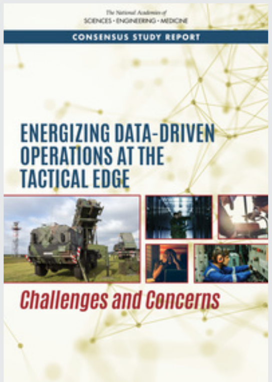

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ENERGIZING DATA-DRIVEN OPERATIONS AT THE TACTICAL EDGE

Challenges and Concerns

Committee on Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force

Air Force Studies Board

Division on Engineering and Physical Sciences

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review

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of this report was overseen by Robert F. Sproull, NAE, Oracle Labs (retired), University of Massachusetts, Amherst. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Preface

In 2019, the U.S. Air Force (USAF) requested that the National Academies of Sciences, Engineering, and Medicine conduct a study to examine challenges and opportunities associated with energy needs for future data-driven operations at the tactical edge. Accordingly, the National Academies, under the auspices of its Air Force Studies Board (AFSB), established the Committee on Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force. Members of the interdisciplinary committee were volunteers, appointed to represent relevant academic, research, and operational experience for this highly specialized topic. This report is the result of the work of that committee. Consistent with the statement of task, reprinted in Appendix A, this report offers insights into the Air Force regarding the energy needs for information systems at the tactical edge.

The committee wishes to acknowledge the many contributors to the study, specifically those who took the time to brief the committee and participate in the many virtual meetings over the period of the study. The committee began work just prior to the onset of the SARS-CoV-2 (COVID-19) pandemic and was able to have only one meeting in person before the restrictions on gathering went into effect. The pandemic restrictions on travel and group gatherings impacted the normal National Academies study process by requiring that all data gathering and interviews be conducted virtually and by eliminating the ability of the committee to collect data from operational locations. The committee would particularly like to acknowledge and thank the participants, including both staff and subject-matter experts, who participated while actively fighting the COVID-19 infection. The committee members and National Academies staff displayed perseverance in the midst of these unusual circumstances, completing the study despite the restrictions. We wish to thank them and the many subject-matter experts for their flexibility and willingness to contribute to this effort.

Contents

Summary

Our primary function as service chiefs is to organize, train and equip our forces for employment. We owe the combatant commanders who use these forces the capabilities that produce a warfighting advantage now and into the future, not simply greater quantities of existing equipment unsuited to competition or conflict with great powers. Achieving this goal will require accelerating investments in capabilities, including hypersonic weapons; AI-enabled remotely piloted aircraft; long-range penetrating strike; truly joint all-domain command and control; unmanned, low-cost, expendable ground, surface and air vehicles; long-range mobile ground-launched missiles; and better integrated air and missile defenses.

—Charles Q. Brown Jr. and David H. Berger, 2021[1]

DATA DEVICES AT THE EDGE NEED ENERGY

As noted in the *Future of Defense Task Force Report 2020*,[2] "advancements in artificial intelligence, biotechnology, quantum computing, and space, cyber, and

[1] See D.H. Berger and C.Q. Brown Jr., 2021, "To Compete with China and Russia, the U.S. Military Must Redefine 'Readiness,'" *Washington Post*, February 1, https://www.washingtonpost.com/opinions/2021/02/01/brown-berger-military-readiness/.

[2] See House Armed Services Committee, 2020, *Future of Defense Task Force Report 2020*, https://armedservices.house.gov/_cache/files/2/6/26129500-d208-47ba-a9f7 25a8f82828b0/6D5C75605DE8DDF0013712923B4388D7.future-of-defense-task-force-report.pdf.

electronic warfare, among others, are making traditional battlefields and boundaries increasingly irrelevant." A critical finding in the report was that significant advances were needed to improve national security and competitiveness by harnessing the growing power of information technologies, such as artificial intelligence (AI) and robotics.

There are ongoing, significant efforts within the U.S. Air Force (USAF) to do just that. Product and process technologies are being researched, experimented with, and integrated into future warfighting concepts and plans. A significant part of this effort is focused on integrating operations, from the strategic to the tactical and across all lines of effort. A question that must be asked in considering these future warfighting concepts is: how will the devices that enable the knowledge-based future be powered?

More precisely, how will the devices that are farthest from stable and permanent locations manage their energy needs? The abundant energy supplies that characterize peacetime operating environments may not be readily available at the far reaches of the force projections—the *tactical edge*—during conflict. Understanding the energy challenges associated with continued data collection, processing, storage, analysis, and communications at the tactical edge is an important part of developing the plans for meeting the future competition on the battlefield.

CONQUERING THESE CHALLENGES

The committee consulted with technical experts in academia, government, and industry to identify challenges and issues associated with energy needs at the tactical edge as well as any potential for solutions to be considered in the future to help address these challenges. There are near-term, mid-term, and long-term efforts that are needed to understand, address, and routinize the integration of energy considerations into operational capabilities. The recommendations in this document address understanding these requirement needs and the cascading effects of not meeting those needs, integrating energy needs for data processing into mission and unit readiness assessments, and research into product and process technologies to address energy-efficient computation, resilience, interoperability, and alternative solutions to energy management at the tactical edge. These recommendations are summarized below.

ENERGY NEEDS AND MISSION READINESS

The core of these recommendations falls under the issue of how much energy will be needed for functionality of data processing and support to combat operations at the tactical edge. Fundamentally, the answer to this question is not currently comprehensively known. It stands to reason that an obvious recommendation would be that the energy needs associated with data processing to support these missions be systematically analyzed and documented.

Recommendation 1: The U.S. Air Force must include energy needs in readiness reporting metrics for all weapons systems.

Concomitant to a comprehensive analysis of the energy needs associated with data processing at the tactical edge, it is important to understand the impacts of energy availability and quality to these functions and what the impact would be to larger mission functions and weapons systems should the energy needs not be met, either at all or in a timely manner. The impact on operations associated with a temporary or sustained loss of power to data capabilities at the tactical edge must be understood, ranging from logistics to management to enabling effects on target. The ability of units to execute mission requirements can be greatly undermined by the inability to collect, process, analyze, and communicate critical data, thereby impacting both unit and mission readiness.

Recommendation 2: In the emerging data-driven operational environment, the U.S. Air Force resource and capability readiness assessments should include the availability of adequate and appropriate energy to data capabilities at the tactical edge.

PULL-THE-PLUG EXERCISES

Field exercises and training often assume that power is available at all times and for any demand requirement. This is also a standard assumption for communications systems, networks, and other support infrastructures. In a forward-deployed situation or in a contested battle space, it should be expected that power and other infrastructures will be targets of attack and therefore will not be continuously available or will be intermittent. Losses may stem from existing poor commercial infrastructure or enemy denial; lack of maintenance; lack of fuel; or human error. To simulate a realistic future environment, the USAF must include a "lights out" situation in training and exercises. These pull-the-plug exercises for tactical units and dynamic basing can reveal dependencies associated with expectations of data availability to the tactical-edge missions.

Recommendation 3: The U.S. Air Force should conduct pull-the-plug exercises for all realistic field exercises, and the effect on tactical-edge data expectations should be documented and relayed to the mission plan developers.

