ENERGY WEB DOMINANCE

A Proposal for a Fourth Offset Strategy

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America's military advantage in power projection has eroded significantly due to adversarial anti-access/area-denial (A2/AD) strategies. A multidomain, networked peer adversary combat environment has emerged from these A2/AD strategies, threatening longstanding military trends. Recognizing that energy is a fundamental element in warfare, researchers at the Defense Advanced Research Project Agency have developed an energy web dominance portfolio to explore innovative methods of optimizing energy distribution to create a more dynamic and resilient network. This energy web dominance framework provides a novel perspective on the fundamental character of warfare, revealing new opportunities for optimizing military effects delivery leveraging wireless energy distribution technology breakthroughs.

Energy and information are fundamental currencies in the battlespace. Since the 1700s, there has been a revolution in information transport, transforming its flow from physical point-to-point transfers such as paper letters into a more resilient multipath network, such as data through the World Wide Web. More recently, ubiquitous wireless communication has dramatically transformed the flexibility and utility of information distribution.

Recent research pioneered by the Defense Advanced Research Projects Agency (DARPA) suggests a similar revolution may be imminent in the energy domain. Causing or delivering military effects costs energy. Wireless power transfer capabilities being developed as part of DARPA's energy web dominance (EWD) portfolio provide one compelling candidate breakthrough technology which may transform the battlespace, providing the next significant technology offset in warfare.

This article introduces energy web dominance as an analysis framework that recognizes the centrality of energy in the battlespace. This framework provides strategic and tactical insight into optimizing military effects delivery considering energy generation, storage, and distribution. The context for this optimization is the networked,

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multidomain sense-and-kill capabilities developed by adversarial nations that the author and team members refer to as the peer adversary combat environment or PACE.

In the 1980s and 1990s, the United States developed stealth- and precision-guided weapons technologies as part of the Second Offset Strategy to defeat the former Soviet Union's legacy integrated air defense systems (IADS), which primarily used ground radars for sensing and centralized command and control (C2) to direct responses. Desert Storm provided validation of the Second Offset's effectiveness against a legacy IADS approach. Seeing that the traditional IADS approach was ineffective against US tactics and force structures, adversarial nations developed anti-access/area-denial (A2/AD) strategies as a counter.[1]

The peer adversary combat environment, then, is the instantiation of A2/AD strategies. Today, this environment is no longer just a strategic framework but rather a physical environment where US forces must survive, operate, and dominate to achieve military effectiveness, and countering this environment requires a new approach. The EWD framework provides a novel perspective on the fundamental character of warfare, revealing new metrics for optimizing the delivery of military effects.

Background

Significantly, the current US military force structure remains rooted in Second Offset weapons and platforms even though the peer adversary combat environment was specifically developed to counter those systems. Second Offset–era trends have led to high-cost, high-capability manned platforms, such as B-2s and aircraft carriers. In the modern combat environment, incremental increases in survivability are prohibitively expensive, leading to limited quantities of these assets. Losing even one of the United States' 19 B-2s or 11 aircraft carriers would have a significant impact on US military capability. This is in addition to the raw cost. It is feasible in the peer adversary combat environment that a $1 million missile could destroy a $2.2 billion B-2, magnifying the cost imposition for the United States and leading to a losing resource race against a peer adversary.[2]

In 2016, recognizing a new strategy was imperative, then Under Secretary of Defense Robert Work proposed a Third Offset Strategy in policy speeches. In this offset strategy, he stated networked human and machine teams in large quantities would be able to overwhelm A2/AD environments and sustain the United States' ability to project military power.[3] A key element of his approach is resilient, multipath information networks adaptively concentrating information for decision-making and command and control. A remaining challenge is developing platforms that can be employed in large quantities at

1. Rebecca Grant, "The Second Offset," *Air & Space Forces Magazine*, June 24, 2016, https://www.airandspaceforces.com/.

2. Jacopo Prisco, "B-2 Spirit: The $2 Billion Flying Wing," CNN, January 29, 2020, https://www.cnn.com/.

3. Ian Livingston, "Technology and the 'Third Offset' Foster Innovation for the Force of the Future," Brookings, December 9, 2016, https://www.brookings.edu/.

long ranges. Insights from the information revolution in Work's Third Offset applied to the energy distribution are the foundation of the DARPA EWD portfolio's presentation of a Fourth Offset Strategy to enable long-range platforms in overwhelming quantities.

Currently, if a platform requires long-range, endurance, or significant weapons-delivery capability, it must be physically large. Platforms are designed as containers that carry the energy needed to complete a mission in the form of liquid fuels, batteries, or chemical explosives. These large platforms are expensive and are therefore purchased in limited quantities. Some research, such as DARPA's Gremlins and LongShot programs, has looked at providing large quantities over long ranges by using large hosts and with small surrogate aircraft.[4] Other research looked at aggregating and disaggregating small platforms to achieve the benefits of efficiency or resilience depending on the threat. These programs suggest such architectures are effective and feasible with current technology but also highlight fundamental limitations in energy storage.

