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BREAKTHROUGHS IN WEARABLE MOLECULAR MONITORING

PAGE 13

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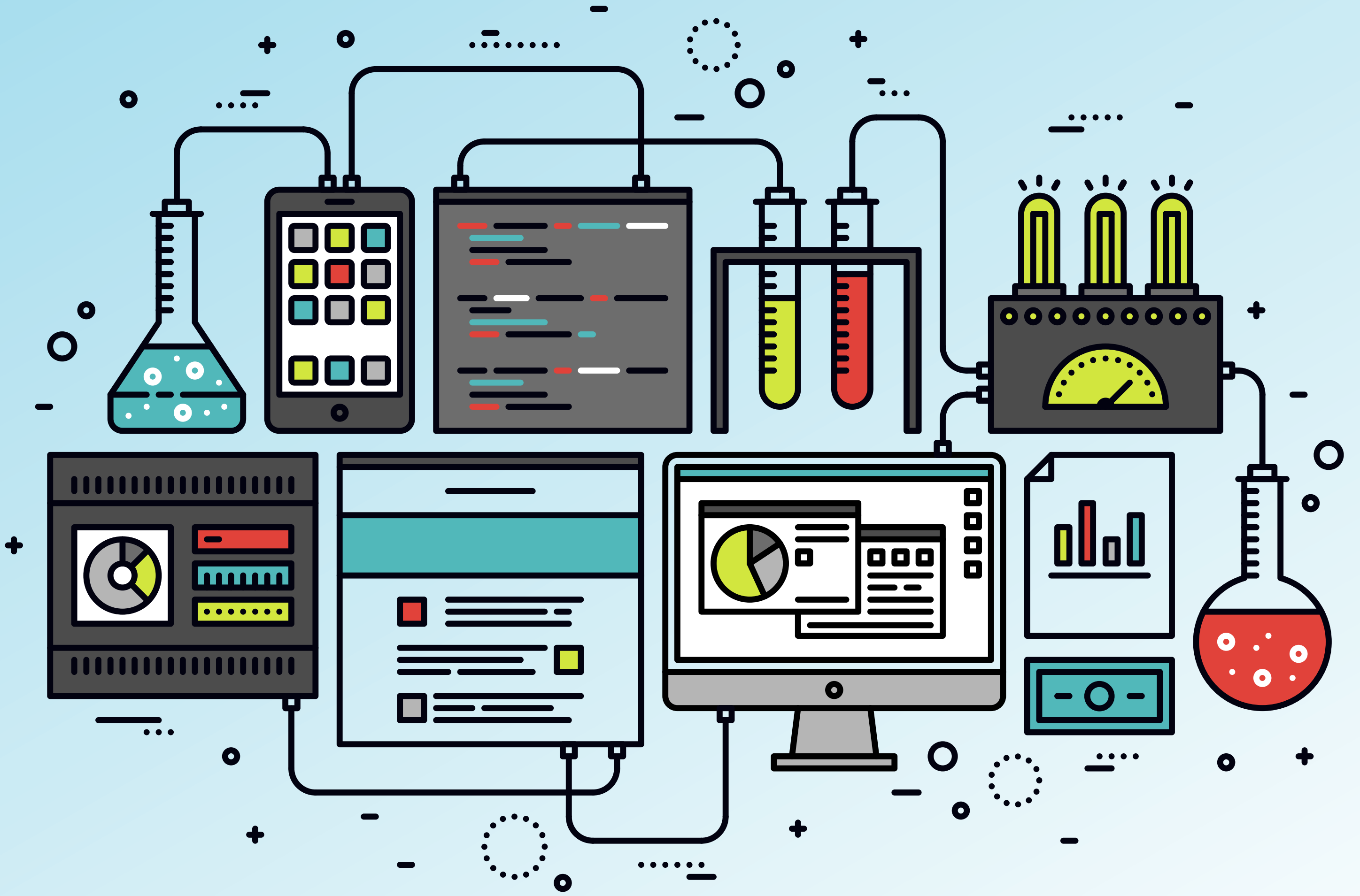

THE NEW CBRN PARADIGM:

ACCELERATING DEVELOPMENT ON BOTH SIDES

BY JOHN CLEMENTS (PHOTO SOURCE: ANTLII [SHUTTERSTOCK])

INTRODUCTION

For over a century, the chemical, biological, radiological, and nuclear (CBRN) enterprise focused on chemicals, biological agents, radiological isotopes, and nuclear weapons proliferation. The shift from the Cold War to counterterrorism changed the employment of the mission, but the fundamentals have stayed the same. The science behind the ability of the United States to detect threats, protect Warfighters from those threats, decontaminate impact areas, and manage the consequences has advanced in a reasonably straight-line trajectory. A new threat may have been identified, or a new capability was conceptualized. A new detector was developed, such as the joint chemical agent detector, or a new decontaminant realized, such as reactive skin decontamination lotion. There are currently three emerging technologies and concepts that may enable and disrupt the CBRN enterprise, depending on who capitalizes on them first. They are as follows: (1) artificial intelligence (AI), (2) additive manufacturing (e.g., three-dimensional [3-D] printing), and (3) communications and networking of sensors.

AI

Although AI has become a buzzword, this does not detract from its importance. Leveraging AI will continue to change how the world does virtually everything. The CBRN enterprise is no different.

Recently, the U.S. Department of Homeland Security (DHS) Countering Weapons of Mass Destruction Office released the "Department of Homeland Security Report on Reducing the Risks at the Intersection of Artificial Intelligence and Chemical, Biological, Radiological, and Nuclear Threats" [1]. DHS identifies six findings on the misuse of AI to enable the development or production of CBRN threats. For each finding, several recommendations are made to enable the U.S. government to combat such threats.

Many AI tools and datasets are available in open-source locations. The DHS report speaks of AI democratization. Generally, "The most common goal of democratizing AI use is to distribute the benefits of AI use for many people to enjoy" [2]. There are several common open-source repositories for AI development. Rebecca Lipton, a data scientist who supports the Homeland Defense and Security Information Analysis Center (HDIAC) and partner Information Analysis Centers, explained, "GitLab and GitHub are two common code libraries/repositories where people/organizations publish code. For GitLab and GitHub, you can clone the code onto your machine, or oftentimes the author will bundle the code up into a package that can be downloaded neatly onto your machine using package/environment management software" [3]. This sounds quite easy for anyone with a small amount of software development knowledge to employ, which is the point of these sites. Yet, as Elizabeth Seger from the Carnegie Council for Ethics in International Affairs points out, "The circle of individuals who would greatly benefit from access to an AI drug discovery tool is relatively small (mainly pharmaceutical researchers); however, these tools can be repurposed to discover new toxins that might be used as chemical weapons" [2].

Another sharing site suggested by Lipton is called Hugging Face. This site houses a variety of open-source models, datasets, documents, and other solutions. The following example only took a few minutes to accomplish. By searching models simply for the word "chemical," there were 90 returns. While some of the returns were incomplete results, a specific model, "biobert_chemical_ner," populated. The developer provided a very simple explanation of the model [4]: "BioBERT model fine-tuned in NER task with BC5CDR-chemical and BC4CHEMD corpus," which is defined and detailed next.

In translation, BioBERT is the Bidirectional Encoder Representations from Transformers for Biomedical Text Mining. Developed in 2019, it "is a domain-specific language representation model pre-trained on large-scale biomedical corpora" [5]. NER stands for named entity recognition, which is "the task of identifying and categorizing key information (entities) in text" [6]. BC5CDR is the BioCreative V chemical disease reaction corpus. The "BC5CDR corpus consists of 1,500 PubMed articles with 4,409 annotated chemicals, 5,818 diseases, and 3,116 chemical-disease interactions" [7]. BC4CHEMD is the BioCreative IV chemical compound and drug name recognition tool. "BC4CHEMD is a collection of 10,000 PubMed abstracts that contain a total of 84,355 chemical entity mentions labeled manually by expert chemistry literature curators" [8].

The simple "biobert_chemical_ner" model utilizes information in other models and databases to train and refine the BioBERT model to help classify and categorize massive volumes of biomedical information. Since this includes chemical disease reactions and interactions and tens of thousands of chemicals labeled by expert chemistry literature curators, considerable research has already been done for anyone wanting to use this tool. Whether a valid university researcher or someone with nefarious intentions, this information can be used to greatly reduce development time of biomedical cures and weapons alike. It should be noted that the "biobert_chemical_ner" model had over 9,000 downloads in the previous month—this is a large amount of white noise for bad actors to camouflage their intentions.

Naturally, AI can be employed to counter CBRN threats as well. The DHS report finds that "integration of AI into CBRN prevention, detection, response, and mitigation capabilities could yield important or emergent benefits" [1]. One of the recommendations tied to this finding is to "optimize the responsible use of AI in the design, testing, and evaluation of personal protective equipment, medical countermeasures (e.g., vaccines and synthetic antibodies), and decontaminants" [1]. The previously mentioned example of the "biobert_chemical_ner" model could be leveraged by developers to identify reactions to specific compounds to speed up development efforts.

For example, the Generative Unconstrained Intelligent Drug Engineering (GUIDE) program's mission "is to leverage its integrated computational and experimental capabilities to accelerate drug development for the Warfighter by harnessing the power of advanced simulation and machine learning" [9]. This program, spearheaded by the Joint Program Executive Office (JPEO) for Chemical, Biological, Radiological, and Nuclear Defense (CBRND), seeks to adapt to the new reality of drug design leveraging AI and machine learning to mitigate the time and expense of investigating various drugs. Figure 1 demonstrates the GUIDE program's user interface.

ADDITIVE MANUFACTURING

Additive manufacturing, especially 3-D printing, offers an even lower bar of entry than AI. 3-D printers come in all shapes and sizes and can be used to manufacture items out of multiple, different materials.

One limitation of employing CBRN munitions is the delivery system where nonstate actors have lacked access to methods to employ CBRN weapons in any meaningful way. In most cases, they would have to rely on getting close to the target and, in turn, endangering themselves. Even those who would be willing to commit suicide for their causes do not want to suffer the drawn-out death of a nerve agent, biological toxin, or radiation poisoning.

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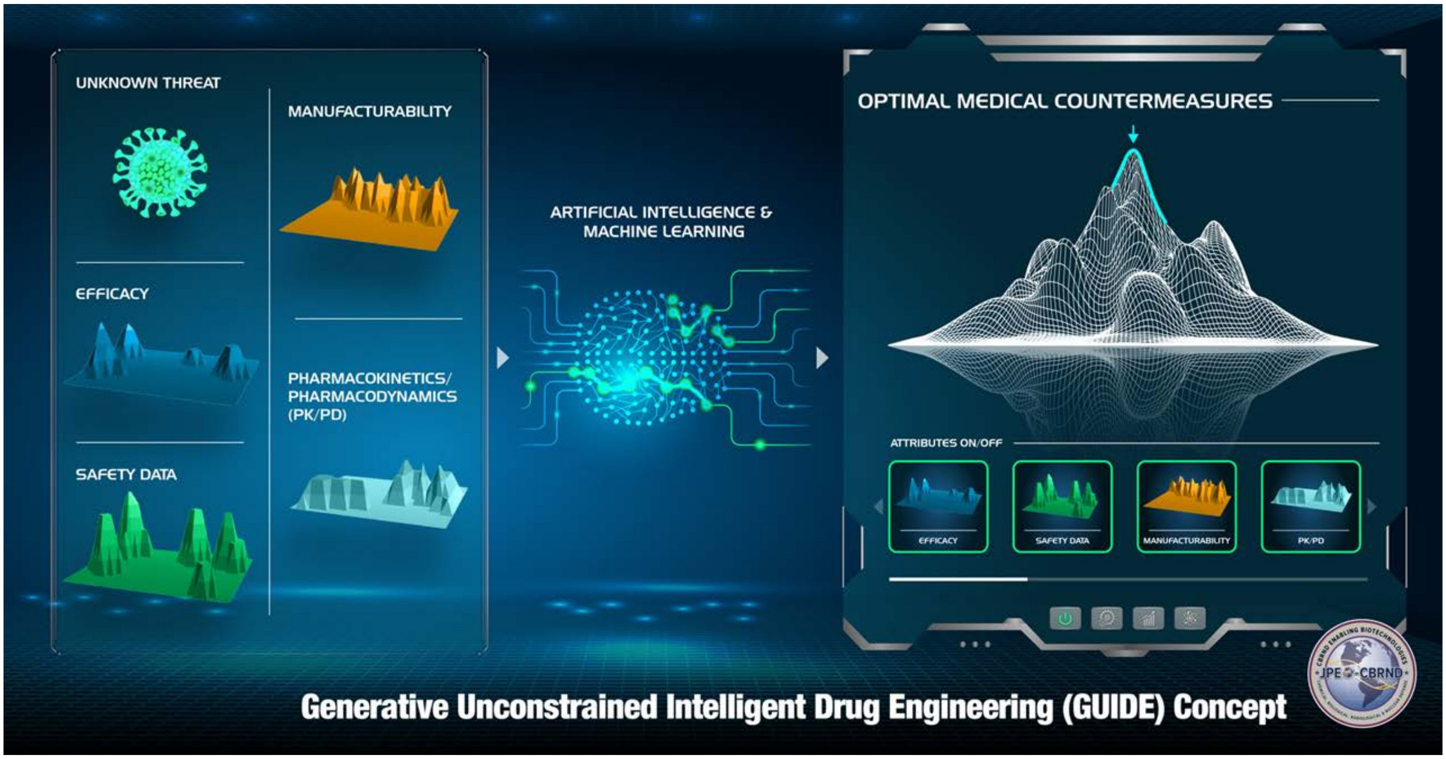

Figure 1. GUIDE Program Through JPEO-CBRND Joint Project Lead for CBRND Enabling Biotechnologies *(Source: Burkhalter [9])*.

