leadership, at all tiers of the directed energy supply chain, should increase awareness of the threat of counterintelligence and economic espionage by foreign adversaries. Counterintelligence and economic espionage are challenging issues that must be addressed by industry leadership at all tiers of the directed energy supply chains. First, existing security measures for cleared employees should be enforced and taken seriously by all tiers of the supply chain. Second, while industry leadership must first acknowledge the threat, they also need to ensure their employees are aware of the consequences this threat can have for an entire company. Finally, industry leadership should craft internal policies, as well as enforce existing policies, to screen new and current employees. Active security personnel also must work to thwart foreign espionage from all levels of the directed energy supply chains.

4. With Congressional funding, OUSD A&S should conduct further analysis into companies within the DEW industrial base with high-risk financial health in order to identify opportunities for potential investment. While the majority of companies analyzed in the DEW industrial base have good financial health, nearly 20% are in the high to very high-risk category. In some cases, this is likely due to the macroeconomic factors outlined above (i.e., inflation, high interest rates, etc.). However, there may be opportunities where DoD could make a small investment via DPA Title III, the Office of Strategic Capital, IBAS, ManTech, or other such mechanisms to secure the DEW industrial base. DoD should conduct further analysis and work with the individual companies to determine the best path forward to strengthening the DEW industrial base and limiting supply chain risk.

Chapter 4: International Partnerships and Allied Nearshoring

Key Topics

- Current International Partnerships on Directed Energy and State of DEW Development in Allied & Partner Nations
- Areas for Allied Nearshoring & Expanded International Collaboration
- Barriers to International Collaboration

Assessment of the Sector

Maintaining alliances and partnerships with like-minded nations around the world is an important component of U.S. national defense. Notably DoD is funding overseas efforts to leverage laser and microwave advancements.[501] In DoD-wide Program Element, High Energy Laser Research Initiatives, roughly $16M was appropriated in FY23 and requested in the FY24 PBR under the project, Joint Directed Energy Basic Research. While it cannot be assumed that the entire funding amount is for leveraging international technology, it is worth mentioning DoD is actively seeking to explore international advancements for both HEL and HPM needs. During the ETI-led working groups and interviews, participants assessed the challenges to DEW international partnerships, identifying key issues, and opportunities for improvement. Overall, international partnerships in directed energy are limited. Considering the sensitive nature of the technology, this is understandable. Given the supply chain challenges highlighted in the previous three chapters, the U.S. needs to take significant action to secure directed energy supply chains. In some places, this action may be onshoring or finding alternatives that lessen reliance on adversaries for critical DEW components and materials. However, in certain cases, it may not be economically feasible to onshore, so allied nearshoring or leveraging capabilities in allied or partner nations may be a preferred alternative. This chapter will evaluate existing international partnerships related to directed energy, the state of DEW developments in allied and partner nations, and discuss potential opportunities to help secure DEW supply chains in the future. Overall, the U.S. should look to Australia and Canada to address DEW testing challenges. Both countries also present an opportunity for the U.S. to diversify supply of critical raw materials and goods. Finally, with appropriate security measures in place, the U.S. should work with Israel to identify opportunities where the two countries can combine demand for key DEW subsystems and S&T components.

Current International Partnerships on Directed Energy and State of DEW Development in Allied & Partner Nations

Multilateral Partnerships

AUKUS

In September 2021, the United States, Australia, and the United Kingdom signed an enhanced trilateral security partnership known as AUKUS.[502] While the first pillar of the agreement focuses on Australia acquiring nuclear-powered submarines, the second pillar includes further trilateral collaboration to enhance joint capabilities and interoperability with a focus on various advanced capabilities, including electronic warfare and counter-hypersonic capabilities.[503] As such, multiple interviewees, working group participants, and public reporting indicated that DEWs are included in pillar 2. Despite the partnership being two years old (at the time of writing), progress in AUKUS collaboration on DEWs seems to be limited. One positive report, that has been tied to AUKUS, was the successful testing at the Klondyke Range Complex in New South Wales, Australia, of a developmental 34kW Australian HEL to counter drones.[504] At the same time, DoD officials have also indicated that a new AUKUS announcement will be issued but it is unclear what the announcement will be and if it will be tied to directed energy weapons.[505] Finally, several challenges with AUKUS have come to light including impediments to international technology cooperation created by ITAR (International Trafficking in Arms Regulations).[506] ITAR was an issue raised by multiple working group participants and will be discussed in more detail later in this chapter. Overall, AUKUS holds incredible potential for the U.S., UK, and Australia to work jointly on advanced capabilities, including directed energy weapons. While reports of joint testing are encouraging, the challenges posed by ITAR will have to be overcome to permit AUKUS to be used to its full potential on directed energy.