Recommendation 4: The results of pull-the-plug exercises on tactical-edge data capabilities should be used to revise and update mission readiness assessments.

EXPLICIT ENERGY REQUIREMENTS

At present, energy needs for computational support, either on-premise or off-premise, are not currently defined in any major weapons system or mission profile. The use of both advanced information technology (IT) capabilities, such as AI, and massively distributed small devices and communications nodes, impact the energy needs at the tactical edge and have implications for the operational readiness and performance of both missions and weapon systems. These energy needs must be defined as requirements for all missions and systems.

Recommendation 5: The U.S. Air Force should include energy needs associated with data expectations, both for support and internal to the mission or system, as explicit requirements for all missions and systems. The terms and conditions for contracts should include language that requires specific and complete descriptions of energy needs, types, and compatibility with logistics support.

Recommendation 6: The U.S. Air Force should explicitly address energy minimization, power consumption monitoring, and energy generation for the tactical-edge information environment, including all small devices and Internet of Things capabilities.

MANPOWER

The manpower skill sets needed to support the energy needs associated with the compute/store functions dispersed across the tactical, operational, and strategic level of warfare, are significant and are a barrier to the successful implementation of data-driven operations. The USAF does not have the organic manpower (manpower that is already within the organization) to manage, lead, supervise, or solve the challenges of energy consumption tied to data-driven operations. Without the organic manpower that understands the entire spectrum of energy needs, including in highly specialized fields such as radio frequency (RF) engineering, the USAF may never achieve a solution that strengthens its operational goals and instead will subject itself to substantial tactical, operational, and strategic risk. This manpower challenge includes recruiting, educating, training, and optimizing the contractor/military blend, and incentives for education.

Recommendation 7: The U.S. Air Force should establish a manpower program to recruit, educate, assign, and train both military and civilian personnel to address energy challenges associated with data-driven operations.

Recommendation 8: The U.S. Air Force should incentivize energy engineers, particularly specialists such as antenna and radio frequency engineers.

ENERGY RESILIENCE AND INTEROPERABILITY

While technology interoperability of deployed American forces in foreign countries is a well understood problem, these issues must be a specified consideration when developing or procuring new power sources or distribution systems. Ideally, new systems should automatically adapt and interoperate with a foreign environment with little or no mechanical switching or reconfiguration.

The challenge of delivering energy to deployed forces is complicated by logistics, which tend to favor simplicity over complexity and large users over small users. At the tactical edge, small users may have a larger role in data collection, analysis, and communication under the Joint All-Domain Operations (JADO) concepts, which would make them a dependency for the operational readiness of the larger units. There are implications for joint or multiservice operations that bear analysis, including cooperation on strategy development across all services.

Recommendation 9: The U.S. Air Force should develop an economic benefit model exploring the utility, opportunity costs, risks, and benefits for different energy delivery modes.

Recommendation 10: The U.S. Air Force should explore the options associated with vehicle-to-grid (V2G) implementations in tactical field exercises.

Recommendation 11: The U.S. Air Force should consider the logistics tail for energy types and methods of delivery from the perspective of cost-efficiency of energy delivery and operational costs associated with single energy sourcing (e.g., using drones to deliver batteries to small users, as opposed to conventional fuel convoys).

Recommendation 12: The U.S. Air Force should consider interoperability with foreign nation power systems and partner military forces (e.g., the North Atlantic Treaty Organization) when designing power systems (more than transformers) including standardization of certain elements and "plug and play" capability.

RESEARCH

As data-driven operations become more critical to operating concepts, the energy implications should be explicitly part of the planning process, including research on how to reduce energy usage, energy source exposure to hostile activity, and improving energy resiliency.

Algorithms and application space to reduce energy consumption have been shown to be very promising. Research has been performed to create energy consumption-aware algorithms at the operating system level and the application level, and it appears that this line of work has great potential for reducing energy needs for computing systems operating at the tactical edge. While it is known that clever algorithm design can yield energy savings, there is still more research that needs to be performed to yield practical and deployed energy-aware algorithms. Needed research includes conversion of theoretical algorithms to practical deployable software. In addition, further research is needed on the role of approximation techniques to reduce energy usage while not compromising accuracy. It is also known that how systems are architected, including details such as types of antennas and transmission strategy, can have an overall impact on energy usage, which means that research into systemic use of energy would be useful. These research efforts could support the operational security goals of reducing signal emanations and heat signatures.

Recommendation 13: The U.S. Air Force should invest in future research in both product and process technologies associated with reducing energy usage, minimizing energy logistics risk, and improving energy resiliencies associated with data operations at the tactical edge.

Recommendation 14: The U.S. Air Force should invest in research into using energy-aware algorithms in practical deployable software.

Recommendation 15: The U.S. Air Force should invest in the development of approximation techniques in software algorithms that are effective in energy reduction without compromising accuracy to unacceptable levels.

Recommendation 16: The U.S. Air Force should conduct experimental campaigns in realistic scenarios, including variety of systems and deployment characteristics of tactical-edge units, to guide the research directions and implementation potentials.

THE PATH AHEAD

These recommendations offer the USAF an approach to integrating energy needs into planning for the future battlefield. Should energy requirements not be explicitly planned for and integrated into operational readiness assessments, it is possible that critical outages will occur that could have cascading effects across the connected battlefield. Executing the agenda described through the recommendations will be challenging, but the results will greatly improve the potential for successful deployment of next-generation technologies to the tactical edge.

1
Introduction

Adversaries compete with each other strategically and tactically. Historically, the tactical edge of the battle space has been where two armies meet face to face or two navies engage on the high seas. As technology has advanced, the definition of the tactical edge of the fighting forces has evolved as well. When a remotely piloted vehicle over a contested region can be controlled from thousands of miles away while small special forces units deep in enemy territory can harness the power of space to leverage their capabilities, the idea of a crisply defined tactical edge becomes difficult. Nonetheless, it still exists, and there are aspects of the tactical edge that are significantly different from what would be normally found in a garrison or at a fixed base. These challenges include providing power to the increasing number of information technology (IT) solutions embedded in deployed units and systems.

The vision of the near-future tactical battle space is one populated with IT-enabled devices:

- Swarms of unmanned systems in the air, on the land, and under the water;
- Warfighters augmented with smart everything: situational awareness systems, physiological monitoring systems, real-time tracking and mapping, and more;
- Sensors deployed everywhere, some camouflaged as terrain features, some embedded in operational vehicles, and some more conventionally static;
- Artificial intelligence (AI) and machine learning (ML) applications enabling speedy decision making;

- Strategic assets, such as satellites and high-altitude loitering aircraft (some manned, some not), monitoring activity and providing data to central control facilities; and
- Military Internet of things (MIoT) devices acting in a web of smart collaboration.

Each of these capabilities brings a staggering amount of data and intelligence to the activity of conflict, enabling a level of precision and collaboration that would have been unimaginable 50 years ago and that now is somewhat difficult to truly comprehend in terms of capabilities and implications.