Among the most notorious terrorist attacks using chemical agents in history is the March 20, 1995, attack by the Aum Shinrikyo cult that killed at least 12 people and hospitalized nearly a thousand. Thousands more suffered effects from the sarin gas released in the subway. The sarin used was not high quality, thus reducing its effectiveness. Mercifully, the method to disperse the gas also reduced the effects. While traveling on trains in the Tokyo subway system, the gas was released from bags punctured by the assailants. This meant a gradual release from a single point on each train. While thousands were affected, the death toll would have been much higher had a better delivery method or chemical with better purity been used [10].

In bygone years, developing a delivery system for a weapon, conventional or CBRN, would require a large investment in machinery and expertise. That paradigm has shifted, and now anyone with access to a 3-D printer and basic materials can manufacture a delivery system.

In March of 2023, "the Relativity Space Terran 1 rocket lit up the night sky as it launched from Cape Canaveral Space Force Station in Florida. This was the first launch of a test rocket made entirely from 3-D-printed parts, measuring 100 feet tall and 7.5 feet wide" [11]. While this is an extreme example at the cutting edge of scientific research, the basic idea that a rocket engine can be produced using additive-manufacturing techniques proves the concept. Figure 2 shows the first additive-manufactured Glenn Research Copper (GRCop) combustion chamber.

In 2020, the Homeland Security Advisory Council released its "Final Report of the Emerging Technologies

Figure 2. NASA Materials Engineers Dave Ellis and Chris Protz Inspect the First Additive-Manufactured GRCop Combustion Chamber *(Source: Kilkenny [11])*.

Subcommittee: 3D-Printing" [12]. Drawn from that report, Figure 3 forecasts 3-D-printing technology development.

Notably, the timelines in Figure 3 have already slid to the left, indicating novel methods of developing delivery systems and their CBRN threats.

Because of this, the United States is working hard to leverage 3-D-printing applications. There have been huge strides in manufacturing items such as replacement parts and medical devices for everyday military and civilian use. There are also successful use cases in laboratories and prototyping.

In the biomedical field, organ-on-a-chip (OOC) technology has allowed researchers to create small microchips that represent human organs and complex systems. The U.S. Army Combat Capabilities Development Command Chemical Biological Center recently completed testing using a 3-D-printed lung chip. According to their report [13]:

> 3-D printing technologies greatly simplify the traditional photolithography processes, reducing the need for experimental procedures and dramatically reducing processing costs and time. Integration between organ chip engineering and 3-D printing in the manufacturing process provides new opportunities for building more physiologically relevant organ chips in a more timely and cost-effective manner.

OOC is just one of many examples where 3-D printing will play a major role in reducing costs, procurement times, and design times. The potential for creating surgical devices, drugs, adaptive devices, and other items is only limited to the imagination. Although there are inherent safety concerns, such as the transmission of infectious diseases through a device that was not produced in a rigorously controlled setting, the future is promising.

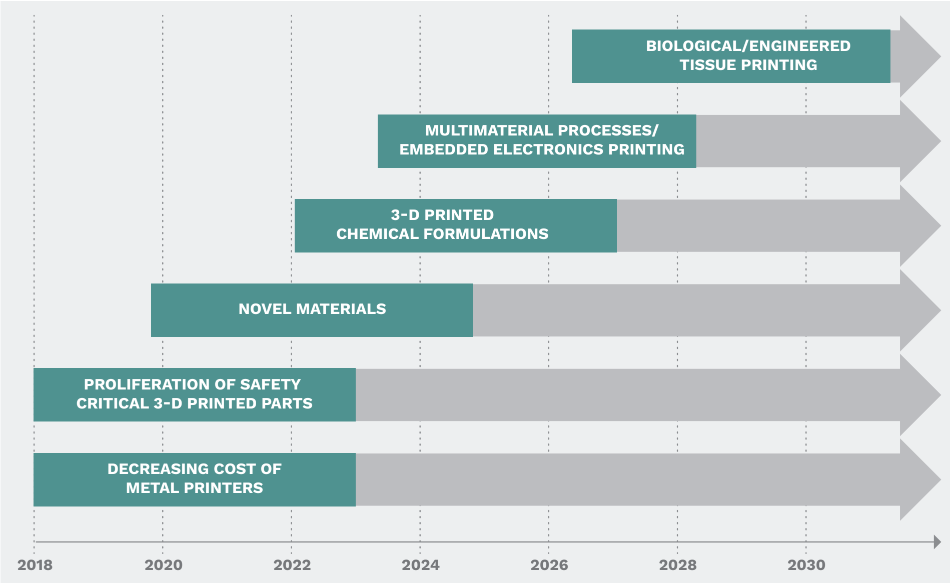

Figure 3. Projected Timeline for the Advancements in 3-D Printing *(Source: DHS [12])*.

COMMUNICATIONS

Communications technology has exploded. For millennia, communications was restricted to the speed of the fastest horse. Now, worldwide, near-real-time communications are a reality. There are some restrictions that require their own solutions, such as bandwidth and security. Another major problem is that there is too much information for any one individual to manage.

Depending on the situation, there are a variety of solutions that may be available. Each one has benefits and risks, and so it is nearly impossible to find a solution, or even a suite of solutions, that solve all the problems.

One potential solution is edge computing. "Edge computing allows devices in remote locations to process data at the 'edge' of the network, either by the device or a local server. And when data needs to be processed in the central datacenter, only the most important data are transmitted, thereby minimizing latency" [14]. In other words, a CBRN detector may include, or be paired with, a method of communications. Instead of transmitting all the data it is receiving, it will only transmit the very basics needed to make a decision. As a hypothetical example, a detector designed to detect the presence of volatile organic compounds (VOCs) and oxygen levels may only send data if a certain level of either is reached. However, if that detector was retrieved, the timestamped data of oxygen levels and any trace VOCs or fluctuations in oxygen levels could be seen. A centralized system may also be set up to pull the data from the sensor on demand.

AI may be leveraged to assist the CBRN community with communications and maintaining situational awareness. Systems exist to translate voice to text (VTT). Conceptually, a VTT system could be trained and refined to understand terms and acronyms specific to the CBRN enterprise. This may include the transcription of specific radioisotopes. Cobalt-60 would be transcribed as how the commander wanted to read it. In a large event where multiple responders are communicating, another program could be scrubbing the text from the VTT and flagging any mentions of Cobalt-60 to the commander. Similarly, the VTT software could be trained to recognize certain chemicals, compounds, or other threats.

The U.S. military communicates on every possible band of the electromagnetic spectrum. While this is an enabler, it is also creating challenges when trying to network disparate sensors, unmanned systems, vehicles, aircraft, ships, etc. The answer for the CBRN community lies in the CBRN Support to Command-and-Control (CSC2) program. "CSC2 will provide integrated situational awareness about potential CBRN hazards to inform decision-making. CSC2 will link sensors together to develop networked tools that communicate and share information to achieve integration of CBRN capabilities and data with existing user systems across the service" [15]. Figure 4 shows the overview of CSC2 system architecture and its interoperability nodes.

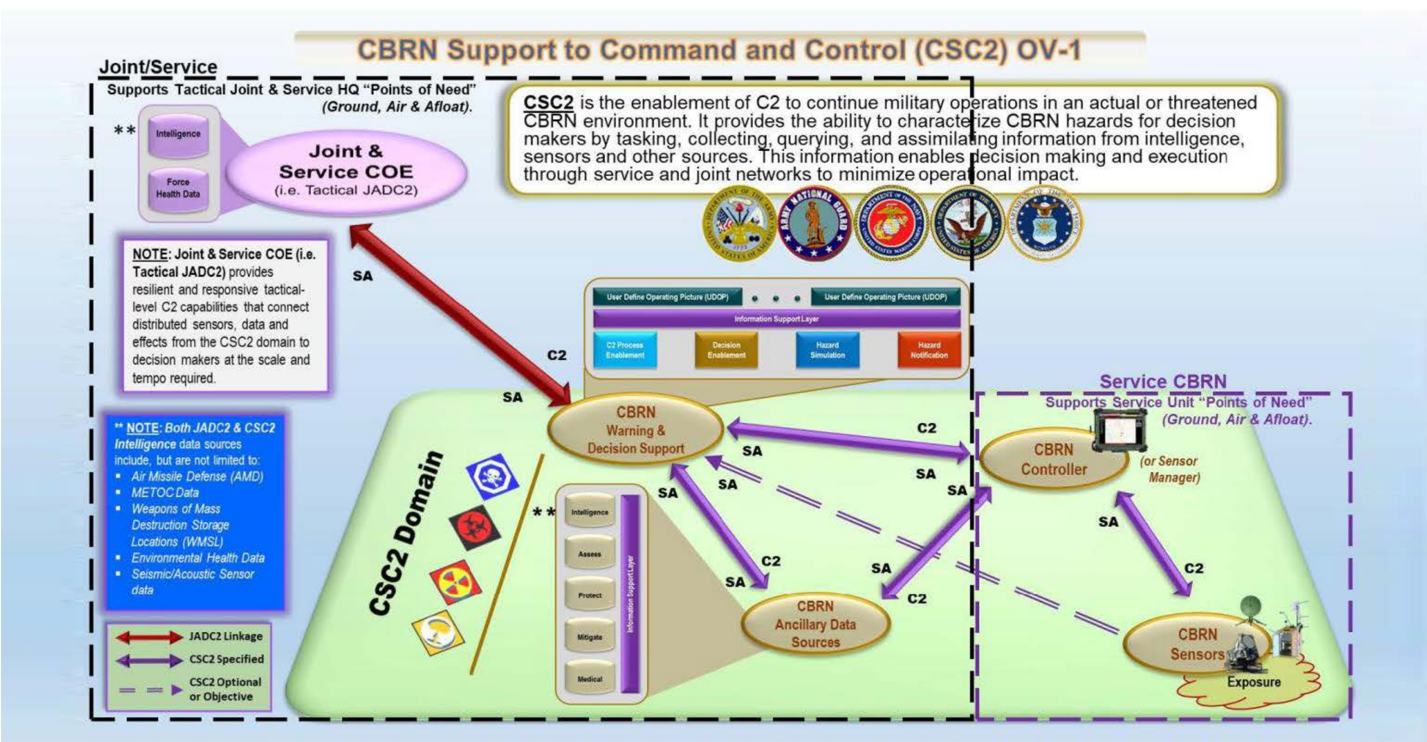

Figure 4. CSC2 Overview *(Source: Murphy [16])*.

> *AI may be leveraged to assist the CBRN community with communications and maintaining situational awareness.*

This is a large undertaking. It is not as simple as networking the induvial sensors together. "The goal is for the networked sensors to be transmitted or 'plugged into' service-specific computing environments and ultimately, Joint All-Domain Command and Control (JADC2)-compatible CBRN Common Operating Environment" [15]. Currently, CSC2 may need to be interoperable with several different systems. The exact architecture still needs to be designed. While this problem is well known within the U.S. Department of Defense, the acceleration of technology means that the architecture becomes more complicated every day.

Still, CSC2 promises to be the CBRN community's answer to communicating with the maneuver forces and combatant commanders to real-time decision-making. According to Paul Gietka, joint project lead for CBRN integration in the JPEO-CBRND, "CSC2 is our overarching system-to-system software capability that provides for the interoperability and integration of CBRN and non-CBRN sensors to achieve the needed situational awareness and understanding interdependent with service and mission partner computing environments" [17]. The program, at least at a high level, understands the challenges ahead.