NATO

The NATO Science and Technology Organization (NATO STO) has identified directed energy weapons as a component of precision warfare, once power and energy issues are addressed.[507] DEWs are also noted by NATO STO for their potential in providing counter-hypersonic and counter-UAS capabilities.[508] In 2018, the multi-national Research Task Group (SAS-140) was established for a 3 year period under the NATO STO to "accelerate the transition of DEW into the mission areas…[and] make the DEW available as a capability…"[509] The subsequent activity by NATO on DEWs is less clear from open-source information. However, one interviewee mentioned that NATO DEW experiments have occurred and even limited reporting corroborates this with news of a 2021 test in Sardinia, Italy against individual and swarming drones.[510]

State of DEW Developments in Allied and Partner Nations & Bilateral Partnerships

Australia

Australia is attempting to develop advanced DEW capabilities. The 2020 Force Structure Plan called for DEWs "capable of defeating armoured vehicles up to and including main battle tanks".[511] Following this call to action, the largest directed energy test range in the Southern Hemisphere was opened in March 2023 at AIM Defence's directed-energy facility in Melbourne.[512] AIM Defence is developing a compact, affordable system that focuses on countering Group 1 drones, called Fractl.[513] The system, which runs about $650,000 per unit, was demonstrated at the Indo Pacific 2023 International Maritime Exposition in Sydney, remotely shooting down a drone that was 900 kilometers away at a range in Melbourne.[514] Australia has also seen other recent DEW developments. In April 2023, "the Defence Science and Technology group announced a $13 million deal with British defense technology company, QinetiQ, to develop a prototype defensive laser."[515] Additionally, directed energy technology is also a priority in the new $3.4 billion Advanced Strategic Capabilities Accelerator (ASCA) program.[516] An Australian defense technology company, Electro Optic Systems (EOS), reportedly field-tested an HEL in May 2023.[517] The 36-kilowatt laser (scaleable to 50 kilowatts) is for counter-drone purposes and could be immediately operational. One interviewee also indicated that EOS has a DEW testing facility in Australia.

United Kingdom

In 2023, the U.K. Ministry of Defence (MoD) began a three-year 'Transition Phase' program designed to support the development and delivery of DEWs to the military over the next five to ten years.[518] This effort is led by the MoD's Defence Equipment and Support (DE&S) organization with the intent to begin user experimentation in 2024 with the goal of fielding HELs and radio frequency systems for air-defense and C-UAS applications. According to a subject matter expert, there are two Information Exchange Agreements (IEAs) pertinent to Directed Energy collaboration between the U.S. DoD and the UK MoD, one for HEL and one for HPM (HPRF). These two agreements allow for discussion between the two government entities on Directed Energy, up to the SECRET level. These agreements are the basis for bi-lateral collaboration between the two nations, and the cross-sharing of technology and field experiments data. The UK's Defence Science and Technology Laboratory is also working with its industrial base and the U.S. Navy to explore advanced energy storage solutions for British warships.[519] This partnership involves the use of Formula 1 energy storage technology, specifically the flywheel energy storage system (FESS), which uses high-speed and lightweight flywheels to provide high-power electric pulses.[520] This collaboration aims to enhance naval power storage systems and improve their reliability and robustness, particularly in meeting the fluctuating power demands of DEW systems. Represented U.S. naval bodies are the Office of Naval Research, and Naval Sea Systems Command's (NAVSEA) Electric Ship Office (PMS 320). One of the UK's most promising laser programs, Dragonfire, also reportedly incorporates the flywheel energy storage system technology, developed jointly with the U.S. and UK. Regarding DEW testing, the partnership also extends to the U.S. Coalition Warfare Program and involves virtual and digital testing at Florida State University's Center for Advanced Power Systems (CAPS) with researchers from FSU and FAMU.[521] The UK's Ministry of Defense is also working with members of the U.S. defense industrial base to develop HEL technology.[522] Collaboration on component technology, i.e. beam control, is likely an ideal candidate for early DEW partnerships, according to one interviewee.

Israel

The United States and Israel have entered into a comprehensive partnership for directed energy cooperation. The United States-Israel Directed Energy Cooperation Act, part of the FY2021 National Defense Authorization Act, authorizes joint research, development, testing, and evaluation of DEW capabilities to address shared threats.[523] Notably, Lockheed Martin and Israeli company Rafael are collaborating on the development, testing, and manufacture of High Energy Laser Weapon Systems (HELWS), including variants of the Iron Beam laser system for both U.S. and export markets.[524, 525] Following the invasion of Israel by Hamas in October 2023, the Biden administration requested $1.2 billion in research, development, test and evaluation funding for Iron Beam which, if approved, would represent the most substantial U.S. investment in Israel's directed energy capabilities to date.[526] According to interviewees, there has also been a recent push for the Missile Defense Agency (MDA) to help coordinate U.S.-Israel collaboration on Iron Beam, given MDA's existing lead role in coordinating Iron Dome collaboration. Finally, the FY2023 NDAA expands the U.S.-Israel counter unmanned aerial systems program to include directed energy capabilities, raising the cap on annual U.S. contributions to the program from $25 to $40 million and extending the program's authorization through calendar year 2026.[527]

Japan

Japan and the United States have established a Memorandum of Understanding for Research, Development, Test, and Evaluation Projects for emerging defense technologies, including HPM systems.[528] Additionally, there is a bilateral, non-binding Security of Supply Arrangement (SOSA) between the U.S. Department of Defense (DoD) and the Japanese Ministry of Defense (MOD) "to exchange reciprocal priority support for goods and services that promote national defense."[529, 530] These agreements facilitate collaborative research efforts and ensure security of supply for emerging defense technologies. Japan has also been focusing on the development of its own C-UAS focused directed energy weapons.[531, 532, 533] According to industry interviewees, Japan is also a source of neodymium but there have been recent concerns from Japanese suppliers about the paperwork burden of supplying the U.S. defense industrial base, especially when they have large automotive clients who do not have as many restrictions.