The U.S. Air Force (USAF) uses a lot of energy. It accounts for 48 percent of the total Department of Defense (DoD) energy expenditures. Within the USAF, 86 percent of the expenditures are associated with aviation fuel.[1] Energy usage by installations accounts for only 11 percent of the energy usage. In the context of these very large numbers, the energy needed for tactical-edge computing is tiny by comparison. And yet, the data generated, used, and communicated in and from the tactical edge is becoming a critical element of the future operating environment.

The ongoing revolution in information technologies, particularly in small appliance-type devices, has enabled this proliferation of capabilities that contribute to efficiency and effectiveness of information-rich activities. Each of these devices, however, requires energy in order to be functional. On an individual device level, the energy needs are typically very small. Further, energy efficiencies continue to improve along several architectural pathways: reduced energy usage reduces operational heat, battery replacement frequency, and electromagnetic radiation. But as the utility of these small devices continues to be proven, more and more of them proliferate in operational environments, leading to aggregate energy usage that can be significant.

The new great power competition[2] will require that the USAF, like the other services, adopt product and process technologies that ensure it is able to compete with adversaries in very fast decision cycles. This need requires active information collection and processing to support decision making, collaborative operations, and multidomain operations. The new great power competition includes rivals that are peer-level or near-peer-level technological forces as well as nonstate actors associated with the ongoing "war on terror." It is also characterized by the increasing use of robots, unmanned vehicles of all types (in the air, at sea, in space, and on land), and the insinuation of artificially intelligent computational agents into

[1] See Air Force Civil Engineer Center, 2017, "Energy Flight Plan 2017–2036," https://www.safie.hq.af.mil/Portals/78/AFEnergyFlightPlan2017.pdf?ver=2017-01-13-133958-503.

[2] See T. Lynch III (ed.), 2020, *Strategic Assessment 2020: Into a New Era of Great Power Competition*, NDU Press: Washington, DC, https://ndupress.ndu.edu/Publications/Books/Strategic-Assessments-2020/.

both administrative and weapon systems. Thus, the information dimension of competition continues to increase in both importance and power, requiring the proliferation of information infrastructure elements to all ends of the force projection continuum.

The vision is compelling, and the planning is impressive. The energy needed to fuel the vision, however, seems to have taken a back seat in the planning process. For the fixed installation information infrastructure planning, this may make sense, because the energy needs of a fixed installation are well understood and managed. The planning for future operations does include dynamic basing as well as the more conventional tactical-edge components, for which energy planning becomes more critical. One question that requires addressing as the planning proceeds is: how much energy will be needed to power the tactical-edge information infrastructure and will that energy be readily available?

Concern over these matters prompted the Air Force to ask the National Academies to conduct a study to examine how energy needs for the information processing needs at the tactical edge are being considered and, if appropriate, to recommend ways in which such planning could be improved.

STUDY PROBLEM

Will the Air Force be adequately positioned to meet the energy needs associated with data-driven operations at the "edge" in the year 2030? To answer this overarching question, it is necessary to parse it into component issues.

- First, *what will the energy needs be at the tactical edge to support data-driven operations?* This question itself spawns many further questions, such as what the expected technology base will be; how energy-efficient computational approaches will be implemented, if at all; and what the energy needs of the edge infrastructure will be, including environmental controls for both humans and machines and the local data transfer between small devices. All of these considerations are dependent on the amount and types of data expected to drive the vision of the future battlefield.
- Second, *how will energy provision at the edge be prioritized among users in the face of competition for scarce resources or in the face of attack on energy supplies?* This question spawns further questions as well, including what is known about adversarial plans or capabilities to attack energy systems; how resiliency is being engineered into the energy at the edge infrastructure; and planning expectations for edge data-driven operations under energy scarcity.
- Third, *does the USAF currently have or plan to have adequate human resources to build, deploy, and maintain the energy infrastructure for data-driven opera-*

tions at the edge? What are the expertise requirements for technical support to data-driven operations at the edge?

These three component questions served as the guiding thoughts in developing a study plan that addressed each element of the statement of task.

STATEMENT OF TASK

The Air Force Studies Board at the National Academies of Sciences, Engineering, and Medicine will establish an ad hoc committee to investigate energy challenges and opportunities for future data-driven operations in the USAF.

The committee will plan and convene a multiday workshop that would investigate and discuss the energy challenges and opportunities of the USAF's future operating environment. Workshop participants shall examine what steps and plans the USAF is taking and/or should be considering now in order to successfully develop, deploy, and sustain the weapon systems needed to compete in an emerging information-rich environment. The workshop shall also investigate energy demands for weapons systems from the airbase to the battle space, including information requirements and needs associated with capture, curation, storage, exploitation, and transmission of energy to enable the deployment and operation of data-reliant systems. The committee shall develop the workshop agenda, invite speakers and other attendees, moderate discussions, and provide resulting meeting materials.

The committee will plan and conduct an in-depth study that would:

1. Investigate the current state of Air Force planning, research and development, and expectations related to energy usage for military operations in the 2030 time frame.
2. Investigate potential threats to energy assurance and access based on recent events and assumptions of future energy dependencies that should inform Air Force/government planning for energy generation, storage, and use.
3. Investigate and describe current research and state of the art in energy-efficient computation, including hardware, software, and big data.
4. Investigate and describe the energy needs for advanced weapons platforms, including static infrastructure that provides support to machine learning, artificial intelligence, and integrated operations.
5. Recommend manpower, research, and expertise requirements needed for the future energy environment.

The committee shall convene meetings of the study committee and other attendees, as required, to gain relevant information. The committee shall also provide a report summarizing the results from this study.

REPORT AUDIENCE

This effort was requested by the Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering (SAF/AQR), and its contents are intended to advise senior leadership responsible for weapons systems sustainment, equipment, and logistics and installations resource requirements, including research. Because the challenge of understanding and solving energy needs for IT at the tactical edge crosses many different specialties, ranging from communicators to civil engineers, this study addresses a broad range of issues. As such, different parts of this report are expected to be of more interest to some offices than to others. However, it is a fundamental conclusion of this report that coordination of efforts across disciplines and responsibilities is a critical element to long-term success in meeting the needs of the future.

THE COMMITTEE'S APPROACH

This effort was initiated in November 2019, and the committee first convened in February 2020. Members of the interdisciplinary committee served as volunteers for the duration of the effort. The committee members were selected and appointed by the National Academies, which focused on ensuring that there was a breadth of expertise, including both researchers and practitioners. Committee members brought expertise in computer science, computer engineering, information security, intelligence, alternative energy sources, military operations, human-systems integration, and engineering economics. See Appendix E for committee member biographies.

To conduct its study and develop consensus for the final report, the committee intended to travel to and meet with a broad range of organizations and individuals. Because of the SARS-CoV-2 (COVID-19) pandemic restrictions, which went into effect in March 2020, the committee held all meetings with subject matter experts virtually. The inquiry began with a 3-day workshop held in April 2020. The proceedings of this workshop are included in Appendix C of this report. Subsequent to the workshop, Zoom[3] meetings were held with a variety of authorities and stakeholders over a period of 6 months. The agendas for the committee's

[3] Zoom is a publicly traded corporation, headquartered in San Jose, California, that provides software to enable virtual conferencing capabilities. See Zoom, "About," https://explore.zoom.us/about.

data-gathering sessions are listed in Appendix B. Presentation materials used are available, by request, from the National Academies through the public access file.