Second Offset technology has logically led to a platform-centric force structure due to assumptions about information and energy. Decision-making was accomplished at the platform level by human operators putting a lower limit on platform size and driving survivability requirements to preserve human life. Energy is also stored at the platform level, coupling performance to volume.

Following Norman Augustine's 16th "law," as platform capability has increased, there has been an exponential increase in costs: "In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3½ days each per week except for leap year, when it will be made available to the Marines for the extra day."[5]

Though Augustine published his laws as satire, the data has validated the underlying trend: in static or linearly increasing budget environments, the number of platforms purchased has steadily decreased.[6] As the number of platforms decreases, the need for individual platform survivability increases, which further accelerates the trend. This is sustainable if survivability can be improved commensurate to the cost increases and if enough platforms still exist to provide flexibility.

Yet threats in the peer adversary combat environment have changed significantly, making further incremental increases in survivability prohibitively expensive. At the same time, technological opportunities have also changed, challenging the underlying assumptions that led to the current force structure. Advances in autonomy and networked information allow for distributed C2 so that a human operator is not necessary on many platforms. A wireless energy web could provide a radical alternative by allowing platforms to act as conduits rather than containers.

4. See Paul Calhoun, "DARPA Emerging Technologies," *Strategic Studies Quarterly* 10, no. 3 (Fall 2016), https://www.airuniversity.af.edu/; "Gremlins," DARPA (Defense Advanced Research Projects Agency), accessed April 11, 2024, https://www.darpa.mil/; and John Casey, "LongShot," DARPA, accessed April 11, 2024, https://www.darpa.mil/.

5. Norman R. Augustine, *Augustine's Laws* (Boca Raton, FL: United Press International, May 24, 1986).

6. Calhoun, "DARPA Emerging Technologies."

The amount of energy a platform could carry would not be a performance constraint; rather, the energy that flows through the network would enable capabilities. Offboarding energy storage and generation would decouple platform size from performance. Of note, many military missions require more energy than is available by only harvesting or scavenging energy—for example through photovoltaic solar cells—which drives the need to externally augment energy inputs. Wireless energy beaming (WEB) technologies in development at DARPA coupled with distributed C2 would enable small, inexpensive platforms to have significant capabilities, such as practically unlimited range, indefinite persistence, and arbitrary amounts of power available for their payloads or weapons.

In contrast to the Second Offset's platform-centric approach, the Third and Fourth Offsets encourage a network centric-approach where capability is scalable by adjusting the quantity of platform nodes employed in any given scenario. The network, not the platform, becomes the nexus of capability. Individual nodes are attritable and thus can be dramatically less expensive, since the strategy shifts to overwhelming with quantity rather than exquisite survivability. As an example, a B-2 has a fixed capability whether it is employed against a highly defended target or an undefended target. Since the most constraining cases are rare, in most employment scenarios the B-2 has excess capability, which means from a resource standpoint, delivering that effect costs more than necessary.

Scaling capability through quantity considers that the simplest targets are vulnerable to a single wireless energy beaming platform. When facing more complex targets, more WEB platforms are used to overwhelm defenses. As a result, capabilities are scalable across a range of scenarios optimizing resource allocations.

There is an ongoing, robust debate about the correct mix of high-technology and low-technology platforms. Assuming a solitary platform type can scale in capabilities across all scenarios is overly simplistic, but such an assumption provides useful guidelines, implying that WEB technologies provide advantages across the spectrum of threat environments. Relying on inefficient capabilities overmatch as done now may be acceptable against a resource-poor adversary. Against an economic peer, however, sustained operations rely on efficient effects delivery.

Energy in the Battlespace

The revolution in platform capability is an important element of implementing WEB, but understanding the impact of energy flows in the battlespace is actually even more fundamental. Throughout history, warfare has favored the combatant who can effectively maneuver and resupply their forces. As General John J. Pershing once said, "Infantry wins battles, logistics wins wars."[7] Fundamentally, logistics is about

7. Jason Lee, "New Logistics Commander Praises 'Complex,' 'Important' Work at Hill Air Force Base," KSL.com, August 31, 2017, https://www.ksl.com/.

transporting the capability to cause military effects, and energy is the coin of the realm. The form of that energy has evolved over time.