There is one major drawback and perhaps a massive one—the increase in sensors and communications equipment increases the electromagnetic footprint that U.S. military forces will produce. When dealing with a peer or near-peer adversary in large-scale combat operations, this can quickly become a disadvantage. The problem is twofold: adversaries may be able to pick up the signal and thus target forces or equipment and adversaries could attempt to block signals, rendering the equipment useless. "One of the biggest lessons from Russia's incursions in Ukraine—stemming from 2014 to its current invasion—is how units can be located and targeted with kinetic munitions solely based on their emissions within the electromagnetic spectrum" [18]. The need to sense CBRN threats in a tactical environment must be balanced with the potential for friendly forces being located simply by operating that equipment.

CONCLUSIONS

During the CBRN Defense Conference hosted by the National Defense Industrial Association, retired U.S. Army Brigadier General William King asserted that the CBRN enterprise is at an inflection point. This indicates a change in direction from the previous way of thinking and operating. Here, three major changes to how the CBRN community thinks and acts have been examined. AI, additive manufacturing, and communications are each a technology not specific to CBRN defense, but all will create radical changes in the CBRN landscape. On the flip side, adversaries can use these same technologies to accelerate their own capabilities. The inflection point truly is upon us. ■

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Rebecca Lipton, a data scientist supporting HDIAC, provided simple answers to complicated questions to assist in the AI portion of this article. Her help was instrumental in the AI and Communications sections of this article.

> *CSC2 promises to be the CBRN community's answer to communicating with the maneuver forces and combatant commanders to real-time decision-making.*

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BIOGRAPHY

JOHN CLEMENTS is the technical lead for HDIAC. He served 20 years as a combat engineer in the U.S. Marine Corps Reserve and deployed three times to Iraq in support of Operation Iraqi Freedom. His prior work includes test and evaluation on procedures and systems related to CBRN decontamination, mortuary affairs, cyber insider threat, open-source and social media information, the Common Operational Picture used by combatant commands, and the Mounted Computing Environment. He has extensive experience working with joint, interagency, and allied partners at the strategic and tactical levels. Mr. Clements holds an M.A. in homeland security from the American Military University.

Photo source: Helena Lopes (Canva)

BREAKTHROUGHS IN WEARABLE MOLECULAR MONITORING

BY JASON HEIKENFELD, ZACHARY WATKINS, ALEKSANDAR KARAJIC, AND THOMAS YOUNG

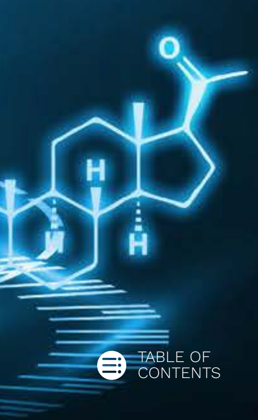
(PHOTO SOURCE: SERGRAY [SHUTTERSTOCK] AND VIACHESLAVIRTYSHCHEV [CANVA])

BACKGROUND

Homeland defense and security depends on peak performance of field personnel and early detection of exposure to chemical/biological threats. Field-deployable molecular monitoring both on body or in body is finally becoming a believable near-term prospect.

INTRODUCTION

Humans continue to be mission-critical components, thus limiting mission efficacy in performance and health. This human-dependence highlights the need to monitor, augment, and intervene in human performance. The importance of human monitoring is not new. Six decades ago, despite their reluctance, the astronauts



in the U.S. Apollo missions were monitored with a battery of electrodes to collect electrocardiograms (heartbeat waveforms), a heated thermistor to detect breathing, and a rectal temperature probe (Figure 1).

Figure 1. Wearable Biosensor Kit Used in the Apollo Space Missions to Track Astronaut Vitals *(Source: National Air and Space Museum [1])*.

After these early breakthrough successes, the advancement of wearable monitoring has been slower and somewhat evolutionary. Conveniently, more wearable health monitoring can be obtained in just a smartwatch; however, the problem persists that these sensors lack specificity [2]. Less specific means exactly how it sounds—the measure is weakly specific to any cause or condition. For example, how many different causes are there for changes in heart rate? If greater specificity for a condition is desired, then molecules inside the body will need to be measured. Most people experience this molecular measurement each year as they are tested for a plethora of molecule concentrations via blood draws at their annual physical exams. U.S. defense experts recognized 20 years ago the importance of high-frequency or continuous molecular monitoring [3]:

> Monitoring is necessary to ensure that operational personnel are as physically fit as possible because success on the battlefield is to a great extent dependent on the ability of combat service members to carry and operate weapons, to overcome physical obstacles, to traverse distances in harsh environments, and to endure a host of physical stresses and strains that could easily overwhelm unfit individuals.

However, to maximize both specificity and actionability during a mission, measurement should occur in real time in a simple wearable format. Real-time measurement is now possible with the revolutionary success of continuous glucose monitors for diabetes management (Figures 2c and 3). While implanted biochemical monitors are starting to emerge, for most foreseeable future applications, wearable biochemical monitors will have the greatest utility for most users.

However, challenges remain in moving beyond just glucose. This article will address these challenges and cover recent advances showing that after decades of pursuit by the U.S. Department of Defense, wearable molecular monitoring is arguably right around the corner. Once available,

While implanted biochemical monitors are starting to emerge, wearable biochemical monitors will have the greatest utility for most users.

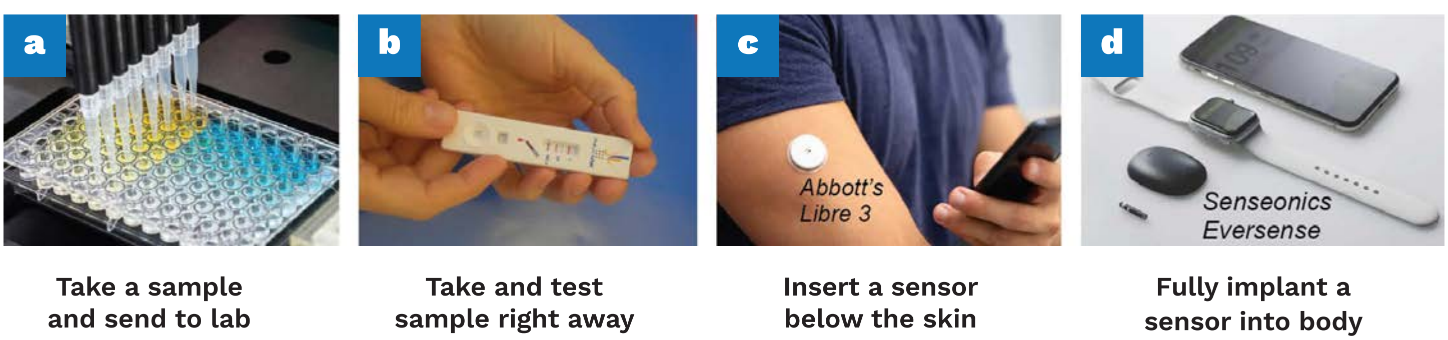


Figure 2. Evolution of Diagnostics Throughout the Decades *(Source: J. Heikenfeld)*.

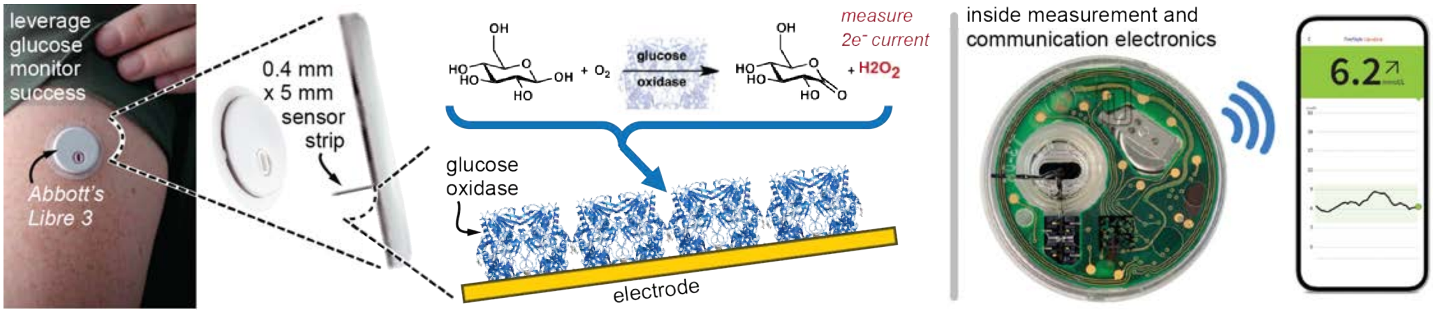


Figure 3. Example Success in Molecular Monitoring With a Specific Example of Abbott's Libre 3 Glucose Monitoring System *(Source: J. Heikenfeld)*.

some examples of potential outcomes that could raise homeland defense to an entirely new tier of performance include the following [3, 4]:

- Monitor individual health and performance status to optimize individual self-regulation and workload distribution across the team.
- Accurately identify exposure to chemical-biological agents before the symptoms of potential exposure are even suspected and administer medical countermeasures before permanent harm occurs.
- Optimize individual health and performance readiness outside the performance of duty, including enabling faster recovery from strenuous performances.
- Warn the individual and team when performance failure is imminent from physiological, psychological, or environmental overload.
- In training, quickly identify and characterize the individual needs in high-stress and strain situations to prevent washback (loss of trainees).
- Monitor the effects of long-term health risks and associated exposures to stress, strain, and environment.

DON'T RECREATE THE WHEEL

Although the largest challenge for biochemical monitoring is moving beyond the success of glucose monitoring, the wheel does not need to be created. For example, when applying a modern glucose monitor, a simple one-step, spring-loaded, and pain-free insertion method implants a glucose sensor into the skin on a tiny ~5-mm-deep and ~0.4-mm-wide plastic strip. The device automatically activates, allowing diabetes patients to accurately track their glucose levels via Bluetooth communication to their smartphone for up to two weeks of wear time. This has been a resounding success.

Instead of recreating the wheel, advances in glucose monitors by companies such as Abbott, Dexcom, Medtronic, and others should be leveraged. While several emerging alternative monitoring approaches are in development like sweat or other fully nonskin-invasive techniques, these alternatives are unproven and, at best, will be inferior in specificity and accuracy to today's glucose monitoring approach [5]. Modern-day glucose monitors required decades of work by multiple armies of scientists and engineers, but their development also benefited from a molecule inside the human body called glucose oxidase.

Glucose oxidase only reacts to glucose and allows glucose monitors to find the needle (glucose) in the haystack (a plethora of all the other molecules in blood). To better explain this concept, a good analogy is a "lock" and "key." Glucose oxidase (the lock) is a unique fit for glucose (the key), which together "open" a chemical reaction that produces peroxide. Peroxide is then electrochemically measured at the electrode surface as a current (Figure 3). Simply put, more glucose ⟶ more peroxide ⟶ more electrical current. However, this lock and key by design only works for glucose—so how are other molecules measured?

> ***Modern-day glucose monitors required decades of work by multiple armies of scientists and engineers, but their development also benefited from a molecule inside the human body called glucose oxidase.***

FINDING OTHER NEEDLES IN THE HAYSTACK

Measurement specificity for molecules is, at first glance, a very difficult challenge to overcome. For example, how can a sensor be developed that can distinguish cholesterol (a waxy sterol) from estrogen (female sex hormone) from testosterone (male sex hormone) from cortisol (stress hormone) given that they are all structurally very similar (Figure 4)? This is where >99% of the biosensors demonstrated in a beaker in academic journals will fail in the real-world use because their sensor surface when touching biofluid in the body interacts with far more than just what they are trying to measure. They suffer from being nonspecific. How can specificity issues be circumvented to move forward?

Enzymes are one way to solve this problem. Glucose oxidase used in the monitor shown in Figure 2 is made up of 604 amino acids. There are 20 different amino acids used to build proteins and enzymes. Having n=tens to hundreds of amino acid combinations with 20 different types of amino acids adds up to 20^n options, which seems like an infinite number of locks (the sensor) to make to fit a key (the molecule). While the number of potential amino acid combinations is seemingly limitless, creating a molecule that causes a specific enzymatic reaction is quite difficult and cannot be easily engineered in a lab. Furthermore, the enzymatic approach is limited to high-concentration molecules such as glucose, lactate, ethanol, and ketones, which are around millimolar concentrations (thousandths of a mole in a liter of solution).