The committee thanks all presenters for the frank and open discussions, particularly in light of the difficult circumstances. The committee is particularly grateful to those who were suffering from COVID-19 and still consented to participate with the study inquiry. Their commitment to progress and analysis is commendable. The committee felt that it was important to verify that the subject of study was in fact an important topic and, as a result, made it a practice to ask each speaker some version of the following question:

Is this an important topic and is this the right time to be studying it?

The answers received back were universally affirmative on both counts: the changes occurring in the uses of data processing at every level are causing unforeseen challenges that need to be considered. The committee came away from these meetings with a very deep appreciation for the thoughtfulness, inventiveness, and dedication of those working in and for the U.S. government to address these challenges. The future is in good hands.

REPORT ORGANIZATION

This report is organized in a way that mirrors the task given, with the material presented in each section to highlight the findings and conclusions developed by the committee. This chapter has presented the rationale and methodology for the study. The remaining portions of the report are as follows:

- Chapter 2 provides an analysis of the problem, a discussion regarding the potential threats to energy provision, and energy dependencies and demand issues. The current state of the art in energy-efficient computation and architecture is presented, as is a discussion on energy needs from an enterprise perspective.
- Chapter 3 summarizes the findings and recommendations derived from the data collection and analysis and suggests a priority order for addressing the recommendations.
- The report concludes with several appendixes that provide additional detail on several aspects of the report, including the study's data gathering activities and committee member biographies.

2

Analysis of the Problem

Energy has always been an important consideration for military operations, both in peacetime and during conflict. It is becoming an increasingly important aspect owing to the rapidly exploding and exponentially growing use of data to drive military operations, particularly at the edge of conflict. Part of the challenge at the tactical edge is understanding and addressing the needs of the various users: those in semi-fixed deployments, those in mobile units conducting conventional activities, those who operate in highly variable conditions that require both movement and fast operational changes, and those who are in low-profile special operations activities. Besides having different power needs, each has different logistical support structures. Each, of course, must be supported, but how they are supported must be considered as part of the overall mission planning efforts.

THE ENERGY ECOSYSTEM

It is helpful to have a common structure when considering the challenges associated with the consumption of energy by the U.S. Air Force (USAF) specifically, and the Department of Defense (DoD) writ large. Without a common structure, individuals and groups are likely to view the problem from specific vantage points and miss the larger holistic issues or fail to take into consideration the effect on the entire ecosystem. The illustration in Figure 2.1 provides structure to this discussion.

At the center of the discussion and central to the diagram in Figure 2.1 is the thesis that the explosion of data and data analytics is going to both drive an increase in demand for energy but also, perhaps more importantly, reshape how that

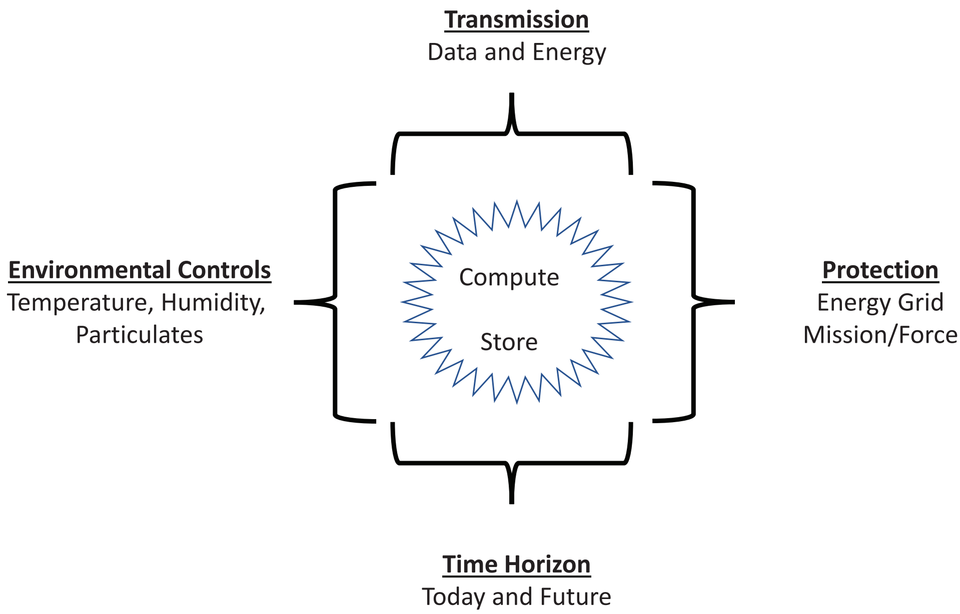

FIGURE 2.1 The energy ecosystem.

energy is stored, delivered, and dispersed across the globe in support of military operations. When considering the problem, it is imperative to first break down data and data analytics into pieces so that we can better understand how this field will impact energy consumption.

> **Finding 1:** The explosion of data creation, sharing, and use, including data analytics to support near-real-time decision making, will drive an increase in demand for energy.

> **Finding 2:** The increase in demand for energy will influence the energy supply chain and accompanying logistics.

Compute and Store

Data analytics, at its core, has four main components: compute, store, math, and software.[1] Understanding these four components, both how they come together to

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[1] See H.R. Lieberman and L. Robinson, 1967, "The Electronic Digital Computer: How It Started, How It Works and What It Does," *New York Times*, January 9, Section National Economic Review, page 136.

form the data capabilities used by the military (and civilian society in general) and how energy is consumed, leads to a better understanding of how solving the energy challenge is possible.

Data analytics is the use of mathematics to solve problems.[2] Taken alone, this is not new: in reality, it has impacted military operations for millennia. Since the birth of modern computing based in the application of mathematics to cryptography and artillery tables in World War II, which birthed the electronic numerical integrator computer (ENIAC), the importance of data analytics to military operations has grown exponentially. Because these early computers were enormously large and complex, they were permanently housed in large facilities with extensive fixed power systems. Over the course of time, these big computers from the 1940s evolved to the handheld calculators of the 1970s, hardware-driven machines that used energy to execute fixed algorithms. While these machines could compute, they were not very good at storage, which was next to impossible on a handheld calculator, and phenomenally expensive on mainframes.[3]

The advances of the research community, fueled by the requirements of the space race,[4] the miniaturization of electronic components, and the application of computation to an increasingly broad swath of human activities, resulted in several leaps forward in computational capabilities. The "personal computer" untethered the ability to execute programs from bulky mainframes, ushering in an era where individuals could store and analyze information at their desks. This began a new arms race[5] in computing that led to the Desert Storm 1990-era command centers that moved the compute function farther away from fixed national sites and into regional and deployed operational command centers.[6] Even then, the movement of information between the edge computers was slow and expensive. Thus, they needed to be collocated, which simplified the associated energy challenges even as it gave rise to large operational command centers.[7]

The technological disruption resulting from the commercialization of the Internet, the growth of cellular telephony, and the emergence of mobile computing

[2] See Masters In Data Science, 2020, "What Is Data Analytics," 2U, July, https://www.mastersindatascience.org/learning/what-is-data-analytics/.