During the Roman Empire this energy came in the form of food for horses and men converted to military effects through physical action. In the Civil War, coal for trains and gunpowder for muskets were the preferred energy storage mediums. In the modern era, chemical energy is stored in explosive warheads and liquid hydrocarbon fuels. Energy transport breakthroughs such as Roman roads, railroads, mechanized warfare, and air-refueling tankers that more rapidly and resiliently move energy through the battlespace have provided decisive military advantages. Indeed, contemporary American military dominance has been built upon asymmetric advantages in air refueling tankers and a nuclear navy, allowing the United States to position mobile energy wells forward in the battlespace.

Noting this advantage, adversary nations have specifically developed weapons to counter air refueling tankers and carrier strike groups as a core tenet of their A2/AD strategy from which the peer adversary combat environment has emerged. While tankers and nuclear carriers have provided that decisive advantage in the past, maintaining energy web dominance in the future will require a new approach.

To paraphrase Antoine Henri Jomini, the science of war is focusing energy on decisive points.[8] The corollary art of war, which is analyzing the battlespace to determine where those decisive points exist, can be considered an information domain endeavor. In John Boyd's now canonical observe, orient, decide, act (OODA) loop, there are information and energy domain elements for each iteration.[9] Observation requires some sensor with physical presence that requires energy to persist in its given environment. Orienting is an information domain function consisting of sifting data for sense making then delivering that information to a decision hub. Deciding is an information domain activity to determine an optimal course of action based on available data. Acting requires an energy transaction to both cause and deliver the intended military effect.

Since the early 2000s, net-centric warfare has revolutionized information flows, including significant work over the last decade in developing artificial intelligence/machine learning tools to enhance decision-making.[10] Energy logistics, on the other hand, have remained relatively static since the advent of mechanized warfare, which still relies primarily on mass-based transfers of liquid fuels that are slow, linear, and vulnerable. Energy web dominance considers end-to-end effects delivery with no clear boundary between logistics and tactics. Instead, there is a continuum where the optimal network adjusts between efficiency and resilience, depending on the existing threat. Generally, networks with fewer nodes are more efficient while networks with more redundant nodes are more resilient.

8. Antoine Henri Jomini, *The Art of War* (St. Paul, MN: Wilder Publications, 2008).

9. John R. Boyd, *A Discourse on Winning and Losing*, ed. and comp. Grant T. Hammond (Maxwell AFB, AL: Air University Press, 2018).

10. Arthur K. Cebrowski and John H. Garska, "Network-Centric Warfare – Its Origin and Future," *US Naval Institute Proceedings* 124, no. 1 (January 1998), https://www.usni.org/.

Imagine the battlespace populated by energy nodes. In the all-domain battlespace of today, a tanker is a node, an aircraft carrier is a node, and an F-22 is a node. Each participant consumes and delivers energy as needed to achieve military effects. Imagining the battlespace as a network of energy nodes provides a new optimization surface for quantifying effects delivery versus costs. If these nodes are connected by physically transferring energy via liquid fuel, they accept limitations in flexibility since such a transaction is predictable and slow. As technological advances create nodes that flow energy wirelessly through the electromagnetic spectrum, combatants will see considerable increases in speed and flexibility.

Within the current energy logistics construct, chemical energy stored in a warhead might be used to destroy an enemy radar site. To deliver that military effect from the factory where that warhead was made, it would be placed on a ship to cross the ocean, consuming fuel as energy along the way for delivery to a forward staging area. From there it might be loaded on an F-22, likely with insufficient energy reserves to deliver that effect the full distance, requiring fuel from a tanker en route. If any part of this chain of subsequent energy transactions is broken, the military effect would not be delivered.

The platforms associated with these energy transactions—tanker ships and air refueling aircraft—are large, expensive, and difficult to replace. Furthermore, the fixed infrastructure supporting these transactions, such as ports and runways, takes weeks or months to reconstitute if destroyed. As a result, energy logistics today are slow, brittle, and do not recover quickly from disruptions.

Consider instead a web of wireless energy nodes. These nodes might be unmanned aerial vehicles (UAVs), ships, manned aircraft, preplaced hidden ground stations, space assets, undersea assets, or any number of multidomain options. To deliver an effect, power generated from an aircraft carrier might be delivered to a satellite across thousands of miles to another satellite and then routed through a network of UAVs to focus directed microwaves at the radar site to destroy it. In this scenario, if any single node of the web were disrupted, other nodes would be used to deliver the energy.

This wireless energy web would be constructed with built-in multipath resilience, so it degrades gracefully when under attack. These nodes can be both small and persistent, because they are being constantly recharged by the energy web. If a $1 million missile is needed to destroy a $50,000 energy node UAV that could be immediately replaced by dozens of others, an adversary is faced with a cost and resources dilemma. Rerouting to another multipath option can be accomplished in seconds, and full reconstitution by replacing missing nodes can be accomplished in hours or days.