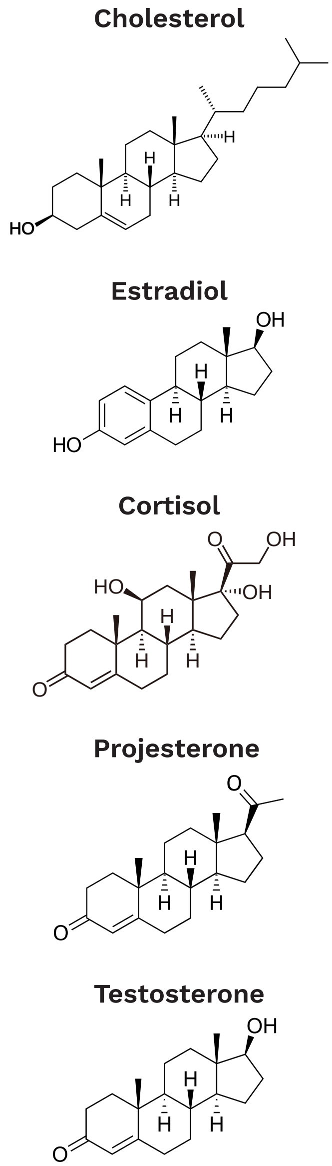


Figure 4. Steroid Hormones Circulating in the Body *(Source: J. Heikenfeld).*

In contrast, most of the high-importance molecules to measure are hormones and proteins, which are at nanomolar to picomolar concentrations—this is a million to a billion times lower than glucose [6]. The only way to resolve this problem is to mimic the body's own molecular signaling mechanisms by using tunable molecular-affinity based interactions as the lock and key.

A simple example of affinity binding is cortisol, which is a hydrophobic (water disliking) steroid hormone (Figure 4) that binds to cortisol receptors in the body. These cortisol receptors contain, at least in part, hydrophobic amino acids enabling favorable hydrophobic interactions with cortisol (disliking being in water). As cortisol concentrations increase in the body, there is more cortisol in the blood (in water), thus increasing the chance for it to interact with its receptor. Therefore, when a concentration goes above the nanomolar range, cortisol begins to bind to its receptor. More cortisol, more receptor binding—less cortisol, less receptor binding, which

> As cortisol concentrations increase in the body, there is more cortisol in the blood (in water), thus increasing the chance for it to interact with its receptor.

typically occurs over a measurable range of ~100×. The body itself achieves incredible specificity for cortisol vs. similar molecules (Figure 4) by using different sequences of amino acids. Leveraging different sequences of amino acids for affinity binding is how antibodies specifically find their target in the body. Mother nature had over a billion years to slowly develop these perfect lock amino acid sequences for specific keys—time that cannot be afforded to develop biochemical monitoring for homeland defense applications. How can selecting the right lock for the key (molecule) be expedited?

Fortunately, there is a way to quickly engineer these lock-and-key interactions for most types of interest analytes. The trick is to use short, single-stranded DNA called aptamers. The good thing about aptamers is that anyone can now purchase a large library of aptamer molecules with random sequences of nucleotides (A, T, C, or G, or manmade options) instead of different amino acids like with proteins and enzymes. For example, once a standard library of 10^{15} different aptamer sequences is obtained, a process called SELEX can be used to wash these aptamers (different types of locks) over the target molecule (the key). This process finds the possible lock-and-key fits, uses DNA amplification to amplify the best fits, and then repeats for several rounds until a few aptamer sequences are obtained that specifically match the target molecule. Does this really work in practice? Absolutely, considering that commercially SomaLogic now sells an assay based on this technology that can quantify >11,000 human proteins from a single, tiny, 55-µL blood sample (i.e., 1/50th of a teaspoon of blood to simultaneously measure 1/3 of the human proteome).

SomaLogic's lock and key for the important inflammation monitoring protein, IL-6, is shown in Figure 5.

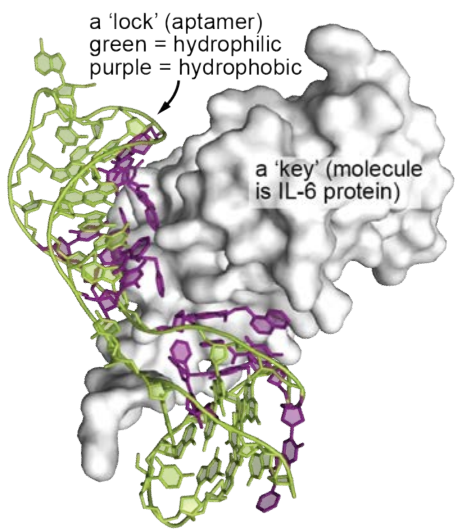


Figure 5. An Exquisite Lock-and-Key Fit of an Aptamer to an Inflammatory Protein Like IL-6 *(Source: SomaLogic 2023 [7])*.

The purple parts of the aptamer are manmade nucleotides with greater hydrophobicity. These more hydrophobic, manmade nucleotides on the aptamer dislike water and are attracted to the hydrophobic amino acid portions of the IL-6 protein. Other companies like Aptamer Group, Aptagen, and Aptus Biosciences are realizing the power of these manmade nucleotides and offering them commercially.

PULLING IT ALL TOGETHER

How can a single measurement assay *technology* (Figure 2a) like SomaScan be converted into a continuous measurement sensor (Figure 2c)? In 2005, Kevin Plaxco and colleagues at the University of California Santa Barbara found that by attaching a redox active molecule like methylene blue to one end of the aptamer and using the opposite end to attach the aptamer to a gold electrode, these powerful lock-and-key mechanisms can be measured electrically [8]. As shown in Figure 6, as the molecule of interest binds to the aptamer, the aptamer changes shape, which moves the methylene blue closer to or farther from the gold electrode. As the methylene blue molecule moves closer to the electrode, greater redox electron exchange occurs with the electrode; therefore, greater current is measured. These current changes can then be easily correlated with measured molecule concentration. Because lock-

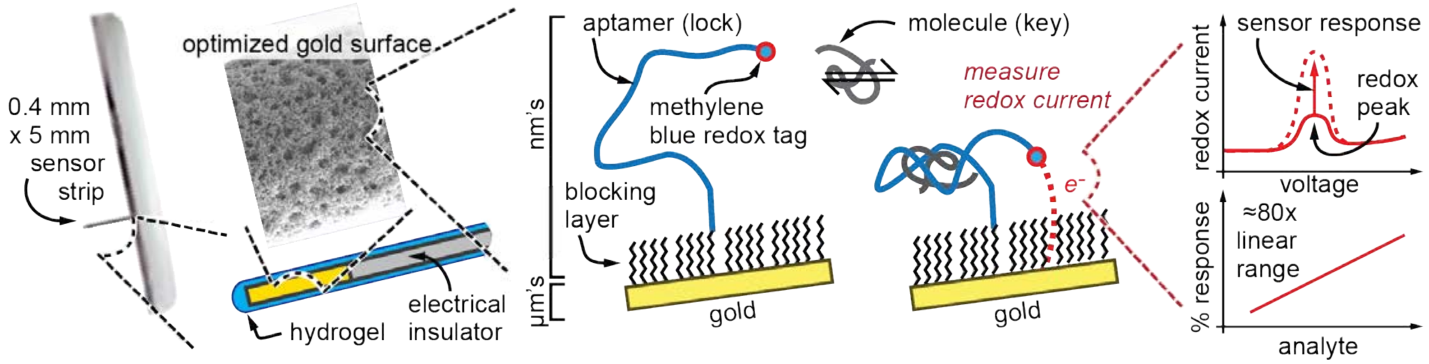


Figure 6. Adapting Aptamer Sensors Onto Continuous Glucose Monitoring Device Formats *(Source: J. Heikenfeld)*.

and-key binding between the aptamer and measured molecule is reversible and requires no other reagents (like assays require), this allows continuous monitoring in the body.

If aptamer sensor technology were available in 2005, why is significant commercial progress just now being seen? The single biggest challenge that hindered aptamer sensor development was its fragility, which only permitted short-term tests using surgically implanted sensors in animals [9].

RESULTS AND DISCUSSION

Figure 7 shows some of the recent breakthroughs that will make performance and health monitoring a reality. In the past four years, through corporate, U.S. Air Force and Space Force (Patrick Bradshaw and Steve Kim), Office of Naval Research, National Science Foundation, and National Institutes of Health support, the coauthors and their affiliated organizations have demonstrated the following:

- Aptamer sensor stability for *multiple months* in whole serum (Figure 7a) exceeding even the two-week commercial benchmark established for glucose sensors. This longevity is an impressive achievement for aptamer sensors measured in a biofluid like that found in the body.
- Batch fabrication of these sensors with uniform performance across the entire batch, enabling factory calibration (i.e., make hundreds of sensors, calibrate a small subset at the factory, and use that calibration data with software to provide accurate operation for the uncalibrated sensors in real-world use).
- Most importantly, the sensors are fabricated on tiny hair-sized plastic electrode strips that match the dimensions and materials used in commercial glucose monitors. Therefore, the sensors can leverage the proven device architectures for glucose monitors (Figures 2c and 3), including single-step and pain-free, nonsurgical sensor insertion into the skin.

Two equally important areas of work remain before commercial deployment of these improved aptamer-based molecular monitors. The first requires commercialization efforts to translate these research and development innovations into a real product. This process involves numerous safety and reliability checks, manufacturing yields, and other issues that will require time and effort. Fortunately, the pioneering progress that glucose monitors have already demonstrated will de-risk many of these translational steps. The University of Cincinnati and Kilele Health Inc. are laser focused on this strategy of adapting glucose monitor technology for use with aptamer sensors, a strategy that surprisingly most others have not adopted [5].

The second area of important work requires figuring out the best molecules to target. This is where

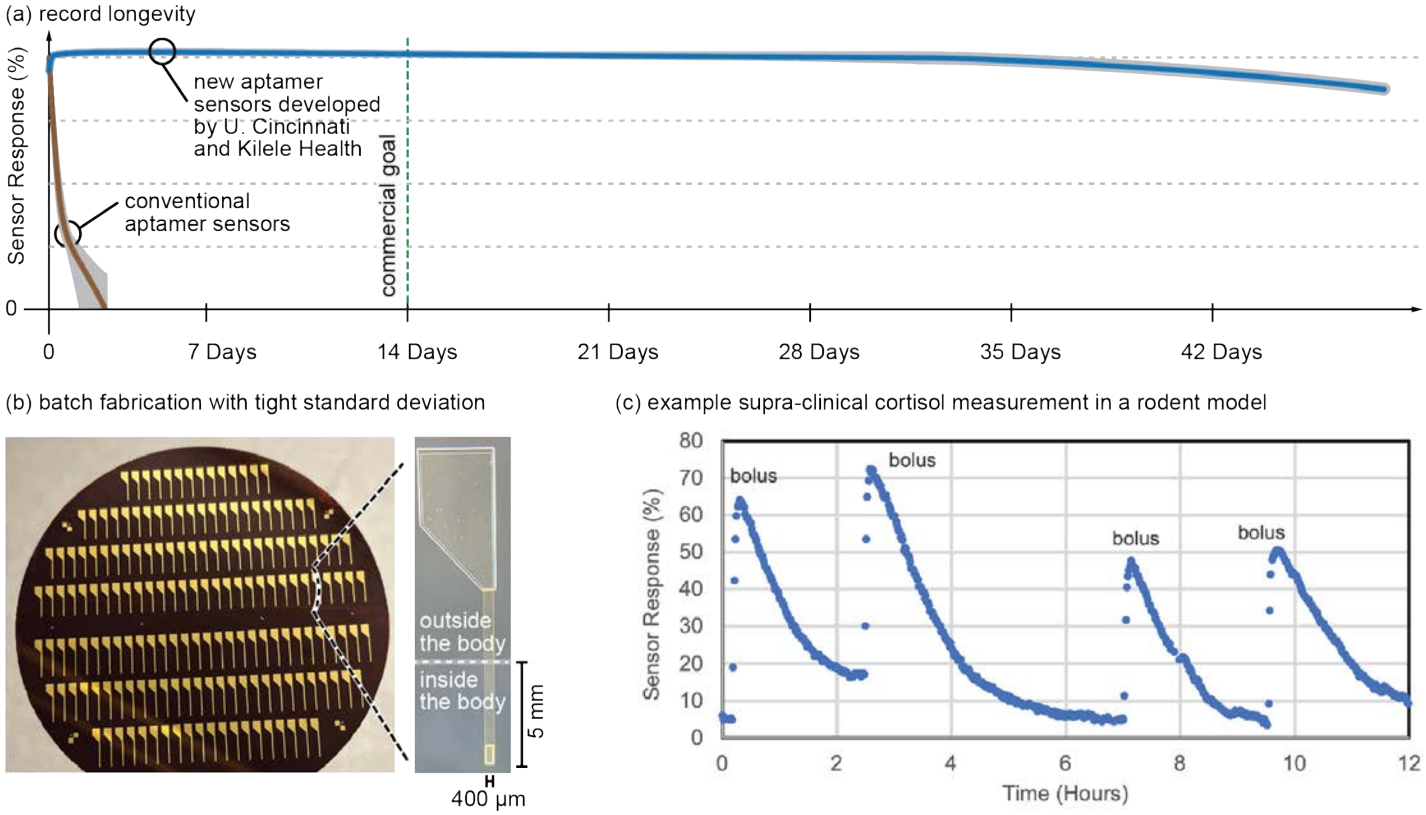


Figure 7. Reasons to Believe that Aptamer Sensors Are Ready to Enable Molecular Monitoring Beyond Glucose *(Source: J. Heikenfeld)*.

the U.S. Department of Defense (DoD) requires more fundamental work to identify what molecules will best address the goals of the example applications listed and discussed in other reviews on human performance by Lee et al. [6]. Team members from the University of Cincinnati and Kilele Health Inc. are currently partnered with organizations like the Institute for Human and Machine Cognition to identify those next-level biomarkers [10]. Some long-discussed molecules such as cortisol (Figure 7c) and inflammation molecules may be early targets and will be critical to monitoring mental and physical stress status and resiliency.