[3] See K.A. Zimmerman, 2017, "History of Computers: A Brief Timeline," LiveScience, September 7, https://www.livescience.com/20718-computer-history.html.

[4] See B. Hayes, 2019, "Moonshot Computing," *American Scientist*, May-June, https://www.americanscientist.org/article/moonshot-computing.

[5] See M. Van Creveld, 1989, *Technology and War: From 2000 B.C. to the Present*, Macmillan, New York, NY.

[6] See A. Campden (ed.), 1992, *The First Information War: The Story of Communications, Computers, and Intelligence Systems in the Persian Gulf War*, AFCEA International, Fairfax, VA.

[7] See D. Alberts and R. Hayes, 2003, "Power to the Edge: Command and Control in the Information Age," Command and Control Research Program (CCRP), Washington, DC.

on very small handheld devices solved the next link in the data analytics distribution puzzle by disconnecting the compute and store functions from the device. The iPhone,[8] for example, could send queries far away and get answers back almost immediately. In many ways, this mirrored the earlier mainframe architectures. A critical distinction was distributing that information to individuals, virtually anywhere in the world.

Cloud computing, in essence, replicated the personal computer (PC) revolution of the 1980s but at an enormous scale.[9] This enabled individuals using mobile devices to have as much compute and store capability at their fingertips as any nation-state had in the 1970s. These "cloud" sites require very large data centers to support both storage and computation. Because of their size and the emergence of "big data" computational approaches, the sites are energy consumption monsters, located where access to energy was assured. A fundamental feature of these sites is that they are both large and fixed, and so during a large war could be easily targeted and destroyed—it is very difficult to hide a large data center.[10]

> **Finding 3:** Cloud computing enables highly distributed and mobile information technology (IT) that is very powerful.

> **Finding 4:** Back-end data centers require an enormous amount of energy, are fixed sites, and are potentially a target during wartime, both physically and virtually.

An additional development that both complicates and enables information technology applications in distributed environments is what is known as the Internet of Things (IoT).[11] The IoT is a way of referring to very small and specialized devices, such as thermostats, fitness trackers, and energy meters, that are augmented with intelligence and network enabled.[12] As these "smart" devices are coordinated over networks through data centers, creating the IoT, a systemic synergy is created,

[8] See L. Goode and D. Pierce, 2018, "The WIRED Guide to the iPhone," *WIRED*, December 7, https://www.wired.com/story/guide-iphone/.

[9] See R. Polding, 2018, "Cloud Computing: The Invisible Revolution," Robert Polding, PhD, blog, August 10, https://medium.com/@rpolding/cloud-computing-the-invisible-revolution-52e82d43c465.

[10] See World's Top Data Centers, 2021, "America's Size Rankings," http://worldstopdatacenters.com/americas-size-rankings/.

[11] See National Research Council (NRC), 2001, *Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers*, The National Academies Press, Washington, DC, https://doi.org/10.17226/10193.

[12] See National Academies of Sciences, Engineering, and Medicine (NASEM), 2018, *A Primer to Prepare for the Connected Airport and the Internet of Things*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25299.

over and beyond what any individual component could contribute. Taking advantage of deployed smart devices, back-end data centers, and nearly ubiquitous communications pipelines, the battlefield is being drenched in devices that are sensing and creating data.[13] A tipping point is rapidly being reached, however. At first, and most commonly still, this data is transmitted to off-premise computational centers for processing and then sent back to the tactical edge, oftentimes in seconds.[14] As the amount of data produced increases, the bandwidth needs for communications will concomitantly increase. The back-end processing solution is working right now because the ability to transmit this information is still adequate and, more importantly, has not been contested. In a future war, that cannot be assumed.

Finding 5: The integration of smart devices into the tactical edge is resulting in a very large increase in data generated at the tactical edge. As the amount of data being produced increases, the bandwidth required to transmit it back to off-premise computational centers will also increase.

Finding 6: Reliance on communications between tactical-edge centers and off-premise data centers is a vulnerability that could be exploited by an adversary.

This trend is illustrated by Special Operations Command (SOCOM), which is now generating more data inside the tactical bubble than outside the bubble.[15] This constitutes a reversal of the status quo, in which data was fed to the tactical edge from both back-end sensors and computational devices. Combining the data flow reversals with the expected contested transmission of data will force the movement of required compute and store functions all the way to the tactical edge. Not only will this change warfare but it will also profoundly affect how energy is consumed on the battlefield.

Finding 7: The reversal of data flows to and from the tactical edge will force the movement of computational devices to the tactical edge, which will profoundly affect the energy supply chain requirements.

For the past several decades, since Desert Storm, energy consumption has been structured around large, fixed command centers directing far-flung operations. The

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[13] See D. Alberts et al., 1999, *Network Centric Warfare: Developing and Leveraging Information Superiority*, CCRP, Washington, DC; D. Alberts et al., 2001, *Understanding Information Age Warfare*, CCRP, Washington, DC; D. Gombert et al., 2006, *Battle-Wise: Seeking Time-Information Superiority in Networked Warfare*, NDU Press, Washington, DC.

[14] See Ginny et al., 2021, Smartphone processor architecture, operations, and functions: Current state-of-the-art and future outlook: Energy performance trade-off, *Journal of Supercomputing* 77:1377–1454, https://doi.org/10.1007/s11227-020-03312-z.

[15] See conversation with Col. Matt Benigni in April 2020, Appendix C.

next several decades are likely to see this function of compute and store distributed across the battlefield, both for operational efficiency and also for the need to survive. This will change how much energy is needed, where the energy is needed, how energy is moved, and how it is stored. In many ways, the past several decades have lulled DoD into a false sense of energy security. Data centers and operational command centers could cheaply and easily be supplied with energy. Breaking this apart will be inherently inefficient and messy. An interesting parallel in history is illustrated by the adoption of the internal combustion engine to the activities of conflict.[16] Then, nations had to acquire the ability to generate appropriate forms of power and then distribute that power to machines around the world.[17] In the current situation, it is not oil that has to be moved but electricity, and the physics of moving and storing electricity is vastly more complicated than liquid fuel.

Finding 8: Movement of electricity to power data-driven operations at the tactical edge is a critical need that is more complicated than moving petroleum products.

Energy Challenges in the Ecosystem

The distribution of compute and store functions across the battlefield, embedded in hundreds of millions of devices, will impact energy consumption in several different ways. The problem includes four primary components: (1) transmission (energy and data); (2) environmental control (hot and cold); (3) protection (how to mitigate the risk to force and mission); and (4) time horizon (now and 10 years from now). This structure is not meant to be the answer to how to fix the challenges that the Air Force will experience concerning the use and distribution of energy given the data-driven operational warfare envisioned in the future. Instead, it is meant to provide a structure through which conversations can begin, so that decisions can be made to solve the problems of the 2030s, during this decade of the 2020s.