Such a network is robust, resilient, and can be rapidly repaired. Additionally, in this wireless energy web, transfers are happening at the speed of light, which for reference is roughly Mach 1 million. The United States has invested heavily in hypersonic weapons that are orders of magnitude slower. While hypersonics do serve an important function, the potential of delivering speed-of-light effects at scale provides a compelling alternative. Dynamic strike flexibility, where the focus of an attack can shift thousands of miles in less than a second, revolutionizes the concept of maneuver warfare, making it nearly impossible for an adversary to position and maneuver reaction forces to counter all of the potential attack vectors.

Energy Web Dominance Framework

The energy web dominance framework is not a new technology set but rather a recognition of a fundamental aspect of warfare. Within this framework, DARPA has identified breakthrough distribution technologies as an area ripe for disruption. There are already considerable investments in developing new energy storage and generation technologies, and DARPA seeks out areas where focused investments can have dramatic impact, such as wireless energy beaming. The EWD framework does not assert that wireless power transfer is the right solution for all energy scenarios. Rather, it seeks to optimize energy flows for speed and resilience.

Indeed, in some scenarios the energy density required cannot be supplied wirelessly. Supersonic aircraft, for example, are relatively small and require more energy than can likely be provided wirelessly without significant transmission and cooling challenges. Wireless energy beaming is an important addition to the technology toolset, but this does not mean continued progress in other areas of energy generation, storage, and distribution is no longer relevant. Fundamentally, EWD will look at advances in all areas and continue to optimize the energy network for effects delivery. If, for example, batteries were developed with ten thousand times the current energy storage density, wireless power beaming would become a less important part of the overall energy optimization.

This framework does suggest a new focus on the network as the basis of maneuver rather than platforms, which is greatly enhanced by beaming energy wirelessly. This allows effects delivery in many cases through nodes that do not require much energy instead of fast platforms. Instead of energy hungry, expensive, supersonic aircraft delivering effects, think instead of relatively slow-moving, energy-efficient, and inexpensive high-altitude nodes acting as the conduits through which the speed-of-light effects are delivered. So while delivered energy density does remain a challenge for some platforms using wireless power transfer technologies, the EWD framework itself provides potential solutions.

The peer adversary combat environment is multidomain and mesh networked. The *National Defense Strategy* has identified China as the pacing threat, and thus the Chinese peer adversary combat environment is the primary context inspiring DARPA's EWD portfolio.[11] Defeating a single sensor or shooter in this environment is insufficient to creating sustained advantage. As former Commander of US and International Security Assistance Forces Afghanistan and Joint Special Operations Command General Stanley A. McChrystal often said, "To beat a network you need a network."[12] While the context

11. Lloyd J. Austin III, *National Defense Strategy of the United States of America including the 2022 Nuclear Posture Review and the 2022 Missile Defense Review* (Washington, DC: Office of the Secretary of Defense, October 2022), https://media.defense.gov/.

12. Stanley McChrystal, "It Takes a Network," *Foreign Policy*, February 21, 2011, https://foreignpolicy.com/.

of McChrystal's proclamation was focused on human networks, it reflects the deeper truth that building resilient and dynamic connections across a network provides a competitive advantage.

Evolution in military technologies increasingly makes all warfare reliant on networks. The energy web dominance framework significantly expands the scope of network capabilities by also considering energy to holistically look at the pathway from energy generation through decision-making to effects delivery. With history as a guide, it is clear that leveraging energy effectively in the battlespace is at the heart of operational art.[13] Exploring new energy technologies is vital to modernizing the US military.

Wireless Power Transfer Technologies 101

An analysis of the current state of the art in wireless power transfer coupled with targeted DARPA investment reveals the military utility of wireless power transfer. The concept of wireless power transmission gained popularity with Nikola Tesla and the electrification of civil society. In Tesla's time, the concept was ahead of the technical status quo. Today, however, emerging technologies, including robust high-energy lasers, high-efficiency monochromatic bandgap matched photovoltaics, and dynamic radio frequency (RF) beam forming that includes distributed coherent techniques, provide the fundamentals required to create effective wireless power beaming links. DARPA's novel energy web dominance efforts aim to unite these technologies in a multipath network to overwhelmingly counter the peer adversary combat environment.

Certain fundamental wireless power technologies serve as the building blocks for the wireless energy web, including close- and long-range links.

Close-Range Links: Field-Based Wireless Power Transfer

Wireless power transfer over relatively short ranges can be accomplished using electromagnetic field effects. Induction uses changing magnetic fields to create currents in conductive materials. Field-based power transfer only draws power from the host when there is a recipient present. This allows for very high-power transmission efficiencies up to 99 percent.[14] Standard inductive coupling is effective for ranges equivalent to the inductive coil's diameter.[15] A familiar example is an iPhone charging pad. While useful in some contexts, however, standard inductive coupling lacks the range to provide much utility for an extended wireless energy web.