India

The Biden and Modi administrations have committed to "promoting policies and adapting regulations that facilitate greater technology sharing, co-development, and co-production opportunities between U.S. and Indian industry, government, and academic institutions" and are making "regular efforts to address export controls, explore ways of enhancing high technology commerce, and facilitate technology transfer between the two countries."[534] The leaders also

> **"pledged to hasten bilateral collaboration to secure resilient critical minerals supply chains through enhanced technical assistance and greater commercial cooperation, and exploration of additional joint frameworks as necessary."[535]**

Solidifying this goal, India was welcomed as the newest member of the Mineral Security Partnership (MSP), an agreement designed to accelerate the development of diverse and sustainable critical energy minerals while adhering to environmental and governance standards.[536] Substantial emphasis has also been placed on joint workforce development efforts.[537] Regarding DEW development, Indian officials have emphasized the central role that directed energy weapons will play in future defense planning.[538] However, it is unclear from publicly available information if there is any partnership between the U.S. and India on DEWs specifically.

Areas for Allied Nearshoring & Expanded International Collaboration

Opportunities for Allied Nearshoring

Throughout the working groups, interviews, and internal research, participants raised several opportunities where international collaboration could potentially reduce DEW supply chain risk. As discussed in chapter 1, the United States is dangerously reliant on foreign adversaries for several critical raw materials relevant to directed energy systems. While domestic onshoring might guarantee more secure sourcing, sometimes it is not economically feasible or will take many years to reach full production. An alternative in the near term, might be allied nearshoring. However, implementing allied nearshoring strategies requires careful planning, investment, and collaboration among governments, defense industries, and research institutions, especially when identifying suitable allied partners for relocation or expansion. While it may entail initial costs, the long-term benefits of enhanced supply chain resilience, reduced risks, and strengthened international partnerships make allied nearshoring a prudent strategy for securing critical materials for DEWs.

Critical Raw Materials & Components

Australia and Canada, two strong allies of the United States, have large deposits of various materials necessary for directed energy weapons. The Canadian company, Teck Resources, is the largest producer of germanium in North America.[539] This could present an opportunity for the U.S. to limit reliance on adversary nations and instead source a critical DEW material from a close ally, if it is not already being leveraged. Similarly, with large deposits of rare earth elements, both Australia and Canada could provide an important alternative to China. An industry interviewee also noted that Japan has an available supply of gallium wafers, which the interviewee recommended the U.S. consider leveraging.

Another opportunity identified by a subject matter expert was sourcing beam control components from the United Kingdom. The expert described this as a component for which the UK had particular expertise and a well-established industry. During another industry interview, EEE components (Electrical, Electronic, & Electromechanical) were identified as components that could be sourced from allies, provided appropriate security measures were in place.

Given the strong collaboration between the U.S. and Israel, there could be additional opportunities specific to DEW supply chains and technical advancements. Considering Israel's Iron Beam program and the existing U.S.-Israel Directed Energy Cooperation Act, DoD could look for opportunities to leverage Israeli DEW supply chains in order to strengthen U.S. DEW supply chains. While the specific areas would need to be evaluated in the context of maintaining strict security, there could be opportunities at the component or sub-component level. Finally, one interviewee mentioned that the U.S. should consider leveraging DEW technical advancements by Israel especially in coherent beam control.

While there is very little in open literature on Swedish DEW development outside of basic academic research[540], one interviewee suggested collaborating to address system integration challenges.

Given that Sweden is the only European country to build indigenous fighters and fly their own domestically built Air Force, the interviewee highlighted a potential opportunity for collaboration with the U.S. on airborne DEW systems. While such a collaboration necessitates appropriate security measures to protect sensitive technology, this could be a potential opportunity to leverage a systems engineering workforce with significant experience.

Testing

Joint testing offers nations the opportunity to combine their resources, research facilities, and scientific expertise, resulting in comprehensive, cost-effective evaluations of DEW technologies. This collaborative approach allows for a more extensive exploration of DEW systems, drawing on a broader range of insights and innovative ideas. It also provides access to specialized equipment, ranges, and facilities that individual nations may not possess. Such collaboration accelerates the development of cutting-edge DEW technologies, ensuring that the best minds from around the world work together to solve complex problems. Furthermore, joint testing of DEW technologies often occurs in varied operational environments. This includes testing in different geographic regions, climates, and scenarios, offering valuable insights into how these systems perform under real-world conditions. Joint testing also promotes interoperability among allied forces, a critical element in modern military operations where international cooperation is often required to address global threats. When DEW technologies from various nations are tested together, it encourages the development of common standards and protocols. This ensures that DEW systems can seamlessly operate alongside each other during multinational military operations, enhancing overall effectiveness.