Transmission

Transmission can be thought about in two ways: distribution of energy across many devices and distribution of data across many devices. Together, the transmission function of energy to power the devices and energy to move the data

[16] See G.W. Phillips, 1927, The internal combustion engine and its influence on war material, *Royal United Services Institution* 72(488):789–807.

[17] The adaptation of internal combustion machines to the conduct of conflict enabled speed over distance in movement but also required the creation of fuel logistics—the movement of fuel in trucks and ships along with the ships, submarines, tanks, and airplanes.

are separate issues that need to be solved in order for both of the components to operate effectively.

Data transmission (moving data from servers to clients, between clients, between servers, etc.) does not normally create a significant increase in energy demand as compared to the computer systems themselves. However, the communications infrastructure's energy needs cannot be overlooked. Data transmission requires switches, routers, and radios (for cellular, satellite, or other wireless modes), all of which require electric power. Planning should also include energy needs for security devices such as firewalls, intrusion detection systems, and other appliances.

Much like electricity distribution, there will be an internal communications network inside a military installation or forward-deployed base that will require power. Some commercial wireless providers will build their towers and infrastructure inside an installation's footprint in order to increase coverage. The need for more antennas and higher-powered transmitters, and thus the need for more electric power, will increase as 5G[18] (and eventually 6G, 7G, and xG) technologies are adopted.

The distribution of energy across many devices is the challenge of getting enough and appropriately configured energy to each device in a timely enough fashion that usage is not affected out of established tolerances. When many (where "many" can mean millions of) devices, which are increasingly small and battery powered, are spread across the battlefield, energy must be distributed to each device in order for all of them to be operational.[19] The farther the device is from the supply site, the more challenging it can be to distribute the energy supplies. The problem is exacerbated if there are many different energy configuration standards (such as different battery types required), in that the supply of energy can become logistics-unfriendly.[20]

> **Finding 9:** Highly distributed small devices require energy to operate. The form of that energy can pose challenges unless the supply of energy is logistics-friendly.

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[18] Owing to the still evolving standards associated with 5G, there is still significant variation in energy need estimations. Standards are not expected to be finalized until 2022. See Department of Homeland Security (DHS), 2020, "Feature Article: 5G Introduces New Benefits, Cybersecurity Risks," https://www.dhs.gov/science-and-technology/news/2020/10/15/feature-article-5g-introduces-new-benefits-cybersecurity-risks.

[19] See K. Matthews, 2019, "Energy Consumption and IoT Technologies: What to Know," Information Age, October 29, https://www.information-age.com/energy-consumption-and-iot-technologies-what-to-know-123485884/.

[20] Logistics-friendly power is that which requires the least amount of variation in both form and content, so that the supply chain is not burdened with the problems of accounting and distribution of customized solutions. See NRC, 2014, *Force Multiplying Technologies for Logistics Support to Military Operations*, The National Academies Press, Washington, DC, https://doi.org/10.17226/18832.

The other transmission problem is the movement of data between the devices. Moving data consumes energy. The default configurations of small devices in fixed base and civilian organizations provide that energy through communications technologies, including fiber, copper, and cellular technologies. This renders the energy usage invisible and also provides users with an assumption of energy availability in communications. When these devices are widespread in deployed or contested environments, neither of these characteristics are potentially true: there may be a differential energy need between the communications nodes and the computational devices that may need to be managed. Small devices may use tiny amounts of energy to process limited amounts of data but not have enough energy to power transmission of the data beyond highly localized nodes. In other words, the need to power the data transmission infrastructure is nontrivial and should not be assumed away as part of the device power challenge.

Finding 10: Small devices spread across a deployed force may need to have separately powered transmission capabilities.

Environmental Control

Environmental control includes both temperature and humidity, both of which can adversely affect both humans and technologies in an operational construct. At extremes of temperatures, human bodies become lethargic and then fail. Similarly, equipment is designed with thermal envelopes, the exceeding of which can cause equipment to fail. Humidity poses its own challenges, in that excess humidity can cause the human body temperature management system to malfunction and cause electronics to short circuit or spark.[21]

Temperature is an interesting challenge. Typically, the analyses regarding temperature are that of excess heat, but conflicts can take place in many different weather conditions, including very hot and very cold and in an area with many microclimates.[22] Compute and storage devices may need to be cooled or warmed just to operate. Excessive heat and excessive cold can drain energy from storage devices, such as batteries, and cause power generation and transmission systems, such as diesel generators, to malfunction.[23]

[21] See Circuitnet, 2020, "Average Temperature/Humidity for an Electronic Assembly Facility?" July 29, https://www.circuitnet.com/experts/40104.html.

[22] Microclimates are those that exist as highly localized phenomena that are markedly different from the area climate. See L. Perry, 2021, "Microclimates: What Do They Mean to You?" University of Vermont Extension Department of Plant and Soil Science, https://pss.uvm.edu/ppp/articles/microclimates.html.

[23] See University of Michigan, 2019, "How Extreme Cold Weather Affects Vehicles and Batteries," https://news.umich.edu/how-extreme-cold-affects-vehicles-and-batteries/.

Finding 11: Storing energy in environmentally appropriate ways and keeping the devices operational through managing the environmental characteristics is a necessary and important analytical element.

Protection

Protection exists in two forms: minimizing risk to force and minimizing risk to mission. This is a fundamental part of the military's mission but one that is not a primary concern for most commercial sector entities. With some exceptions (such as cyberattacks), the commercial sector in the United States generally does not expect to be actively targeted for wholesale destruction by an adversary. Defense of assets and systems is a fundamental function of military operations and DoD must assume that data transmission paths and centers will be attacked, energy supply lines will be targeted, and detectable electromagnetic emissions will be exploited. All of these put both the force and the mission in jeopardy. Whatever solutions are found to the distribution of energy across the battlefield must take into account measures to reduce the risk to the force and to the mission.

Commercial power providers optimize their generation, transmission, and distribution assets to lower their customer's costs, to minimize environmental impact, and to maintain a required minimum level of reliability. Threats to a commercial power provider's infrastructure are normally centered on weather or nature and not on deliberate, targeted attacks. Military planners will need to consider human attacks against their power infrastructure in addition to threats from nature.

Industry normally reacts to consumer demand and typically will not invest in technologies or solutions that will not generate profit or that have a limited market. Currently, however, there is increasing interest for developing new power generation, transmission, and distribution capabilities with a focus on renewable power sources and more efficient power consumption. There will be parts of the solution space where USAF can ride the commercial investment, such as chip manufacturing and storage; however, mobile, fixed, austere energy storage and production may be something that USAF has to invest in on its own to develop because the commercial marketplace is not that big.

Finding 12: Adversaries will target both data capabilities and communications, including the energy used to power such capabilities.