It has been a long road for the DoD in pursuing wearable molecular monitoring beyond glucose. Now is the time to seize the opportunity, as aptamer-based molecular monitors provide an alternative to glucose by showing robust performance for multiple weeks with a commercially proven glucose monitor format. If all goes according to publicized commercialization plans, early applications of such sensing technology may begin to appear in medical applications in 2027, with homeland defense applications following shortly thereafter. ■

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> ***Some long-discussed molecules such as cortisol and inflammation molecules may be early targets and will be critical to monitoring mental and physical stress status and resiliency.***

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BIOGRAPHIES

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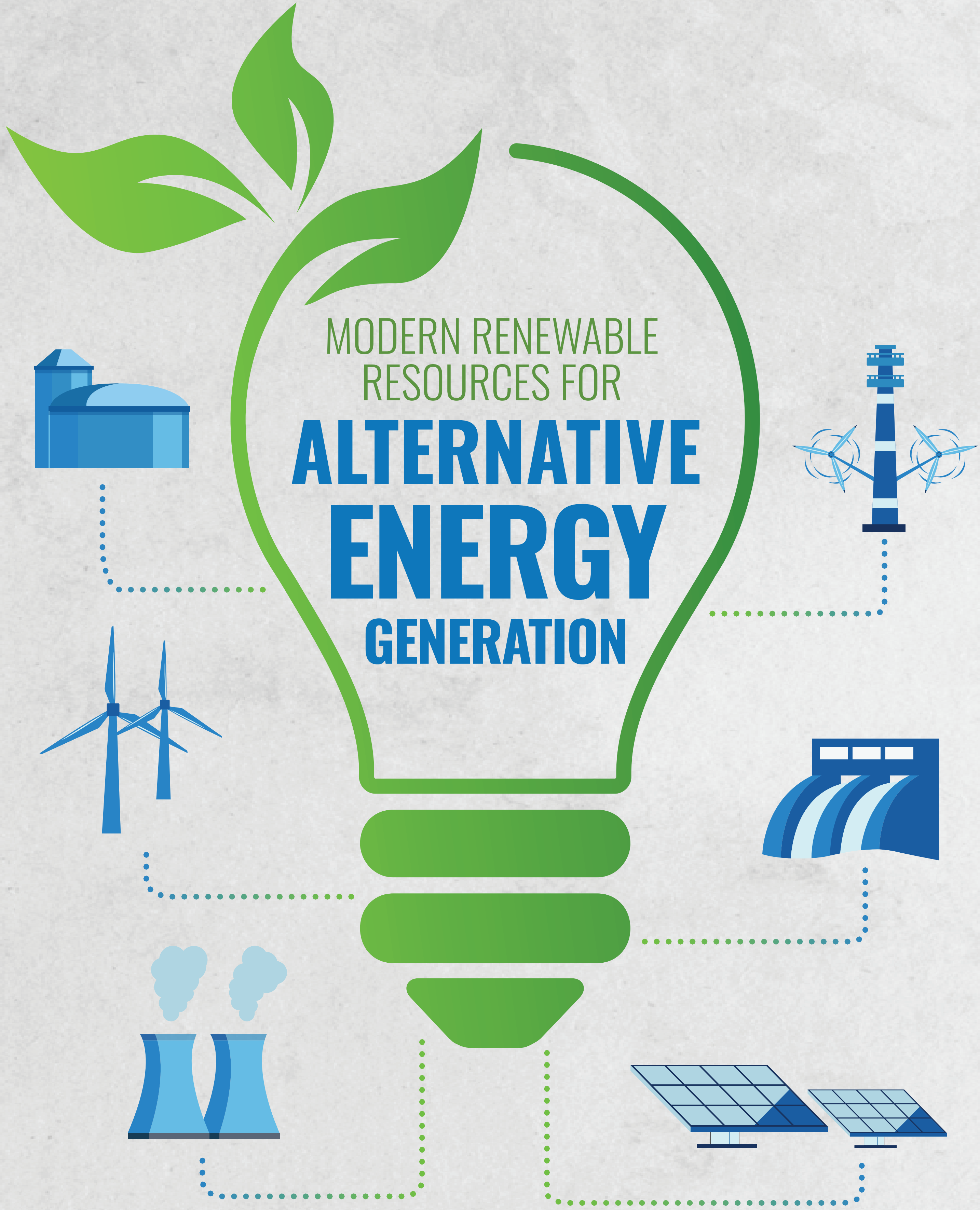
ALEKSANDAR KARAJIC is the principal scientist at Kilele Health Inc., where he develops wearable electrochemical aptamer sensors to continuously monitor various bioanalytes. His work has focused on wearable electrochemical sensors, electrocatalysis, biofuel cells, and material science. Dr. Karajic holds an M.S. in chemistry and an MSc in analytical and electroanalytical chemistry from the University of Belgrade and a Ph.D. in physical chemistry (electrochemistry) from the University of Bordeaux.

ZACH WATKINS is a research affiliate at the University of Cincinnati in the Novel Devices Laboratory, where he has focused on integrating electrochemical aptamer sensors into point-of-care and continuous wearable biosensing platforms, with an emphasis on extending sensor operational lifetimes for multiweek use. Mr. Watkins holds a bachelor's degree in biomedical engineering from North Carolina State University and a Ph.D. that focused on integrating electrochemical aptamer sensors into point-of-care and continuous wearable biosensing platforms from the University of Cincinnati.

THOMAS YOUNG is a biomedical engineering Ph.D. student at the University of Cincinnati in the Novel Devices Laboratory. His dissertation research focuses on the feasibility of continuous protein monitoring using electrochemical aptamer sensors.



MODERN RENEWABLE RESOURCES FOR ALTERNATIVE ENERGY GENERATION

BY DANIEL FLEMING

(PHOTO SOURCE: KALEN [ADOBE STOCK], LGOGOSHA, NAZARII M, MVSHOP, MJ1995S, NSIT [SHUTTERSTOCK])

SUMMARY

This article explores existing alternative energy capabilities that the U.S. Department of Defense (DoD) can leverage to ensure technological operability in austere environments, mitigate costs required for long-term installations, and provide clean energy considerations where feasible. It aligns with the government's existing renewable energy generation and storage critical technology area and can provide researchers, engineers, and technical managers with the expertise and lessons learned from previously researched efforts. Various types of renewable resources, such as bioenergy, wind energy, geothermal energy, solar energy, hydropower, and tidal energy capabilities, are discussed.

INTRODUCTION

In a list of critical and emerging technologies published in February 2024 by the National Science and Technology Council's Fast Track Action Subcommittee on Critical and Emerging Technologies, clean energy generation and storage was highlighted as being potentially significant to U.S. national security [1]. Several subcategories of interest are highlighted as key subfields to describe the scope of clean energy generation and storage. Progression in these subfields will support the target renewable energy generation of the 2022 National Security Strategy [2]. These subcategories include the following [1]:

- Renewable generation,
- Renewable and sustainable, chemistries, fuels, and feedstocks,
- Nuclear energy systems,
- Fusion energy,
- Energy storage,
- Electric and hybrid engines,
- Batteries,
- Grid integration technologies,
- Energy efficiency technologies, and
- Carbon management technologies.

Starting in fiscal year (FY) 2020, $7,343,126,002 have been included in budget justifications to research various renewable energies for research, development, test, and evaluation (RDT&E) budget justification (R2); procurement justifications (P40); unified research and engineering databases (UREDs); DoD grants; Small Business Innovative Research/Small Business Technology Transfer (SBIR/STTR) awards; and federal procurement data system (FPDS) spending (Figure 1) [3]. Most of this funding (total

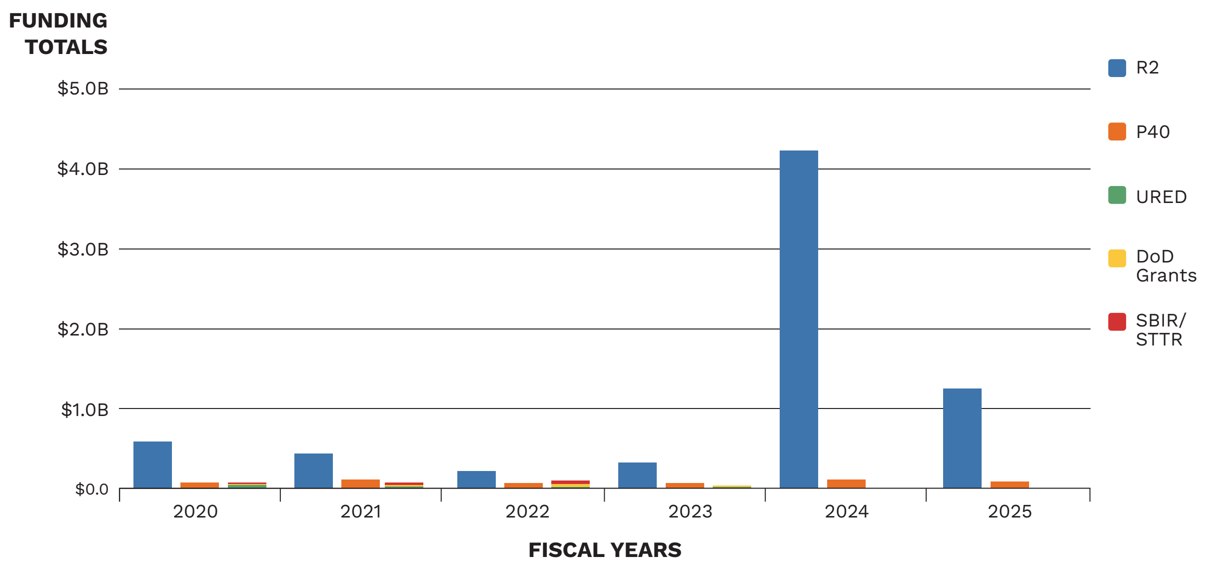


Figure 1. Funding Obligations for R2, P40, URED, DoD Grants, SBIR/STTR Awards, and Federal Procurement Data System Spending *(Source: The Defense Technical Information Center's [DTIC's] Horizons [Beta] Platform).*

obligated funding since 2020 - $334,661,596) was sponsored by the DoD components ($232,041,495) and the U.S. Department of Energy (DoE) ($85,895,763) (Figure 2) and used to research bioenergy, wind energy, geothermal energy, solar energy, hydropower capabilities, and nuclear energy.

ENERGY TYPES

Several types of renewable energy efforts are highlighted. While not an exhaustive list, it should serve as a considerable start to find what information is publicly available on the types of renewable energy research efforts.

Bioenergy Research

"Bioenergy is a form of renewable energy derived from recently living organic materials, known as biomass, which can be used to produce transportation fuels, heat, electricity, and products" [4]. While the research into utilizing bioenergy is focused on generating energy, there are various pathways to generate or increase the efficiency of energy [5–7]. Organizations supporting this research under U.S. Army funding like Enexor BioEnergy use their knowledge in clean energy generation by using biofuels found in organic materials, plastics, and sargassum [5] to increase Army capabilities. Other agencies or organizations augment the research capabilities of their DoD partners.