Australia presents substantial potential as a testing partner. The previously mentioned testing range outside of Melbourne is an advanced facility "expected to house high-power laser research and development labs, sensors capable of operating and analyzing high-power lasers, advanced fabrication equipment, [and] an additive and subtractive manufacturing center".[541] Further, the facility has the ability to rapidly prototype, build, and test high power laser systems in both simulated and real-world environments without the need to conduct expensive outdoor trials.[542] One challenge raised by working group participants and interviewees was the higher cost of testing with Australia, given the cost of moving systems physically to the Australian continent. However, considering current testing limitations in the U.S. (discussed in chapter 2), facilities such as these could play a major role in speeding up the development of DEW capabilities, especially regarding C-UAS weapons. Both working group participants and interviewees raised that Canada could also serve as a potential testing partner, given its vast and remote territory with fewer major commercial flight paths, that could provide opportunities for realistic evaluations of DEW systems. Finally, one interviewee mentioned that American Indian Reservations with airstrips provide an opportunity for additional DEW testing that does not face the same FAA restrictions.

Barriers to International Collaboration

According to working group participants, international partners and allies face significant barriers in engaging with the U.S. on emerging technologies, including DEWs. Regulatory complexities, classification issues, and intellectual property challenges have all proven to be consistent limiting factors. Additionally, the lack of a unified approach to collaboration and a clear, single point of entrance for entities wanting to work with DoD, makes international collaboration challenging. This often results in duplicated research, inefficient allocation of resources, and missed opportunities for collaboration in DEW development. These factors may also be exacerbated by inter-service competition as different branches vie for funding and superior equipment. In all cases, streamlining collaboration is essential to overcome these challenges, fostering a more coordinated, efficient, and effective approach to advancing DEW technologies and securing their future supply chains.

ITAR Challenges

The International Traffic in Arms Regulations (ITAR), which "governs the manufacture, export, and temporary import of defense articles, the furnishing of defense services, and brokering activities involving items described on the United States Munitions List (USML)", pose a series of challenges for international collaboration on DEW technology.[543] Challenges with ITAR were raised by numerous working group participants and interviewees. While a full analysis of the challenges of ITAR is beyond the scope of this report, this section will discuss a few related to directed energy technology. These challenges are especially daunting given the potential that select international markets possess to facilitate an expanded demand signal to American industry and to provide niche expertise in the development of new directed energy technologies. One of the primary challenges posed by ITAR is its broad and often stringent control over the export of DEW-related technologies and information, according to working group participants.[544] As a result, researchers, scientists, and institutions in allied countries may face considerable difficulties in accessing essential DEW-related data, equipment, or expertise, impeding the collaborative exchange of ideas and advancements. Furthermore, the bureaucratic complexities of ITAR compliance can lead to delays and uncertainties in international DEW collaborations. Navigating the intricate web of export control regulations demands significant time and resources, potentially causing promising collaborators to hesitate or abandon projects altogether. The requirement for licenses and authorizations adds another layer of complexity, potentially causing delays that can be detrimental to research timelines and innovation.[545] Additionally, the complexity in the application of ITAR regulations to cutting-edge DEW technologies, many of which are dual-use, can create confusion and risk aversion. Researchers and institutions may err on the side of caution, opting not to engage in collaborative endeavors for fear of inadvertently violating export control laws. This hesitancy can hinder the free flow of ideas and collaborative spirit that are crucial for advancing DEW research and development. A recent report on the challenges that ITAR especially pose to AUKUS summed up these challenges into two categories, 1) "practical issues relating to inefficiencies in the current suite of export control frameworks and processes," and 2) "intangible conceptual issues including the desire for control over innovation…"[546] The same report describes the crux of the problem as

"...under present guidelines, Australia is effectively regarded as being on equal legal terms as a country like Serbia."[547] This regulation does not set AUKUS up for success and therefore impedes the potential for international cooperation on emerging technologies, including DEWs. To overcome these obstacles and promote international collaboration in DEW research and development, there is a pressing need for greater clarity, transparency, and flexibility in export control policies. Striking a balance between security concerns and the benefits of collaboration is essential for advancing DEW technologies and ensuring their future resilience and effectiveness.

Classification Challenges

The overclassification of information, along with the sometimes excessive use of Controlled Unclassified Information (CUI) designations and "not releasable to foreign nationals" (NOFORN) restrictions, presents formidable obstacles to international collaboration on directed energy weapons.[548] These practices, raised by both working group participants and interviewees, are intended to safeguard sensitive information, but often result in unintended consequences that hinder collaboration and innovation. Overclassification can unnecessarily restrict the flow of knowledge critical to DEW research. In some instances, information that should be accessible to trusted foreign partners is classified due to strict security guidelines. This overclassification impedes the sharing of fundamental research findings, technologies, and best practices that could accelerate DEW advancements. Multiple working group participants emphasized that the widespread use of CUI and NOFORN designations further complicates international collaboration. While these designations can be essential for protecting sensitive data, their excessive application can create barriers to effective communication and cooperation. DEW research could often benefit from collaboration across borders, and the stringent limitations imposed by these designations can frustrate the exchange of information, even when it poses no real security risk. Consequently, opportunities for pooling expertise, sharing resources, and collectively addressing DEW challenges become unnecessarily limited. To promote international collaboration in DEW research and development, a more nuanced and flexible approach to classification and information sharing is needed, while still ensuring necessary information is protected.