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13. Moshe Kress, *Operational Logistics: The Art and Science of Sustaining Military Operations* (New York: Springer, 2002).

14. Editors of *Encyclopedia Britannica*, "Electromagnetic Induction (Physics)," *Britannica*, last updated February 2, 2024, https://www.britannica.com/.

15. John Macharia, "Wireless Inductive Charging for Low Power Devices" (thesis, Helsinki Metropolia University of Applied Sciences, January 31, 2017), 6, https://www.theseus.fi/.

One subset of induction enhances range through tightly coupled magnetic resonance. When fitted with a high-quality factor resonator, a device that responds specifically to a particular frequency, the effective range of near-field power transfer can be extended to about 10 times the aperture diameter. Quality factor for resonators is a measure of the precision of the frequency response.[16] In laboratory settings, this technique has been demonstrated out to around 10 feet, effectively.[17]

Using larger antennas and higher-quality resonators, it would be possible to extend this out to dozens of feet. At these ranges, air recharge from an airborne host or persistent power to hovering UAVs from a ground station is a viable application. Likewise, any electric device such as a radio or computer could draw power from a local node, allowing it to operate indefinitely without plugging into an existing grid. There are a number of commercially available products that provide inductive wireless charging solutions.[18]

Long-Range Links: Wireless Energy Beaming

Power beaming sounds exotic, but it actually involves the same physics as that involved in wireless communication. A power source is converted to a propagating wave, typically electromagnetic, sent through free space, collected through an aperture, and converted back to electricity. In a cellphone, that electricity is used as a signal that encodes voice or data. For power beaming, that converted electricity is used directly for power. Point-to-point power beaming has been successfully demonstrated using a variety of transfer methods. Laser and microwave power beaming are the most mature technologies. DARPA has also explored acoustic power beaming for underwater applications. The demos to date serve as excellent proof-of-concept benchmarks but also highlight some of the ongoing challenges.[19]

First, many previous demos were custom built to work with a particular transmit-and-receive pair and generally were not suitable for use in a larger scalable network. Second, conversion efficiencies remain a challenge. In a multihop network, converting from a propagating wave back to electricity back to a propagating wave at each node quickly accrues unacceptable losses. Each one of those conversions is relatively inefficient and multiplying them across a chain is impractical. DARPA has identified effective power-beaming relays as a critical element for overcoming these challenges to creating a practical power-beaming network.

The DARPA Persistent Optical Wireless Energy Relay (POWER) program seeks to make long-distance networked optical power transfer practical by developing effective

16. Estill I. Green, "The Story of Q," *American Scientist* 43, no. 4 (October 1955), https://www.jstor.org/.

17. Macharia, "Wireless Inductive Charging," 6.

18. "Wireless Power Network," Global Energy Transmission, 2024, accessed April 12, 2024, https://getcorp.com/; and "WITRICITY WIRELESS EV CHARGING: The Cure for Charge Anxiety," WiTricity, accessed June 14, 2024, https://witricity.com/.

19. Paul Calhoun, "DARPA Energy Web Dominance Summit Introduction," July 6, 2023, uploaded by DARPATV, YouTube video, October 17, 2023, 45:05, https://www.youtube.com/.

optical energy relays (fig. 1). In this system, a ground-based laser transmitter relays a power beam to a high-altitude relay that then relays that energy to a distant aircraft, which relays the power beam to a receiving station on the ground. An effective optical relay must efficiently redirect energy without conversions, correct wavefront aberrations to maintain a tight beam for long range, and selectively collect some of the energy to power itself.[20]

Figure 1. DARPA's Persistent Optical Wireless Energy Relay Program (POWER)[21]

For optical power beaming, transmission through the lower, thick, and turbulent atmosphere is impractical over long distances due to beam spread and attenuation. High-altitude transmission is quite effective, but having a high-energy laser at high altitudes presents payload weight and cooling challenges. Effective relays allow the combination of ground-based lasers with a high-altitude transmission network, optimizing energy generation and transmission across the system.[22] DARPA envisions this high-altitude optical layer providing the long-range, high-throughput backbone for the wireless energy web.[23]

Shorter-range—tens of meters to several kilometers—distribution to many devices may be most effectively accomplished using RF power beaming. This is more effective through weather and can be easier to operate safely around objects and people. When considering optical versus RF power beaming, it is helpful to understand a bit of the tradespace between wavelength, range, efficiency, and size of the transmit-and-receive apertures.

20. "Power," DARPA, accessed April 12, 2024, https://www.darpa.mil/; and "Persistent Optical Wireless Energy Relay (POWER) Broad Agency Announcement," SAM.gov, accessed April 12, 2024, https://sam.gov/.

21. "Power."

22. "Wireless Energy Relay."

23. "Wireless Energy Relay."