Time Horizon

The Air Force operates with a force that has an average of 10 years of experience and training.[24] The information processing technologies powering the Air Force are evolving at an increasingly fast pace, averaging a generational leap forward every 18 months.[25] The energy systems powering the information technologies are also evolving quickly, leveraging advances in material science, nanotechnology, and integrated manufacturing.[26] These variations in time horizons for the personnel, the information technology (IT), and the power systems require a management approach that is focused on forward-looking design strategies. Such a paradigm shift is not likely to arise from the commercial sector, so the solutions that enable true Joint All-Domain Operations (JADO) must come from within DoD.

> **Finding 13:** The energy needs for deployed forces operating within the JADO construct will require solutions that are not likely to come from the commercial sector.

CURRENT STATE OF THE AIR FORCE

The vision of future Air Force operations is that of a coordinated multidomain environment, fueled by an expectation of ubiquitous information and large data sets powering formidable expert algorithms (AI). What is missing is a treatment of the energy needs associated with realizing this vision. When interviewing people in the offices[27] responsible for fleshing out the vision of multidomain operations, the committee asked two specific questions: (1) Do you know if anyone in your office is taking into account the energy needs at the tactical edge to support these data-rich operations? (2) Is this an appropriate time to be looking into this issue? The answers to these questions were interesting and multifaceted. The planning for the future operational environment is still in early days, so not all details have been identified or included in the concept of operations. The need for energy to be included in these planning efforts was acknowledged as very important. Appropriately including energy issues in the planning efforts includes bringing all parties

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[24] See NASEM, 2021, *Strengthening U.S. Air Force Human Capital Management: A Flight Plan for 2020–2030*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25828.

[25] See A. Berman and J. Dorrier, 2016, "Technology Feels Like It's Accelerating—Because It Actually Is," SingularityHub, March 22, https://singularityhub.com/2016/03/22/technology-feels-like-its-accelerating-because-it-actually-is/.

[26] See S. Aderyani et al., 2020, Comparison of nanoarchitecture to porous media diffusion models in reduced graphene oxide/aramid nanofiber electrodes for supercapacitors, *ACS Nano* 14(5):5314, doi: 10.1021/acsnano.9b07116.

[27] See Appendix B for committee agendas.

together and should include specifically identifying energy needs in the requirements processes.[28]

There is an organizational disconnect between those dealing with future energy needs and those dealing with future information needs: while unfortunate, this would actually be expected, given the extreme differences between the two topics. Those forecasting, planning, and developing future energy needs tend to be civil, mechanical, and electrical engineers, focused on structural aspects, such as providing reliable and defensible power to very large installations. Those forecasting, planning, and developing future information and computational needs tend to be operators, communicators, intelligence officers, and computer scientists, with a sprinkling of radio frequency (RF) engineers for the specialized problems. Thus, the situation begins with a set of functional mismatches: different languages, different time scales, and different expectations. It simply would not be natural for coordination between the two systems to spring up organically. Those doing the forecasting have the luxury of living in a power-rich environment, where people are used to accessing power easily. Understanding if and how energy strategic coordination is being performed, and, of course, how effectively, becomes ever more important as the expectation of and demand for adequate energy supplies increases.

Planning

The Air Force does have an energy strategic plan.[29] This plan identifies three specific goals: "The Air Force Energy Flight Plan reflects the Department's emphasis on operational energy and energy resiliency while reframing the Air Force's approach to energy through three goals: Improve Resiliency, Optimize Demand, and Assure Supply." The Air Force subdivides the energy challenge into two focus areas: operational energy and installation energy. Operational energy is defined as "the energy used by the Air Force that has a direct and immediate impact to missions." This is codified in U.S. law 10 USC §2924. Installation energy is defined as "the energy used by facilities and non-tactical ground vehicles in support of air, space, and cyberspace missions."

The context of the strategic plan is naturally skewed by how the Air Force energy needs are currently balanced. As noted in the plan, the Air Force accounts for 48 percent of the total DoD energy expenditures. Within the Air Force, 86 percent of the expenditures are associated with aviation fuel. With facilities' energy costs

[28] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872.

[29] See Air Force Civil Engineer Center, 2017, "Energy Flight Plan 2017–2036," https://www.afcec.af.mil/Portals/17/documents/Energy/AFEnergyFlightPlan2017.pdf?ver=2019-12-16-105948-090.

coming in at only 11 percent of the budget, it is understandable that most of the attention would be elsewhere. And indeed, it is. Relatively small issues, such as distributed operational energy for data systems, do not currently warrant inclusion in the plan.

With regards to the energy associated with the use of information, there is a single goal in the document: "Employ best management practices for energy-efficient management of servers and data centers." There are two other explicit statements regarding data centers, one of which offers outsourcing as the preferred option: "Third-party performance contracts, such as Energy Savings Performance Contracts (ESPCs) and Utility Energy Service Contracts (UESCs), provide the Federal Government with a partnership opportunity to procure energy savings and facility improvements with no up-front capital costs. The Air Force is pursuing ESPCs across its facilities, targeting depots and data centers, and exploring new ways of bundling ESPCs to take advantage of economies of scale." This overall focus is associated with the goal of optimizing demand, including a push for reducing energy needs. There is a nod to the operating concept for the future Air Force, which "envisions a future in which information technologies permeate almost every object," but no explicit discussion, analysis, or description about how the underlying energy needs are being addressed or planned for.

The Air Force also has an information dominance strategy.[30] The word "energy" does not appear in this document, not even once. The word "power" occurs 19 times, but never in the context of energy needs.[31] The term "data center" also does not appear in the document. The focus of the document is leveraging information for use, rather than on the infrastructure needed to obtain, curate, manipulate, and exploit information.

Research and Development

The Air Force has several offices focused on researching energy needs and developing advanced technology solutions for Air Force operations. The Materials and Manufacturing Directorate at the Air Force Research Laboratory (AFRL) is responsible for "energy assurance/efficiency" and bringing new technologies into solutions for Air Force operational needs.[32]

[30] See Office of the Chief Information Officer, 2017, "Air Force Information Dominance Flight Plan: Operating in, thru, and from Cyberspace," https://www.safcn.af.mil/Portals/64/documents/20170203-%20IDFPv3.pdf?ver=2017-02-16-072244-507.

[31] The use of the word "power" in the Air Force Information Dominance Flight Plan document is in terms such as manpower, power projection, and other uses to indicate force strength and projection.

[32] See Air Force Research Laboratory (AFRL), 2021, "RX," https://www.afrl.af.mil/RX/.

Further, the Air Force has asked RAND to research energy-related issues. Their research has provided insight into how to improve energy coordination and usage.[33]

ENERGY NEEDS AT THE TACTICAL EDGE

Data is the blood of the warfighting body. The heart that powers the movement of data is the logistics of the energy infrastructure. The data moves through the warfighting body, enabling the operations and coordination of the various parts. If the heart stops beating, the data stops flowing, the parts of the body become damaged and possibly die. What is data, though? Increasingly, it is everything: the information in databases, the structural components of the computational infrastructure, the administrative data (metadata), the algorithms, the control structures, the interface protocols, and the things that most people think of as data: words, videos, images, sounds, smells, movements, seismic events, signals, and telemetry.