Intellectual Property Challenges

Intellectual property (IP) challenges are an impediment to collaborative directed energy research and development efforts, often involving multiple organizations, nations, or entities with proprietary knowledge and innovations. While IP challenges are not unique to DEW supply chains and have been addressed in a variety of ways in the past, issues surrounding IP are still too prevalent to ignore. While a full analysis of this issue is beyond the scope of this paper, IP concerns were raised by multiple working group participants and interviewees as a potential barrier to successful international collaboration on DEWs. According to multiple interviewees, one of the primary IP challenges is determining ownership. In cases where multiple entities contribute to the development of a DEW technology, questions arise regarding who owns the resulting intellectual property. Clear agreements must be established upfront to outline the rights and responsibilities of each party involved. These agreements may define joint or sole ownership based on contributions and investments. Licensing and technology transfer agreements are another crucial aspect. Collaborators must decide how intellectual property rights will be licensed or transferred among parties.[549] Furthermore, protecting IP from unauthorized access or misuse is paramount, particularly when classified or sensitive information is involved. Robust security measures and protocols must be in place to safeguard IP assets and comply with national security regulations.[550] Resolving potential IP issues is essential to prevent disputes that could impede the progress of collaborative DEW projects. Effective management of IP ensures that all parties benefit from shared knowledge and innovations while incentivizing ongoing collaboration in the advancement of DEW technologies.

Summary

In conclusion, the United States should leverage international partnerships and collaboration in order to secure DEW supply chains. With large deposits of critical raw materials, Australia and Canada present an opportunity to reduce supply chain risk by reducing U.S. reliance on China. There could also be an opportunity for the U.S. to leverage gallium supply from Japan that should be explored further. The U.S. should also work with both Australia and Canada to address DEW testing challenges in the near term. Given its advanced DEW capabilities, Israel presents an opportunity for leveraging technical advancements. However, significant barriers including complicated export controls, overclassification, and IP challenges often impede international collaboration. These must be addressed in order to secure DEW supply chains for the future.

Recommendations

1. The Department of Defense should actively seek opportunities to increase international partnerships, especially with Australia and Canada, to address DEW testing issues. As discussed in chapter 2, the U.S. faces challenges with the regulations surrounding DEW testing infrastructure. While domestic solutions should be actively pursued, DoD should also look to close international partnerships to address some of the issues. Australia, with its advanced testing range outside of Melbourne,[551] the Klondyke Range Complex[552], and other DEW test ranges, stands as a particularly promising testing partner. While there is a significant cost for moving DEW systems to and from Australia for testing, according to interviewees, the potential for less restrictive testing windows could greatly benefit DEW development. Canada could also offer significant testing opportunities due to its vast and remote territory, much of which is outside of major commercial flight paths. DoD should conduct a feasibility study for a DEW testing range in Northern Canada. If feasible, DoD could then solicit industry investment and a cost-sharing agreement with the Canadian Ministry of Defence to begin construction. Overall, the existing U.S. DEW testing infrastructure is insufficient for scaling up DEWs in the future and expanded international partnerships could address some of these issues.

2. The Department of Defense should designate the Joint Directed Energy Transition Office as the office of primary responsibility for international collaboration on Directed Energy Weapons. Several working group participants described the challenge that international partners face in identifying what organizations to work with within the U.S. Government on directed energy. One way to remedy this is for DoD to designate the Joint Directed Energy Transition Office (JDETO) as the office of primary responsibility for international collaboration on directed energy. While many offices across OSD, the services, and others, have equities, it would benefit international collaboration to have a single point of entrance for international partners.

3. The Joint Directed Energy Transition Office should work with the Israeli Ministry of Defense to identify opportunities where the U.S. and Israel can combine demand for key DEW subsystems and S&T components. While ensuring that appropriate security measures are in place to protect sensitive information, the U.S. should look to expand partnerships with Israel. Given that Israel has fielded DEW systems, the Joint Directed Energy Transition Office should work with the Israeli MoD to identify opportunities for collaboration to mitigate vulnerabilities in the U.S. DEW supply chains. A common challenge heard throughout the working groups and interviews was the lack of demand signal for DEW-specific components. One potential way to address this issue is to work with allies and partners, especially Israel, to identify opportunities to "pool" demand for particular subsystems. Consistent, increased demand will help to grow the manufacturing base needed to secure U.S. DEW supply chains of the future. Second, there may be opportunities for the U.S. to leverage Israeli technical advances in DEWs. One area mentioned by an interviewee was coherent beam control.

4. The Department of Defense (OUSD A&S International Cooperation Office and DSCA) should work with the State Department (Bureau of Political-Military Affairs, Office of Regional Security and Arms Transfers (RSAT)) to adjust the Foreign Military Sales (FMS) program to enable the export of low power (50kw and under), disruptive DEW technology to allies and partners. Given the current lack of substantial government demand for DEW technology in the United States, sales to select allies and partners could complement DoD's DEW roadmap, creating the necessary demand signal to boost U.S. manufacturing while amortizing costs. Expanding the customer base would allow the time-consuming process of building up domestic DEW manufacturing capabilities to begin, enabling American industry to adequately meet DoD requirements in the future. Additionally, these sales could potentially counter the spread of Chinese DEW technology. Given the fairly advanced state of Chinese DEW systems compared to the majority of other nations, and considering China's existing efforts to sell arms abroad, it is possible that the Chinese government will attempt to export DEW technology.[553] This spread would both deprive the U.S. of opportunities to strengthen international interoperability, and could also link more nations to the Chinese defense network. While the sale of more technologically advanced and high-power DEWs is rightfully heavily restricted due to classification concerns and arms sale regulations, low-power disruptive weapons could be the ideal candidates for international sale, according to working group participants and interviewees. Due to their lower complexity and cost, these systems could also be easier to integrate into the force structures of international forces and could present fewer regulatory issues. By enabling the international sale of these weapons systems, to select countries, both strategic concerns and domestic demand signal considerations could be addressed.