Both RF and optical power beaming rely on transmitting electromagnetic propagating waves. For the most efficient power beaming, the beam size at the desired range should be the same size or smaller than the receiving aperture so that all of the energy is captured. As these waves travel through free space, they generally expand through diffraction, so that the farther away the receiver is the larger the spot size.[24] Think of how a flashlight behaves when shining it across a room. As it turns out, the spot size is impacted most significantly by wavelength and the size of the transmit aperture. Larger apertures create smaller beams and spot sizes while smaller wavelengths produce smaller beams and spot sizes.

Optical beams have much smaller wavelengths than RF beams, which means they can have smaller spot sizes. A smaller spot size can mean a smaller aperture at a set range, or it can mean that for a particular aperture size efficient transmission is possible at larger ranges. For electromagnetic waves, frequency and wavelength are inversely related, so a higher frequency has a smaller wavelength. Generally, since RF waves have much larger wavelengths (lower frequencies) than optical waves, efficient transmission over an equal distance requires much larger apertures.[25]

In 1975, the Jet Propulsion Laboratory, sponsored by the National Aeronautics and Space Administration (NASA), transmitted 34 kilowatts at a frequency of 2.45 gigahertz (GHz) over a distance of 1.5 kilometers (km) with 82 percent transmission efficiency, setting a still-standing benchmark in throughput.[26] At this same frequency, if the receive antenna was moved out to 10 km, an antenna area of 1,224 square meters (sq m) would be needed to capture 60 percent of the incoming wave.[27]

Higher frequencies (smaller wavelengths) allow for smaller antennas. For example, at 100 GHz at that same 10 km, 60 percent of the wave is captured with a 30 sq m antenna.[28] This is further complicated by variable atmospheric effects dependent on frequency. Generally, in the RF portion of the spectrum, lower frequencies have less absorption in the atmosphere and can penetrate clouds. While this trend is true in reality across the spectrum, there are known transmission windows with less absorption that are useful for power beaming or long-distance wireless communications.[29]

Notably in the context of power beaming, there is a very efficient atmospheric transmission window around optical frequencies, which incidentally helps to explain why human vision detects electromagnetic waves in this portion of the spectrum. RF

24. Jacob Gavan and Saad Tapuchi, "Microwave Wireless-Power Transmission to High-Altitude-Platform Systems," *URSI Radio Science Bulletin* 2010, no. 334 (September 2010): 30, https://ieeexplore.ieee.org/.

25. Shaopeng Wan and Kama Huang, "Methods for Improving the Transmission-Conversion Efficiency from Transmitting Antenna to Rectenna Array in Microwave Power Transmission," in *IEEE Antennas and Wireless Propagation Letters* 17, no. 4 (2018): 540, https://ieeexplore.ieee.org/.

26. "1975 NASA JPL Goldstone Demonstration of Wireless Power Transmission," Citizens for Space Based Solar Power, uploaded by Rob Mahan, March 11, 2008, YouTube video, 2:15, https://www.youtube.com/.

27. Gavan and Tapuchi, "Microwave Wireless-Power Transmission," 30.

28. Gavan and Tapuchi, 31.

29. "The Atmospheric Window," National Oceanographic and Atmospheric Administration, last updated April 10, 2023, https://noaa.gov/.

power transfer has proven effective, but there are considerable trades to be made between aperture sizes, frequency, and efficiency for implementation within a networked energy framework.

Active electronically scanned arrays have brought considerable flexibility to radio frequency beamforming. Using a single transmitter with signals split between an array of emitters, they phase shift coherent signals to each emitter to create concentrated beams of RF signal using constructive and destructive interference. As discussed in the previous paragraph, beam width/spot size and transmit aperture size are inversely related. A larger transmit aperture produces a smaller beam which supports a smaller receive aperture.

Coherent beamforming using distributed arrays allows multiple separate transmitters to appear electromagnetically like one large aperture. Thus, less expensive distributed systems can achieve these same beam widths as a single large aperture and do so more resiliently since they are no longer a single point of failure system. The primary technological challenge is ensuring the waves are synchronized, since they are now generated by multiple transmitters and are thus not coherent from the outset. Several techniques have proven effective in laboratory testing.[30] Further research will test if this can be employed reliably in operational environments including dynamic tracking of moving platforms.

Distributed arrays provide two significant advantages for wireless power transfer: (1) concentrated beamforming with significant power gain, and (2) lower power required per transmitter, which allows for small, low-cost platforms. Distributed arrays have a power gain that scales by the square of the number of nodes in the array. Intuitively one might expect a linear scaling, where four transmitters' signals combine for four times the power at the receiver. Linear scaling is in fact the case for noncoherent transmission. Yet, as discussed above, with coherent transmission, the area of the distributed arrays combines, giving an added transmission gain due to the smaller beam width and spot size.