> ***While the research into utilizing bioenergy is focused on generating energy, there are various pathways to generate or increase the efficiency of energy.***

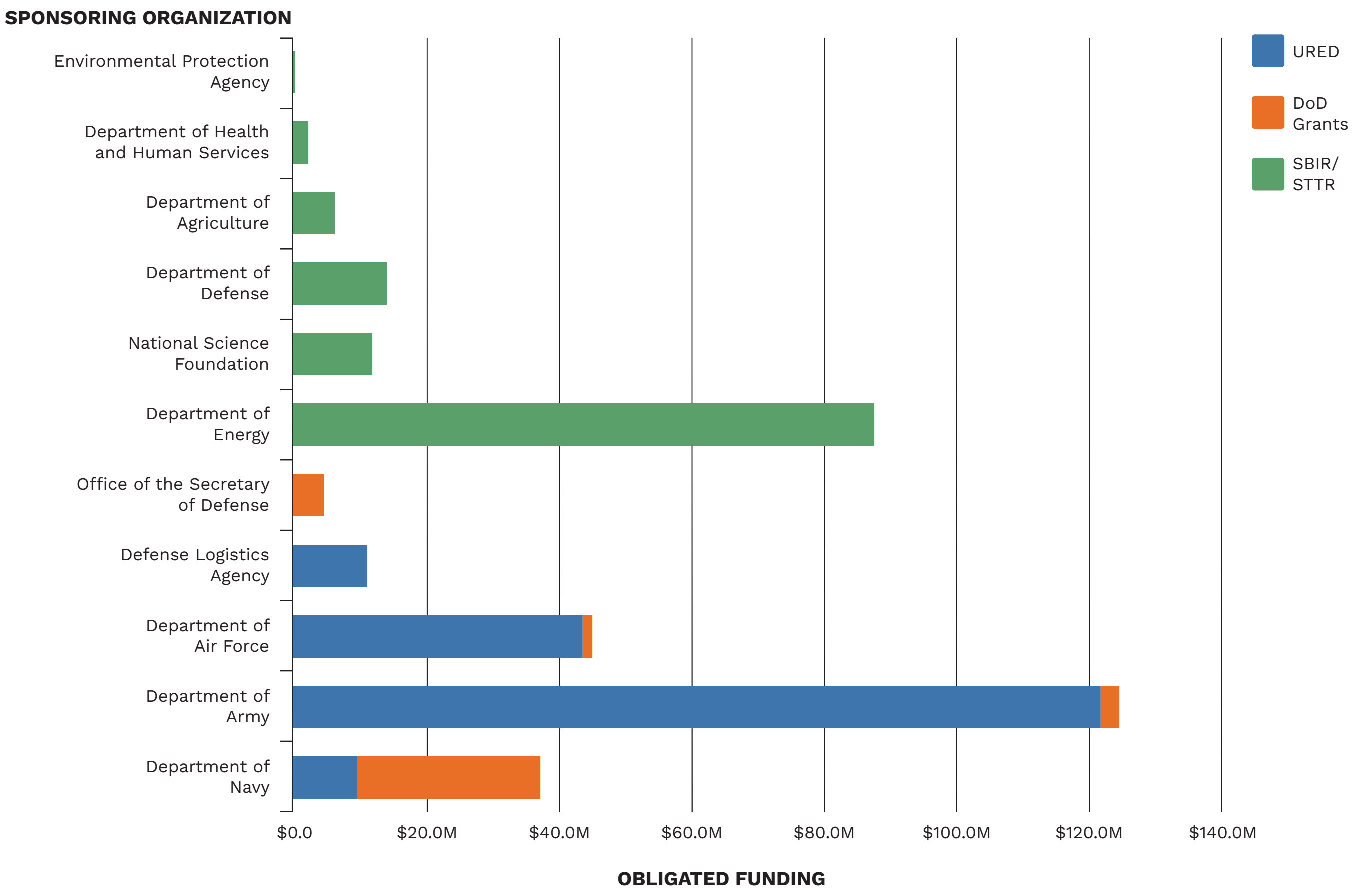


Figure 2. Funding Obligation for Sponsoring Organizations for URED, DoD Grants, SBIR/STTR, and FPDS Data Sources *(Source: DTIC's Horizons [Beta] Platform).*

For example, Hedgefog Research Inc. provides a quantum-enabled, nondestructive optical microscopy approach to enable bioenergy-based research [6], allowing a deeper understanding of how to best use plant-based biomaterials as a fuel source.

Similar to Enexor's organic material research, CF Technologies, Inc. has developed a process to utilize waste greases (previously unusable due to sulfur contaminations in the greases) to create a biofuel pure enough to use in transportation, heating, and marine industries [7]. These forms of bioenergy convert stored energy and transport it to austere environments for use as a fuel source, similar to current fossil fuels. These biofuels can also be stored under specific conditions in long-term facilities, such as military installations, to mitigate fossil fuel reliance and grid load.

Wind Energy

Wind energy "harnesses the power of wind to collect and convert the kinetic energy that wind produces into electricity" [8] and can generate a significant amount of energy from land-based farms and offshore platforms. In a 2022 assessment conducted by the National Renewable Energy Laboratory (NREL), it was estimated that offshore wind energy technology alone could generate three times the electricity consumption of the United States [9]. This identified a potential 1.5 terawatt (TW) of energy generation in modern fixed-bottom wind farm capabilities and another 2.8 TW from floating offshore farms (restricted to areas of the contiguous United States). Yet additional research is being conducted to mitigate the cost and increase the yield from modern designs.

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When considering wind energy technology, the structure's design and conversion capabilities are important in the cost and energy generation of these systems. Partnerships like those between the National Science Foundation (NSF) and RCAM Technologies and XFlow Energy Company [10, 11] and the DoE and Deep Ranch Technology, Inc. [12] are researching ways to promote cheaper or stronger materials and designs used in wind turbines. Although reliant on wind being present and in the proper environments, wind energy could be harnessed to ensure in-the-field priority technologies like medical operations or communications. This type of energy can have a primary or potentially redundant energy source or be used to charge energy storage devices like batteries for continued operations.

Geothermal Energy

Geothermal energy is derived from the heat sources in the earth, such as reservoirs of hot water, or human-made resources found below the earth's surface [13]. Current uses for geothermal energy include electricity generation since the stable presence of heat can be used to generate steam to power turbines. Geothermal energy can also be used to heat and cool buildings by using the ground as a heat sink to regulate thermal distribution. The largest geothermal power station, the Geysers geothermal plant located in California, can generate several terawatt hours (TWh) as an annual output [14]. Current research efforts seek to increase the potential capabilities of plants like these. Organizations like Nrgtek, Inc. and Tech4Imaging LLC, both funded through the DoE, have been researching potential system benefits for geothermal research [15, 16]. Harnessing geothermal energy could be very convenient for energy storage charging in the field or it could be used for permanent installations to provide a staging area for storage.

Solar Energy

Solar energy, also referred to as electromagnetic radiation energy, harnesses energy emitted by the sun to provide power through various technologies. Solar energy technologies can be broken down into two main types—photovoltaic (PV) and concentrating solar thermal power (CSP). According to the DoE's Solar Energy Technologies Office, "the amount of sunlight that strikes the earth's surface in an hour and a half is enough to handle the entire world's energy consumption for a full year" [17], indicating the potential usefulness of harnessing this type of energy. Under these two types of solar harnessing technologies, an estimated 238 TWh/year average was generated from U.S. PVs in 2023 [18], while a concurrent estimated 4.656 TWh/year average was generated across 27 national concentrating solar power project farms in the United States [19].

Additional capabilities are being researched to further the capabilities or mitigate the cost of both types of harnessing capabilities. For PVs, several research contracts are being coordinated between the DoE, the NSF, and the DoD, coordinating with industry partners to better utilize the peak PV energy generation times, budget PV cell real estate or viable staging locations, and mitigate costs of current systems [20–24].

In one research effort, the U.S. Air Force partnered with Digital Solid State Propulsion, Inc. to research how to mitigate costs and the potential load on the electric grid. By studying energy usage on Air Force housing installations, Digital Solid State Propulsion found that the energy generated during peak hours for PV activity was being wasted and instead could be used to heat water systems through a hot water controller. This would not only mitigate the cost of heating water during peak-cost hours, but the heated water could act as a thermal battery for later use or potential thermal energy conversion [20]. In addition to mitigating the costs, it would be challenging to intentionally deny an opposing force access to solar harvesting. This would provide DoD forces a potentially reliable alternative energy option to pair with energy storage capabilities in forward-operating, warfighting environments.

As an alternative to the DoD research, the NSF is funding efforts with industry partners to better utilize zones not fully optimized for PV platforms. Through Taka Solar Corp., a study is being performed to determine if PV cells or island platforms could be developed to harness solar energy that falls over oceanic environments [21]. Bodies of water within the United States could possibly generate over 300 GW with current technologies. Concurrently, NSF is partnered with Portable Solar Inc. to provide a solution for residential supporters of PV platforms, enabling more widespread access to renewable energy to the already established infrastructure [22]. As these systems become more widespread, demands on the electric grid will lessen.

The DoE is also supporting active PV research efforts. Similar to the NSF's partnerships, one effort supported by the DoE is a symbiotic usage of agricultural settings [23]. In a partnership with VesprSolar, Inc., research is being completed to allow the agricultural sector to have "agricultural photovoltaics." This effort colocates solar tracking cells with various agricultural products, allowing better usage of natural biological processes and economic relief to modern agricultural professionals as they contribute to local electrical grids while mitigating their own electrical demand.

In a second DoE-funded effort, Nanosonic Inc. is developing a production capability for low-cost, perovskite cells with resilience to environmental degradation [24]. With the current power conversation efficiency of perovskite solar cells and

> ***Bodies of water within the United States could possibly generate over 300 GW with current technologies.***

a goal to reduce production costs by roughly 90%, Nanosonic is looking to integrate these cells in many everyday commercial applications. This includes national electrical grid contributions, local power arrays, solar lamps, parking meters, emergency telephones, trash compactors, temporary traffic signs, charging stations, and remote guard posts and signals and replacing electric lines for remote locations.

A third effort funded by the DoE—focusing on the concentrated solar-thermal power generation—is testing new heat exchangers to mitigate costs and technology requirements for using supercritical carbon dioxide in CSP operations [25]. This funding will allow testing of various alloys for the heat exchangers in the CSP platforms and could enable technological developments for lower temperatures and pressure applications for next-generation designs.

Hydropower/Tidal Energy Platforms

A hydropower platform, also referred to as hydroelectric power, is one of the most traditional forms of renewable energy that "uses the natural flow of moving water to generate electricity" [26]. In an article published in 2023 by the U.S. Energy Information Administration, hydroelectric power accounted for 28.7% of the total produced renewable energy domestically in calendar year 2022 [27]. While being one of the most established forms of renewable energy to date, hydroelectric power still relies on climate and weather, which can prove challenging to regulate in less-robust environments. In a study from Intersphere Inc. and funded by the NSF, research is being conducted to mitigate the weather and climate risks associated with hydropower applications [28] by training machine-learning (ML) models and integrating those models into current geoscience practices. These models can generate powerful assistance platforms for not just hydropower considerations but for closely related research efforts like wind energy, geothermal energy, and tidal energy. By leveraging this research, the DoD could use hydropower capabilities and the developing models to preemptively parse the most reliable waterways for energy generation, while leaving minor footprints in austere environments, and provide allied forces key details to these potential capabilities if these waterways fall within their domains.

> ***While being one of the most established forms of renewable energy to date, hydroelectric power still relies on climate and weather, which can prove challenging to regulate in less-robust environments.***

Tidal Energy

Tidal energy, like hydroelectric energy, can be a harvestable form of renewable energy by converting the kinetic energy from water whose "natural rise and fall of tides caused by the gravitational interaction between Earth, the sun, and the moon" can be fed through turbines, converting the kinetic energy into electric energy [29]. In support of utilizing this type of renewable energy, the DoE has partnered with two organizations to further tidal energy capabilities. In two studies, the Ocean Renewable Power Company, Inc. is developing a scalable application of marine renewable energy to generate a microgrid in False Pass, Alaska [30] and the Cook Inlet of Alaska [31]. Both efforts serve to study the reliability and capabilities of tidal energy in a similar geography while highlighting challenges that should be considered for follow-on studies.