5. The U.S. Department of Commerce working with the Department of Defense and the relevant interagency players,[xiii] should create a joint export control policy for directed energy weapons. According to working group participants, the Navy International Programs Office (NIPO) recently published the first service export policy for DEWs. While this is an important step towards determining the appropriate level of international collaboration on DEWs, a joint export control policy would benefit the government and industry by standardizing regulations. At the same time, it would also benefit foreign partners by supporting and simplifying international collaboration on DEWs, where appropriate. This policy should take a variety of factors into account, but subject matter experts agreed DEW exports would benefit from being tiered by country and DEW technology.

xiii This will require numerous agencies and offices including the State Department, Department of Commerce, White House, and Congress.

Conclusion

The United States has long relied on technological superiority to give its military an immeasurable advantage on the battlefield, and the defense industrial base has played a critical role in maintaining this advantage. Now, in a new era of great power competition, battlefield advantage is often determined by how countries are developing and deploying emerging defense technologies efficiently and at scale. In the U.S., multiple directed energy weapons programs are moving closer towards transitioning from the lab onto the battlefield. However, as this report demonstrates, the current directed energy supply chains are insufficient to support fielding DEW systems at scale. As such, DoD, industry, and academia must take steps today to strengthen the DEW supply chains of the future.

The lack of a consistent demand signal from DoD, accompanied by clearly articulated strategic vision for DEWs has led to an industrial base only capable of fielding small numbers of systems with long lead times. DoD must provide a clear vision and demand signal through consistent funding as the first step in securing DEW supply chains for the future.

At the same time, U.S. reliance on adversarial nations for critical raw materials and goods is another significant issue not only for DEWs but many other sectors and supply chains as well. Germanium, gallium, and rare earths are all critical across the spectrum of DEWs, and all are primarily sourced from or processed in China. The United States must work to build domestic production capacity for critical resources, enhance stockpiling efforts, increase supply chain transparency, expand interdepartmental collaboration efforts, and invest in alternative options to the most vulnerable materials.

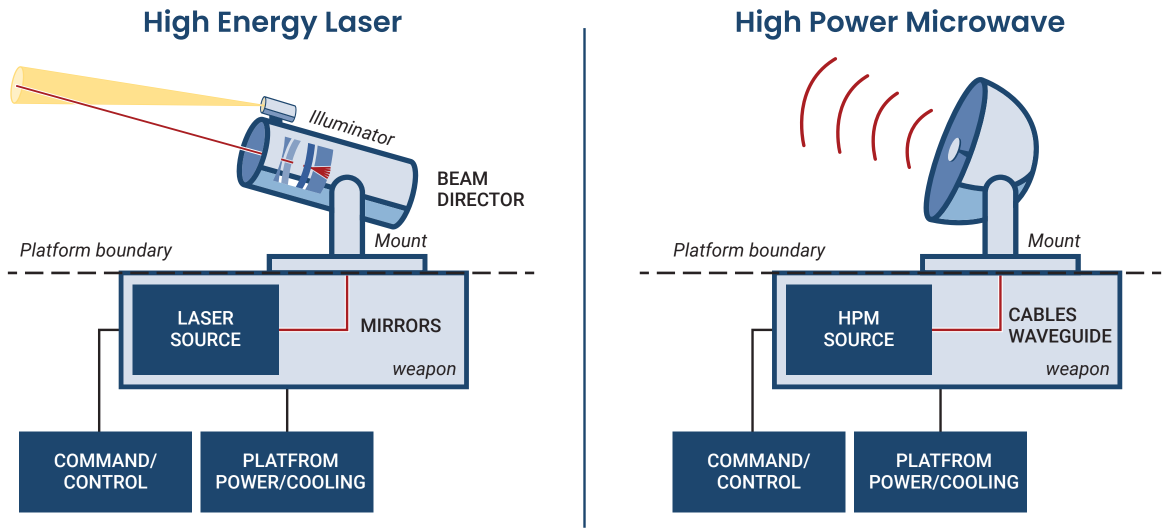
The DEW manufacturing base and workforce also require significant attention in order to address key vulnerabilities. Once DoD establishes clear strategic guidance regarding the number of DEW systems it requires, on what timeline, and for what tactical and operational purpose, the DIB can adequately begin to prepare to meet anticipated demand. Many DEW components, especially optical components, require high degrees of customization and time-consuming manufacturing processes that can result in long lead times and delays. This challenge is exacerbated when there are a limited number of suppliers and shortages of critical components. The supply of batteries and semiconductors also poses tremendous challenges for the future. Additionally, regulatory issues severely limit domestic testing capabilities. Without adequate testing, even the most promising DEW technologies will fail to transition from the laboratory to the field. However, steps can be taken now to address these issues. DoD ManTech should invest in the domestic DEW coatings manufacturing base in order to expand capacity and quantity. Industry and DoD should work together to identify and leverage commercial technology for DEW components to facilitate a more efficient production process and secure supply chains. DoD should designate more existing testing sites as "Special Use Space Ranges" to permit expanded testing of DEWs. DoD should also invest in testing workforce development as well as artificial intelligence and machine learning to improve DEW testing capabilities during the early stages of R&D. To further facilitate workforce development, DoD should also establish a Directed Energy University Consortium with the clearly defined goal of creating a strong workforce to meet future directed energy weapon needs.