As a result, for an array with eight nodes, the received power is 64 times greater than what would have been received from a single transmitter node.[31] This allows each node to operate at lower power levels, which supports inexpensive systems. Scaling up to potentially dozens of nodes in an array, the gain becomes even more significant. Additionally, systems with many transmitting nodes are resilient when compared to a single transmitter. If one or more transmitters fail in a multinode system, the power transfer decreases gradually.

30. Raguraman Mudumbai et al., "Distributed Transmit Beamforming Using Feedback Control," *IEEE Transmission Information Theory* 56, no. 1 (2010), https://doi.org/; Robert. D. Preuss and D. Richard Brown III, "Two-Way Synchronization for Coordinated Multicell Retrodirective Downlink Beamforming," *IEEE Transmission Signal Processing* 59, no. 11 (2011), https://doi.org; and Jeffrey A. Nanzer et al., "A Review of Microwave Wireless Techniques for Human Presence Detection and Classification," *IEEE Transactions on Microwave Theory and Techniques* 65, no. 5 (2017), https://doi.org/.

31. Jeffrey A. Nanzer, interview by the author, and PowerPoint presentation, January 5, 2020.

Recently a DARPA-funded demonstration validated graceful degradation in a distributed coherent beam forming a wireless energy mesh network (fig. 2).[32] Figure 2 represents concept artwork of a real-world demonstration showing a UAV being charged by four distributed RF transmitters. The UAV is flying directly above the transmitters, which have RF waves converging on a receiving aperture on the UAV. The UAV and the transmitter are depicted in a hanger representative of the actual hanger at NASA Ames in the Silicon Valley, where this test took place. Arguably, coherent beamforming using distributed arrays is a critical technology that will enable distributed low-power, low-cost nodes to effectively concentrate effects within the energy web.

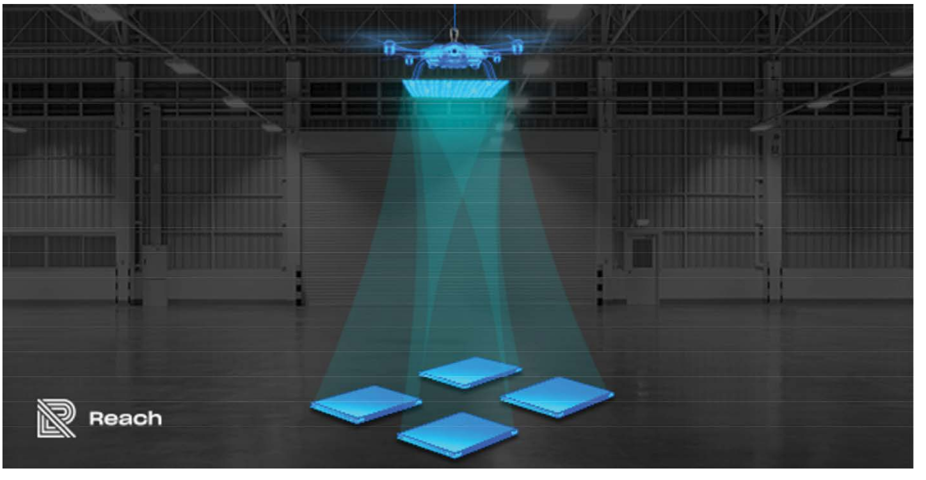

Figure 2. UAV recharged in flight using distributed coherent RF transmitters

Network Effects

The future energy web is envisioned as an expansive network where energy sources and consumers can partake of the network with proper authentications. This will demand careful attention to establish open but secure network protocols. This network should be able to harness multiple transfer modalities depending on environmental conditions and will require new C2 concepts to optimally position nodes based on expected demand.

This open architecture may enable new, exotic energy sources such as space-based solar, moon-based solar, the harnessing of deep ocean waves, or the parasitic stealing of adversary energy.[33] Within the energy web dominance framework one could imagine a

32. A. Porteus, "Reach Enables Wireless Power Mesh Networking for In-flight Drone Charging," Reach, May 23, 2024, https://reachpower.com/.

33. Daniel Wood, "Space-Based Solar Power," Energy.gov, accessed March 22, 2020, https://www.energy.gov/; and Dave Criswell, "Lunar Solar Power (LSP) System: Practical Means to Power Sustainable Prosperity," Search and Discovery Article #70070 (2009), 17, https://www.searchanddiscovery.com/.

stealthy UAV perching on enemy power lines and beaming that power to incoming American forces to use against that adversary.