Another effort funded through the DoE engages with industry partner Industrial Consulting Inc. to provide a pathway for marine spatial planning specialists to have informed and collaborative planning capabilities that do not detrimentally impact the sociocultural, ecological, environmental, and economic barriers which could limit deployment [32]. With many permanent DoD installations dotting the coastlines, tidal technologies could find a wide breadth of testing environments, with domestic, long-term energy considerations as the primary focus. In addition to civilian application, DoD-specific testing could focus on ways to leverage tidal technologies for military operations in nonlandlocked locations that allow an alternative form of energy storage when converted properly.

CONCLUSIONS

While renewable energy efforts are wide in scope and effect and some funding is available, there are still many gaps in research and barriers for entry across the different renewable energy capabilities [33]. Solar energy platforms can be further refined for more efficient energy generation or more ubiquitous zones [19–25]. Hydropower platforms are learning from ML applications via modern research capabilities [28], identifying some additional challenges where innovative research efforts can be applied. Similarly, tidal energy and hydroelectric capabilities are negatively affected by climate and geological limitations, and uncertainties in ecological impacts could result in detrimental conditions going forward if not properly developed [32].

However, as research efforts continue, researchers can create more efficient methods to harness alternative sources of energy. These efficiencies create untapped potential in contributing positively to current large- and small-scale electrical grids. When seen from a combined standpoint, these forms of renewable energies are ubiquitous, allowing energy capture to occur almost anywhere globally. As the DoD leverages these technological advancements, renewable energies could provide a solution to generate and store energy and distribute power to small, expeditionary teams and larger, stationary, permanent installations while reducing the environmental impact and long logistics tails associated with fossil fuel use. ■

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BIOGRAPHY

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ENHANCING ARMY COMBAT EFFECTIVENESS AND SURVIVABILITY THROUGH MICROGRIDS

BY ANDRE SLONOPAS AND LUDO ROCHE

(PHOTO SOURCE: PETOVARGA [123RF.COM])

SUMMARY

As the U.S. Army seeks to improve combat effectiveness and survivability, innovative energy systems are becoming more critical. This article outlines applications of the microgrids as they relate to U.S. Army Regulation (AR) 70-75, "Survivability of Army Personnel and Materiel" [1], survivability criteria and rapid deployment microgrid (Figure 1) successes in providing deployable power to maneuver units. Military applications benefit from microgrids, especially those that use renewable energy sources since they offer a constant, stable power supply in distant or hazardous areas. Although microgrids generate less than 0.3% of U.S. power, their capacity has grown, suggesting their rising relevance in energy resiliency. Microgrids are ideal for military facilities, forward-operating bases, and settings like disaster response, where the usual electricity grid might not be reliable. They are ready to go at a moment's notice, can be adjusted to meet different needs, and can use various energy sources like solar panels and batteries. This flexibility meets the military's survivability needs and supports the Army's operational plans by offering energy autonomy and minimizing fuel supply and energy production logistics. This article also discusses the broader implications of military microgrid use, including integration with Army energy infrastructure, civilian implications, and integration challenges. It leverages recent successes of a test and evaluation of a Resilient Energy and Infrastructure (REI) microgrid work that was funded through U.S. Army Small Business Innovation Research (SBIR) Phase I and II efforts. REI is one of few niche companies

Figure 1. Microgrid Systems *(Source: REI)*.

like BRG Energy, Bloom Energy, BoxPower, POMCube, EnSync Energy, Schneider Electric, and ENGIE using microgrid technologies, which improve the Army's tactical capabilities, enhance survivability, and advance energy security goals.

INTRODUCTION

In an era where technology frequently decides military battles, dependable and efficient energy systems are crucial. Modern military operations include unmanned aerial vehicles and mobile command centers that need a reliable power source. These systems' performance and dependability depend on energy supply stability and availability. Military forces have traditionally used massive, centralized power-generating systems, which are intense but logistically tricky and subject to interruption, especially in war zones. Due to this susceptibility, energy systems must be resilient and flexible to different and dynamic operating contexts.

Microgrids are transforming military energy resiliency in the face of these issues. Decentralized microgrids operate independently from the electricity grid. They smoothly incorporate diesel generators, solar panels, and batteries. Integration improves energy management and assures a steady power supply, which is essential for distant or hostile operations. Microgrids provide localized energy production and distribution, reducing the danger of transferring fuel over compromised channels and the logistical challenges of standard energy systems.

The combination of energy generation, energy storage, and logic for the multiple-input and multiple-output is compactly packed inside a 20-ft container (Figure 2). These cutting-edge microgrids use renewable energy, install quickly, and can scale to support a broad range of missions ranging from small unit operation centers to installation and utility scales. Notably,

Figure 2. The Built Microgrid With 35-kW ExoSolar, Energy Storage, and Energy Management Systems Integrated Into the Connex *(Source: REI).*

these systems fulfill the strict U.S. AR 70-75 survivability standards for military technology, which require systems to operate in artificial hostile situations and maintain operational capability under pressure.

Energy management control systems, also known as microgrids, provide dependable electricity to improve military operations. Solar power, diesel generators, and superior battery storage make up these systems and provide a strong and versatile energy solution that can meet military needs. This hybrid strategy improves operating efficiency and reduces greenhouse gas emissions, connecting military operations with environmental sustainability objectives.

Military energy policy is shifting toward energy autonomy and resilience as microgrids expand. As global military plans concentrate on minimizing logistical footprints and improving operational unit autonomy, microgrids are possible. They help manage resources sustainably and boost defensive capabilities by keeping essential systems independent of external power infrastructure.

As renewable energy technologies improve and sustainability becomes more important, military microgrid technology will increase. This shift toward robust, efficient, and environmentally friendly energy solutions in military plans is crucial. Microgrids are a strategic asset that will define the energy landscape of contemporary military operations, ushering in a new era of flexible, sustainable, and autonomous military energy management.

> *Microgrids are a strategic asset that will define the energy landscape of contemporary military operations, ushering in a new era of flexible, sustainable, and autonomous military energy management.*

BACKGROUND ON MILITARY ENERGY NEEDS

Military operations need a stable and constant energy supply for communication, observation, transport, and weapons systems. Military power systems have relied on diesel generators for centralized power production. Although durable and essential in technology, traditional systems have limits that might hinder military operational capabilities and adaptability.

Fuel is the main drawback of conventional military power systems, which may be logistically challenging. In war zones, hostile troops may attack fuel supply lines, causing disruptions. This vulnerability threatens military operations and gasoline transportation safety. Unscalable and inflexible centralized power-generating systems might be a significant problem in dynamic battlefields with frequently changing energy demands. These systems generate greenhouse gases and other pollutants, causing environmental damage. This violates stricter ecological regulations and limits military operations in vulnerable areas.

In response to these issues, the U.S. Army has set criteria to ensure that all military gear, including power systems, fulfills survivability requirements. The requirements outlined in AR 70-75 aim to improve the survivability of soldiers and equipment in dangerous combat settings. The rule defines Army system survivability as the capacity to escape or survive hostile threats without significant degradation.

Most specifically, AR 70-75 specifies the following key points [1]:

- Army systems must be rigorously tested and assessed for susceptibility and vulnerability in various operating circumstances prior to integration with humans.
- Systems must be built with intrinsic characteristics that limit susceptibility and increase their capacity to perform under unfavorable situations. Advanced materials, redundancy, and protection are needed.

- System survivability should be monitored frequently, especially when new threats and vulnerabilities arise, to maintain system functionality in changing circumstances.

Microgrids revolutionize military energy supply due to conventional power system limits and survivability AR requirements. Decentralized microgrids function independently from the electricity grid. They can combine solar and wind energy with diesel engines and battery storage to create a durable and adaptable energy infrastructure.

Quick deployment, scalability, and high durability in many environments are incorporated into these systems. Mission-critical applications in adverse settings must quickly adjust to power demands and continue operation. Microgrids that use renewable energy sources minimize fuel supply chain dependence, improving operational security and sustainability. Microgrids are suited for military applications that demand high-energy dependability and durability due to their independence from conventional supply lines and adaptation to different operating scenarios.

Military microgrid adoption is a strategic shift that solves conventional power systems' shortcomings. Microgrids improve military units' operating capability, resilience, and flexibility to current warfare conditions by meeting AR 70-75's survivability standards. Microgrid technology will be crucial to military energy strategy in the future, making troops more capable, adaptable, and environmentally friendly.

MICROGRIDS AND THE U.S. ARMY REGULATION ON SURVIVABILITY

Microgrids improve military operating capabilities by providing resilient and dependable energy, which feed directly into the survivability of personnel and materiel (Figure 3). This rule establishes the survival requirements of the military system to ensure that technology works in hostile circumstances. The strategic relevance of microgrids in current military infrastructure is due to their resilience and agility.

> *Military microgrid adoption is a strategic shift that solves conventional power systems' shortcomings.*

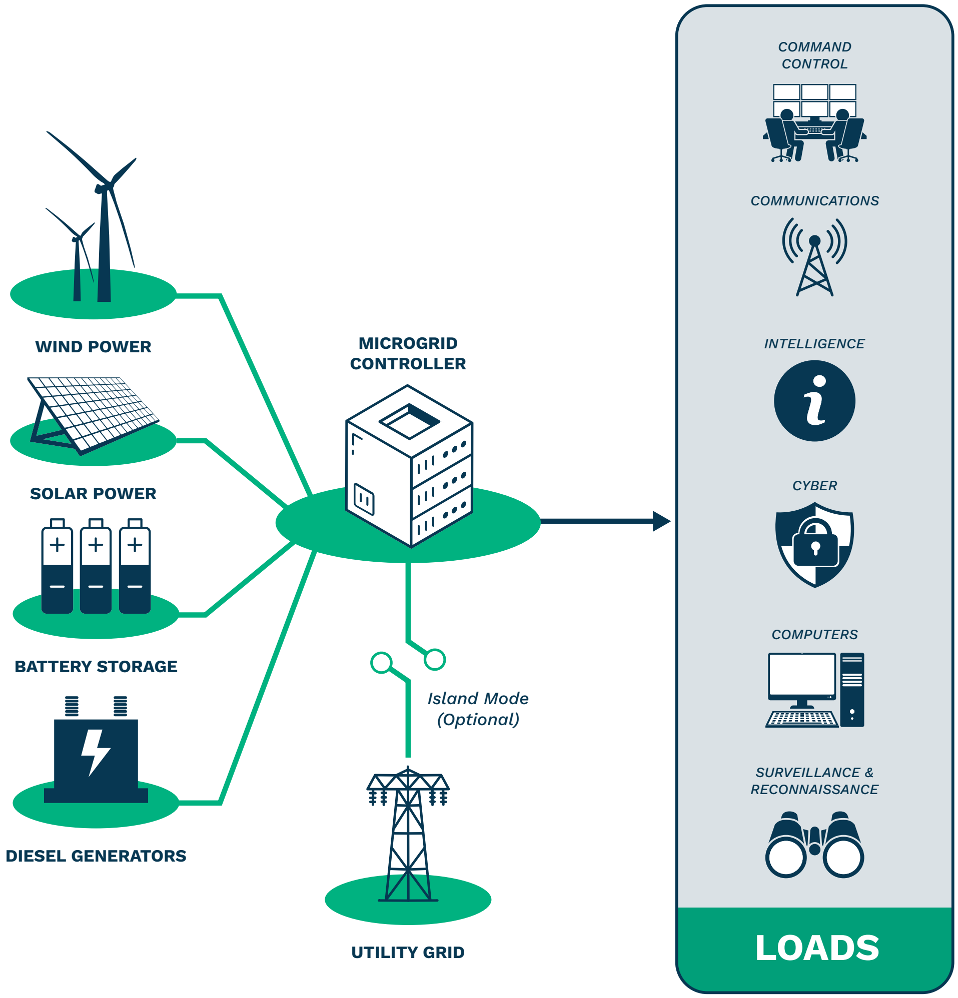

Figure 3. Microgrid Functions *(Source: Canva)*.

AR 70-75 emphasizes the capacity to avoid or endure artificial hazards to safeguard Army people and equipment. Multiple factors make microgrids fit these requirements, such as the following:

- They offer resilience and redundancy by functioning independently of the primary grid to supply electricity even when conventional networks fail, which is valuable in war and disaster zones.
- Microgrids satisfy urgent energy demands on the battlefield or in temporary locations with quick deployment and scalability.
- Microgrids use renewable and conventional energy sources to minimize dependency on insecure fuel supply lines, improving operational security and sustainability.