Within DEW supply chains, limited suppliers pose a significant security risk. While the overall financial health of these companies is generally positive, the failure of even a single company could be catastrophic to the supply chain. Cyberattacks, economic espionage, and foreign investment are also significant security risks. In order to address these challenges, DoD and industry need to take steps today. First, DoD should consider the use of AI to anticipate potential supply chain failure points. This will require a significant change in how DoD approaches data-sharing but is a crucial step to securing DEW supply chains for the future. DoD should also develop and prioritize overlapping components for DEW systems between different programs in order to simplify and secure the supply chains. Finally, DoD should also conduct regular, in-depth analysis of the financial stability and security risks of companies involved in the DEW supply chains.

International partnerships in directed energy could also play a pivotal role in continuing to mature DEW technology and secure DEW supply chains. Increased cooperation with Israel, Australia, and Canada, in particular, could address domestic testing limitations and reliance on adversaries for critical raw materials. However, many obstacles exist that prevent the full realization of U.S. international partnerships. Overclassification consistently prevents both the sharing of critical information and meaningful dialogue from taking place. The complexity inherent with the ITAR and similar export controls creates further barriers to collaboration on DEW technology, often resulting in widespread delays and uncertainties regarding otherwise promising partnership opportunities, while also limiting the DIB's ability to take advantage of foreign demand. Concerns about intellectual property and technological ownership, as well as a lack of clarity on the proper channels to engage the U.S. government and defense industry, also lessen the appeal of collaboration. To address these challenges, the U.S. must streamline and consolidate its approach to international DEW partnerships, and reform archaic guidelines and regulations.

The U.S. does not have the luxury of time with its DEW development. Adversaries have made progress with their own directed energy programs, and this progress shows no signs of abating. While the outlook of this report may at times seem bleak, the challenges that have been identified are not insurmountable. However, a proactive, collaborative approach is essential. Ensuring the health and resilience of DEW supply chains will take a great deal of sustained effort and resources, but this commitment will leave the United States well-prepared for the future.

Annex 1: Visual Representation of HEL vs. HPM[xiv]



Annex 2: DOTMLPF-P

(Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities – Policy)

The development of a comprehensive DOTMLPF-P analytical framework represents a strategic investment in the successful integration, operation, and maintenance of directed energy capabilities within the operational environment. While this issue is not directly relevant to future DEW supply chains, it is very important to the sustainment of DEW systems and was raised by multiple interviewees and working group participants. Supply chains cannot properly prepare for the sustainment of DEW systems without this framework, and, to date, little effort has been dedicated to many of the following considerations. While a full analysis of the topic is beyond the scope of this paper, DoD needs to focus on the following for DEW in the future:

Doctrine: DEW capabilities necessitate the formulation of new doctrines that outline the tactical and strategic employment of these technologies. The analytical framework guides the armed services in developing standardized procedures, rules of engagement, and operational concepts that maximize the impact of DEW systems while adhering to legal and ethical considerations.

Organization: Integrating DEW capabilities within existing military structures requires a reevaluation of organizational hierarchies, roles, and responsibilities. The DOTMLPF-P framework enables the armed services to adapt their organizational structures to accommodate DEW technologies effectively, ensuring efficient coordination and communication among units and personnel responsible for DEW operations.

Training: Successful DEW integration hinges on a well-trained workforce capable of operating, maintaining, and troubleshooting advanced DEW systems. The framework emphasizes the development of tailored training programs that equip military personnel with the skills and knowledge required to effectively operate DEW technologies in dynamic and high-stakes environments. A largely neglected portion of this training is the development of reliable battle damage assessments (BDAs). Currently, there are not clear benchmarks of what constitutes a mission kill, especially when using HPM weapons meant to damage sensors. Since these weapons often leave little sign of physical damage, clear training guidelines are required to properly identify successful engagements.

Materiel: DEW systems involve intricate components, materials, and technologies that require careful selection, integration, and maintenance. The analytical framework guides the armed services in making informed decisions about DEW system procurement, integration, and sustainment, ensuring that materiel choices align with operational requirements and long-term supply chain considerations.

Leadership and Education: As DEW technologies are integrated, strong leadership and education play a vital role in guiding strategy, promoting innovation, and cultivating a culture of responsible use. The DOTMLPF-P framework emphasizes the importance of leadership development and education initiatives that empower military leaders to effectively manage DEW capabilities and foster a skilled and ethical workforce.