Moon-based solar is a particularly revolutionary concept that proposes using self-replicating robots to transform the moon's silicon-rich soil into solar cells. In essence, the moon would become a giant power-generating solar farm, dramatically changing energy dependence on traditional sources.[34] Deep ocean waves can generate significant amounts of energy, but building fixed infrastructure out to the deep ocean is impractical.[35] The key to unlocking these future sources is building a network that can effectively distribute energy over long ranges.

Long before the wireless energy web transforms civil energy infrastructure, it will provide a compelling advantage for military forces. Before a technology can replace its predecessor, it must prove that it is significantly better to justify replacement costs. Competing on efficiency against optimized, stable, and existing civilian energy infrastructure will be relatively challenging. On the contrary, current methods for delivering energy effectively to remote, contested military environments are vulnerable and ripe for disruption. For these reasons, the US military will lead the way in developing new wireless power transfer technologies to merge logistics and tactics in a resilient, adaptive framework.

Ongoing Challenges

Human safety must be a core consideration of wireless energy web applications. For field-based effects, frequency selection mitigates the energy's interaction with biological materials. Further research is necessary to understand long-term effects and ensure that these systems do not interfere with other existing electrical devices, such as pacemakers.[36]

For beaming power, the dense core of these beams is likely to be harmful to anything in its path. Assured safety systems are possible by constantly monitoring the transmission path with a wider low-power beam and interrupting the high-power beam in response to intruders. Navy Research Labs demonstrated this safety protocol as part of their Power Transmitted Over Laser research effort, and this is a foundational goal for the DARPA POWER program.[37]

Ultimately these power-beaming systems will need to be designed with safety built in at the system level so that the system can be certified for operation versus for simply meeting current cumbersome requirements to coordinate laser shots individually with the Joint Service Laser Clearinghouse. While ensuring such system

34. Criswell, 17.

35. Kavadiki Veerabhadrappa et al., "Power Generation Using Ocean Waves: A Review," *Global Transitions Proceedings* 3, no. 2 (November 2022), https://doi.org/.

36. Isaac Chang et al., *RF/Microwave Interaction with Biological Tissues* (Hoboken, NJ: John Wiley & Sons, 2006).

37. Emanuel Cavallaro, "Researchers Transmit Energy with Laser in 'Historic' Power-Beaming Demonstration," US Navy, October 22, 2019, https://www.navy.mil/; and "Wireless Energy Relay."

safety remains a challenge, a successful analogy can be found in considering safe coexistence with the high-voltage power lines that are ubiquitous in the environment.

Although robust communication poses a challenge for wireless energy beaming networks, the existence of the network provides additional opportunities. Safe and effective power beaming requires an underlying low-power communication network to establish network protocols and control the flow of energy. As a result, a WEB network can be vulnerable to the same disruptions associated with traditional communications networks. Yet, because a WEB network provides a framework for many small, indefinitely persistent nodes, the overall reliability of both the networks is improved. Ultimately, the wireless energy web will reliably provide both energy and data using the communication links that are inherently necessary for effective power beaming.

As discussed earlier in this article, the rate or flux of energy transfer possible through wireless means is a challenge. Air refueling provides an extreme example of energy transfer rates possible with liquid fuels. Considering the full energy content of that fuel, the transfer rate during air refueling is equivalent to 2.5 gigawatts, which is orders of magnitudes greater than any laser conceived. Even with aggressive improvements in conversion efficiencies it would be impractical for most applications due to waste heat.

Though technologies will improve over time, there will be practical limitations to wireless power beaming transfer rates, which will limit applications. Yet early DARPA studies showed many meaningful military applications were feasible in the next few years with tremendous growth potential over the next decade.[38] Ultimately, though, improved distribution will not solve all energy challenges, and continuing the generation, storage, and distribution optimization methodology inherent to EWD will be necessary.

Conclusion

The energy web dominance framework provides a novel perspective on the fundamental character of warfare, revealing new metrics for optimizing military effects delivery. The current trend of buying fewer expensive, monolithic platforms that rely on liquid hydrocarbon fuels is unsustainable and vulnerable. Countering the peer adversary combat environment requires a new approach. Leveraging the electromagnetic spectrum to transmit energy wirelessly could enable a complementary network of persistent yet inexpensive platforms that are able to flexibly and resiliently focus military effects at a distance. Emerging technologies reveal a pathway to achieving this new vision.

The linkages in the wireless energy web will be built using a combination of magnetic resonance, optical, and radio frequency beams enabled by a host of supporting developments. To foster such a disruptive change, research should continue to probe the necessary families of technologies to find niche markets where wireless power transfer provides an immediate advantage. From there, the proven technologies can

38. Calhoun, "DARPA Energy Web Dominance."

be scaled into a larger network to achieve sweeping effects. This disruptive transformation will take investment in development, tactics, training, and procedures. Yet by achieving energy web dominance, the United States can maintain an advantage in great power competition for decades to come.[39] Æ

39. See Calhoun.

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