Microgrid case studies demonstrate military microgrid efficacy. Forward-operating bases with high dependability and energy independence use microgrids. These technologies have kept command, control, communication, computers, cyber, intelligence, surveillance, and reconnaissance capabilities running amid grid disruptions. Military microgrids speed up communication and logistics in disaster zones, enabling successful response operations. Portable devices like microgrids may be deployed immediately, proving useful in uncertain circumstances. Microgrids' technological advantages complement the Army's operational and survivability aims. They provide a safe energy supply that reduces sabotage and operational disturbance, preserving tactical advantages. They are flexible because they can incorporate solar panels and diesel engines and eliminate gasoline convoys commonly targeted in war zones, reducing the logistical footprint and improving crew safety.

Finally, microgrids meet AR 70-75 survivability requirements and revolutionize military operations. They improve operational effectiveness by delivering dependable, robust, and quickly deployable energy solutions for demanding conditions. As technology advances, they will increasingly be used in military strategic energy planning so they can function in various global circumstances.

OPERATIONAL BENEFITS AND CHALLENGES OF MICROGRIDS

Benefits

Microgrids improve power supply stability and reliability, especially in distant or dangerous areas without regular energy infrastructure. In "island mode," these sophisticated devices can sustain electricity independently amid grid outages or other disruptions. In remote military operations, steady power is needed for communication, observation, and operational continuity. Thanks to the convert-to-island mode, these vital tasks may continue regardless of power circumstances. Microgrid resilience and sustainability are greatly improved by adding renewable energy sources like solar and wind (Figure 4). Renewable energy is dependable and continuous, unlike fuel-based generators. In war zones or remote places where fuel distribution is difficult and risky, traditional sources frequently have supply problems. On the other hand, solar panels and wind turbines can create electricity whenever there is sunshine and wind, making them perfect for extreme situations.

Renewable energy technologies integrated into smart energy management control systems are effective. These systems optimize solar and wind power to reduce diesel and other fossil fuel use, thus reducing fuel transport and storage logistics and improving operational sustainability. Renewables in microgrids cut carbon emissions, satisfying environmental goals while meeting distant military operations' tough needs. A forward-thinking energy management strategy, microgrids use renewable technology to ensure operational efficiency and sustainability in even the most demanding circumstances.

Using locally accessible renewable resources, microgrids lessen the

Figure 4. Monocrystalline Silicon Solar Panels Placed on Top of Each Tent for Energy Production. A Trailer (Center) Holds the Hardware, Software, and Lithium Ion Batteries That Form the Smart Grid and Provide Energy Backup Should the Grid Fail *(Source: Photo by Donna M. Lindner, U.S. Air Force Research Laboratory).*

logistical strain of transporting fuel, a typical conflict zone target. This logistical reduction reduces the danger of gasoline convoys and increases the military unit's operating range. Units are less dependent on gasoline supply lines and more independent. Operational flexibility is beneficial in fast-shifting battlefields, where energy demands might change unexpectedly.

Challenges

Interconnecting microgrids with military infrastructure is complex. New microgrid technologies must work with older infrastructures not built for decentralized energy systems. The microgrid must coordinate with and augment the primary grid without disrupting power delivery during technological integration. Other logistical problems include installing microgrid components in distant or harsh areas, training workers to operate and maintain new systems, and maintaining a constant supply chain for parts and repairs.

Research and development are increasing microgrids' plug-and-play capabilities to make them more compatible with current systems without significant retrofitting. Innovative grid technology and control systems improve microgrid efficiency and stability by integrating and managing varied energy sources. Research also focuses on developing robust management systems that automatically adapt to energy supply and demand and integrate with existing infrastructures. Advanced software in these systems can estimate energy demands, optimize resource utilization, and detect flaws before they cause difficulties.

Microgrids improve energy dependability and logistical savings; however, integrating them into military

> *Research and development are increasing microgrids' plug-and-play capabilities to make them more compatible with current systems without significant retrofitting.*

operations requires careful technical and logistical management. Innovation and research are needed to fully realize microgrids' promise to improve military energy policies' resilience and efficacy.

BROADER IMPLICATIONS FOR MILITARY AND CIVILIAN USE

Benefits

Military microgrid technology is advancing civilian energy management, notably resilience and operational continuity. Military microgrids provide consistent electricity even during total power outages, allowing important operations to continue. This island mode capacity is essential for military facilities and helpful for civilian infrastructure, particularly in natural catastrophe or power disruption-prone locations. Military microgrid technologies like renewable energy integration and sophisticated energy management systems may be used for civilian purposes. Hospitals, data centers, and emergency services in civilian sectors might benefit greatly from microgrid power security. This is especially important in locations where power outages may cause crucial service interruptions, potentially resulting in loss of life or considerable economic expenses.

Military microgrid resilience research also emphasizes system recovery and power maintenance, which might benefit civilian infrastructure seeking to reduce downtime and increase crisis response. Microgrids' flexibility to renewable energy enhances social transitions toward sustainable energy solutions, matching with global environmental objectives.

Microgrids may improve electricity resilience in disaster-prone or distant civilian areas. Hurricanes, floods, and wildfires may affect the central power system in these locations. Even when the grid fails, microgrids can provide electricity locally. For example, a microgrid-equipped neighborhood can maintain essential services such as medication refrigeration, heating/cooling, and lighting during disaster recovery. In isolated regions, installing standard power infrastructure might be too costly or difficult. Microgrids localize energy generation using renewable sources like solar and wind, decreasing transmission infrastructure and fuel costs. This improves sustainability and gives places more control over energy supplies, possibly lowering energy expenditures.

Challenges

Despite its many advantages, microgrid integration into existing infrastructure presents technical and legal obstacles. Technically, microgrid systems must use advanced control systems and standards to work with current grid designs safely and efficiently. Advanced forecasting and management techniques are necessary to enhance microgrid performance, particularly in systems integrating many renewable energy sources. Existing laws and regulations that do not fit microgrids' decentralized structure create regulatory hurdles. Policy changes that promote microgrid integration, renewable energy consumption, and microgrid technology investment are needed to address these issues. These modifications would benefit military sites and improve the reliability and sustainability of civilian electricity networks.

Military-driven microgrid technology growth will impact civilian energy systems globally. Adopting and adapting these modern energy technologies may boost civilian resilience, minimize environmental impact, and increase energy security and dependability. Research and development will likely decrease the gap between military breakthroughs and civilian uses, enabling microgrid adoption and a more robust global energy environment.

CONCLUSIONS

The revolutionary significance of microgrid technology in military and civilian situations has been thoroughly discussed. Military microgrids improve operational efficiency and energy resilience and provide a model for civilian infrastructure, especially essential or sensitive sectors. Military activities benefit from robust, dependable, and secure microgrids. They can operate outside the grid, maintaining power supply even under extreme situations. This is crucial in military settings where energy demands are high and may change rapidly from operational conditions or tactical requirements. Microgrid solutions demonstrate this progress. These systems provide rapid deployment and scalability for military tasks and incorporate renewable energy sources, lowering fuel use and improving sustainability.

Military-grade microgrids provide equally solid civilian advantages. Hospitals, emergency response services, and data centers may be more resilient using microgrids for natural disasters and other emergencies. Microgrids can provide energy independence and stability to distant and disaster-prone communities, improving their quality of life and economic possibilities. Microgrids promote renewable energy and reduce greenhouse gas emissions, achieving environmental and financial objectives. This supports global sustainability and helps localities find greener energy options. Microgrid implementation is complex despite its many benefits. Innovation and research are needed to integrate these technologies with grid infrastructures, manage renewable energy outputs, and ensure system dependability. Current energy regulations and market systems generally do not promote microgrids' decentralization, creating regulatory issues. Policymakers, industry leaders, and scientists must work together to build a regulatory climate that supports microgrid technology progress.

Microgrids will become more critical in military and civilian energy strategy. As the technology evolves and its advantages are realized, more military and civilian establishments may embrace microgrid systems. This will boost operational resilience and ensure a sustainable energy future. Future military defense policies prioritize energy autonomy and operational flexibility, making microgrids vital. Military applications may teach civilians how to improve catastrophe resilience and emergency management. Microgrids may become famous in local energy systems in locations without grid infrastructure, as the quest for more sustainable and resilient energy solutions continues. Energy democratization and localized energy governance may result from community microgrids providing residents authority over their energy resources.

> ***Future military defense policies prioritize energy autonomy and operational flexibility, making microgrids vital.***

Military and civilian energy management methods have advanced significantly with microgrids. By advancing this technology, society can improve energy security, sustainability, and resilience. Microgrids might transform energy production, management, and consumption across industries. ■

NOTE

This article includes recommendations based on the testing and evaluation of microgrid technology. This evaluation was conducted as part of U.S. Army SBIR Phase I and II efforts. Reference herein to any specific commercial products, process, or service by tradename, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. government or the Homeland Defense and Security Information Analysis Center (HDIAC). The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. government or HDIAC and shall not be used for advertising or product endorsement purposes.

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BIOGRAPHIES

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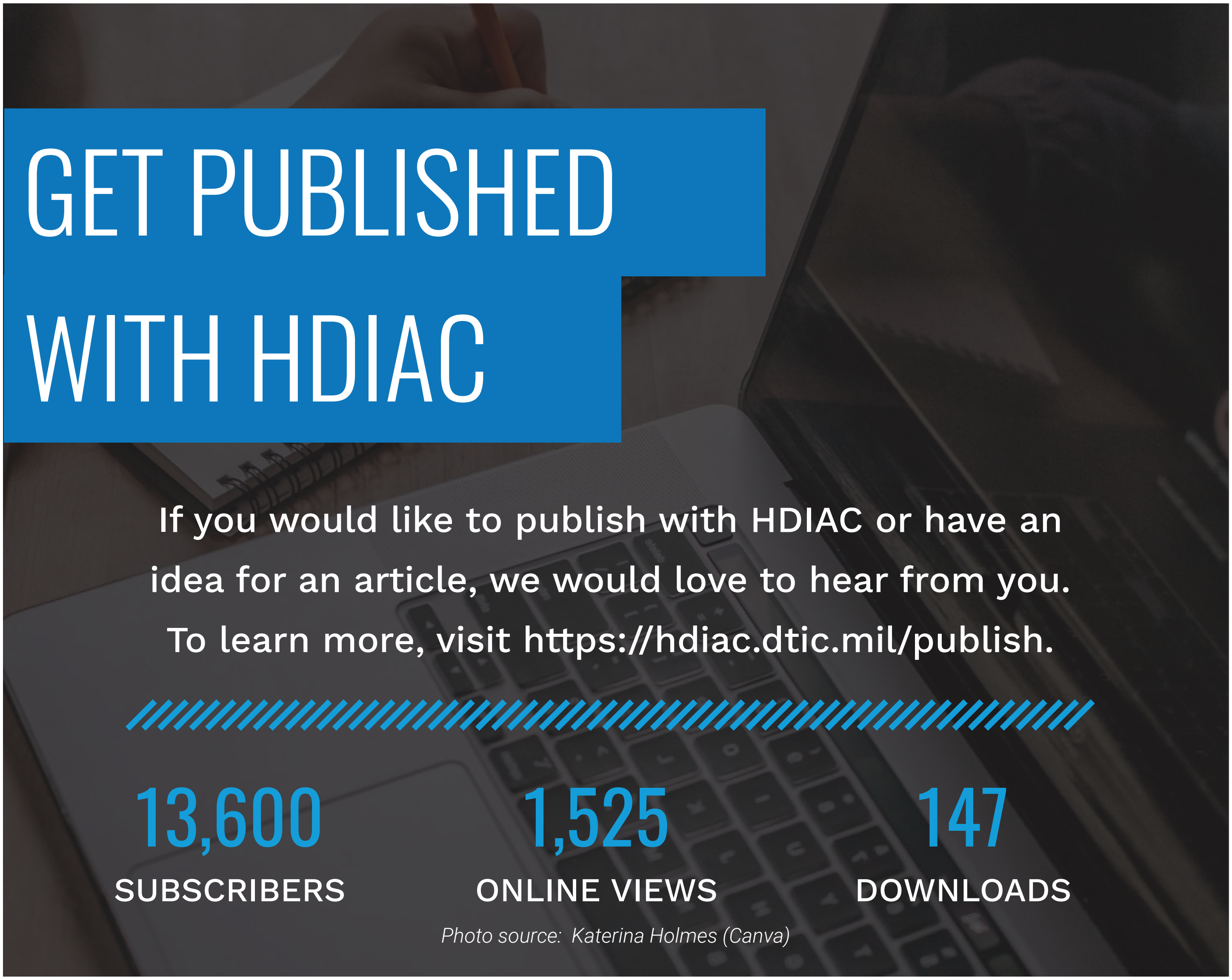

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