Personnel: An integral part of the framework is its emphasis on personnel considerations. It ensures that military personnel with the appropriate expertise and skills are assigned to DEW-related roles, fostering a workforce that is not only capable of using DEW technologies but also dedicated to their ongoing development and optimization.

Facilities: DEW operations may require specialized facilities and infrastructure to support their deployment and usage. The analytical framework assists in identifying facility needs, designing optimal spaces for DEW operations, and ensuring the availability of adequate resources to accommodate DEW capabilities.

Policy: DEW technologies necessitate clear and well-defined policies that govern their deployment, usage, and ethical considerations. The DOTMLPF-P framework encourages the establishment of robust policy frameworks that ensure responsible and secure utilization of DEW capabilities while adhering to legal and ethical guidelines

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Annex 3: Recommendations

Critical Raw Materials and Goods

1. The Department of Defense, working with Congress, should add gallium to the National Defense Stockpile.
2. Industry, in collaboration with academia, as well as federal, state, and local government, should take steps to build a domestic gallium nitride (GaN) production capability.
3. The Department of Defense should invest in synthetic alternatives for DEW optics materials and other critical directed energy weapon materials.
4. The U.S. Department of Defense and Industry should work together to develop a method to increase government visibility of the origin of raw materials for directed energy weapons.
5. The U.S. government should incentivize the use of domestically produced batteries in DEW systems by DoD entering into long term contracts with domestic battery manufacturers, where fiscally prudent, providing financial incentives to promote domestic competitiveness with the long-term goal of reducing current reliance on China.
6. The Department of Defense and the Department of Energy should coordinate efforts focused on ensuring the security and resilience of critical resource supply chains for emerging technologies, including directed energy technology.

Manufacturing Base

1. The Department of Defense should clearly articulate its strategic goals for DEWs and provide a clear demand signal to industry by designating appropriate DEW systems as programs of record.
2. The Offices of the Under Secretaries of Defense for Acquisition & Sustainment and for Research & Engineering, partnering with the Joint Staff and a technical or industrial association, should collaborate with industry and academia on requirements definition of future directed energy systems.
3. The Department of Defense should create a centralized data system under the Joint Directed Energy Transition Office for the services and relevant agencies to compile lessons learned from various DEW research, experimentation, and testing, and, where appropriate, share key takeaways with industry.
4. Through the Department of Defense Manufacturing Technology Program (ManTech), the DoD should invest in the domestic DEW coatings manufacturing base to expand both the capacity and quality of available coatings.
5. Industry and the Department of Defense should work together to identify and leverage commercial technology for DEW components to facilitate a more efficient production process and secure supply chains.
6. The Department of Defense should work with industry to publish testing and measurement standards to clearly identify necessary specifications for DEW components and standardize parts between systems where possible.
7. The Department of Defense should reassess specification requirements for new DEW capabilities to incorporate greater input from the warfighter and technical subject matter experts.

Testing & Workforce

1. The Department of Defense should designate more existing testing sites as "Special Use Space Ranges" to permit expanded testing of DEWs.
2. The Department of Defense should ensure that workforces at DEW testing facilities are adequately trained to test both HPM and HEL capabilities.
3. The Department of Defense should establish a Directed Energy University Consortium with the clearly defined goal of creating a strong workforce to meet future directed energy weapon needs.
4. OUSD A&S should conduct a DEW workforce study to understand the future needs of its planned programs and industry partners.
5. The Department of Defense should invest in artificial intelligence and machine learning (AI/ML) software techniques to improve DEW testing capabilities during the early stages of R&D, thereby reducing the need for above-the-horizon DEW testing and limiting the impact of current testing challenges and restrictions.

Supply Chain Security and Vulnerabilities

1. Following the example of the common-hypersonic glide body, the military services should collaborate on the development of overlapping components and subsystems of DEW systems in order to simplify weapon designs and secure DEW supply chains.
2. Industry and the Department of Defense should use AI-driven predictive analysis to anticipate failure points in both DEW supply chains and individual DEW systems.
3. Industry leadership, at all tiers of the directed energy supply chain, should increase awareness of the threat of counterintelligence and economic espionage by foreign adversaries.
4. With Congressional funding, OUSD A&S should conduct further analysis into companies within the DEW industrial base with high-risk financial health in order to identify opportunities for potential investment.

International Partnerships and Allied Nearshoring

1. The Department of Defense should actively seek opportunities to increase international partnerships, especially with Australia and Canada, to address DEW testing issues.
2. The Department of Defense should designate the Joint Directed Energy Transition Office as the office of primary responsibility for international collaboration on Directed Energy Weapons.
3. The Joint Directed Energy Transition Office should work with the Israeli Ministry of Defense to identify opportunities where the U.S. and Israel can combine demand for key DEW subsystems and S&T components.
4. The Department of Defense (OUSD A&S International Cooperation Office and DSCA) should work with the State Department (Bureau of Political-Military Affairs, Office of Regional Security and Arms Transfers (RSAT)) to adjust the Foreign Military Sales (FMS) program to enable the export of low power (50kw and under), disruptive DEW technology to allies and partners.
5. The U.S. Department of Commerce working with the Department of Defense and the relevant interagency players, should create a joint export control policy for directed energy weapons.

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