Every aspect of operations is impacted by the promulgation of information technologies. As shown in Figure 2.2, the tactical edge is no exception and is increasingly dependent on organic capabilities for sensing and processing. For the Air Force, it is tempting to assume that the energy needs will be met through the auspices of the fuel logistics for aircraft operations. However, it is worth pointing out several facts. First, aircraft fuel contributes to the generation of electricity only when the aircraft engines are activated.[34] Further, advanced aircraft require significant ground support capabilities that are powered through separate generation systems.[35] Last, the proliferation of information technology within and surrounding operations all require electricity to operate.[36] The inexorable conclusion is that energy needs at the tactical edge separate from aircraft fuel are an increasingly important issue.

The focus of this report is on the energy needs for the data processing at the tactical edge. Trends that are influencing the growth of data processing at the tactical edge include the following:

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[33] See RAND, 2021, "USAF+Energy," https://www.rand.org/search.html?query=usaf+energy.

[34] See Skybrary, 2020, "Ground Handling," September 20, https://www.skybrary.aero/index.php/Ground_Handling; S. Vora, 2017, "Why Planes Get Hot—and How to Stay Cool When They Do," *New York Times*, July 24.

[35] See Government Accountability Office, 2019, "F-35 Aircraft Sustainment: DOD Needs to Address Substantial Supply Chain Challenges," https://www.gao.gov/assets/700/698693.pdf.

[36] See Congressional Research Service, 2020, "F-35 Joint Strike Fighter (JSF) Program," https://fas.org/sgp/crs/weapons/RL30563.pdf.

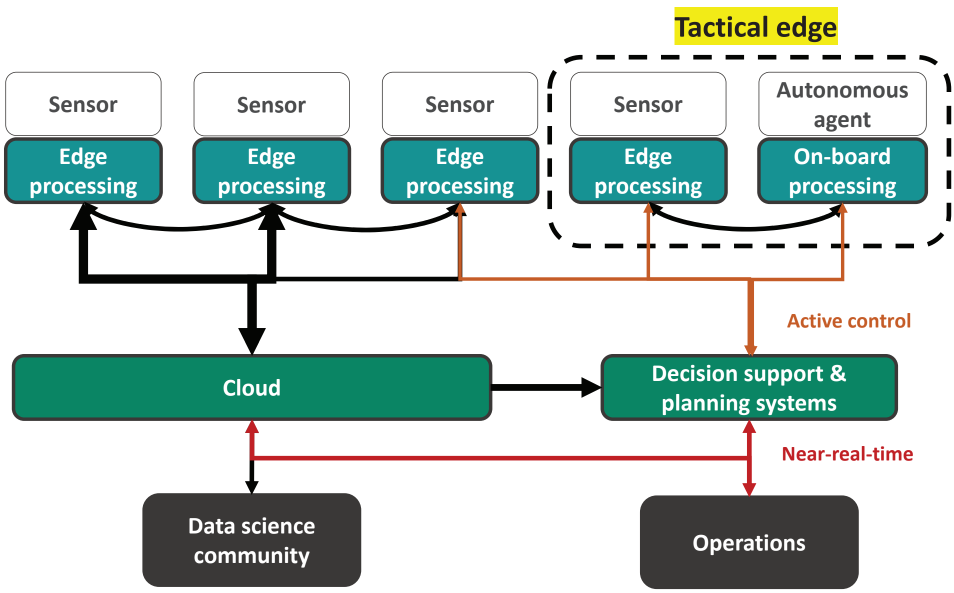

FIGURE 2.2 Computing at the tactical edge.

- Application of "artificial intelligence" technologies for operations, support, and management of activities;[37]
- Doctrinal adoption of multidomain operations, which necessitates active coordination through near-real-time data collection, analysis, and communications;[38] and
- Application of information technologies to operations management efforts, including the proliferation of "smart devices."[39]

Further, the advanced information technologies can have specific energy needs in terms of power stability and allowable variations in current flow.[40] For mobile

[37] See C. Kawasaki and Pacstar, 2019, "Four Future Trends in Tactical Network Modernization," U.S Army, January 24, https://www.army.mil/article/216392/four_future_trends_in_tactical_network_modernization.

[38] See NASEM, 2018, *Multi-Domain Command and Control: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25316.

[39] See R. Uppal, 2019, "Military or Battlefield Internet of Things (MIOT/BIOT) Will Network Sensors, Wearables, Weapons, Munitions, and Platforms for Information Dominance," International Defense, Security and Technology, August 8, https://idstch.com/cyber/internet-things-battlefield/.

[40] See Manufacturing.net, 2013, "7 Ways Signal Noise Can Impact Your Electrical Equipment," November 13, https://www.manufacturing.net/industry40/article/13057416/7-ways-signal-noise-can-impact-your-electrical-equipment.

platforms, such as trucks, increasing the number of devices that require power may result in the need to add more batteries or higher output alternators. Within the "battlefield of things," there will be a multitude of devices without access to mobile platforms.

It is axiomatic that the tactical edge is not in garrison and may even be behind enemy lines. The planning and research for steady and reliable energy for fixed bases is a different problem from planning for deployed operations and dynamic basing. The adoption of intelligent devices, unmanned systems, and artificially intelligent services enables a complexity of deployed forces that minimizes the number of people who need to be involved. Each of these technologies needs energy. As these technologies proliferate, the energy needs will grow. Where the energy comes from, how it is managed logistically, and how demand at the tactical edge and beyond is mediated are all issues that warrant consideration.

Finding 14: There will be energy needs associated with the proliferation of smart devices, AI applications, and unmanned systems.

Batteries serve as extremely useful forms of portable energy, especially for small or distributed devices. They serve an important part in any energy infrastructure, particularly in powering highly mobile electronic information processing systems. There are several major issues in battery technologies of interest in designing tactical-edge architectures: physical dimensions (size and weight), cycle life (how many discharges the battery can sustain), and volatility (propensity to explode either from insult or spontaneously).[41] When choosing a battery solution, finding the optimum mix of small size, light weight, high cycle life, and low volatility can be a challenge, particularly in batteries that are integrated into battle gear, such as clothing or helmets. Additionally, sources of power to charge the battery must be considered, particularly if the batteries used are meant to be recharged on site.

Currently, lithium-ion batteries are chosen owing to their combination of light weight and high cycle power. Problems with volatility, as illustrated by spontaneous ignition, are concerning, but manufacturing continues to improve their safety profile. Unfortunately, lithium-ion batteries have a narrow environmental operating envelope and are unsuitable for ambient temperatures lower than 5°C (41°F) or higher than 55°C (131°F).[42]

[41] See T. Moynihan, 2017, "Don't Blame the Batteries for Every Lithium-Ion Explosion," *WIRED*, March 19, https://www.wired.com/2017/03/dont-blame-batteries-every-lithium-ion-explosion/; N. Jenkins et al., 2018, *McEvoy's Handbook of Photovoltaics (Third Edition)*, Academic Press, Cambridge, MA, https://doi.org/10.1016/B978-0-12-809921-6.00025-2.

[42] See T. Deng et al., 2018, "Temperature effect and thermal impact in lithium-ion batteries: A review," *Progress in Natural Science: Materials International*, 28(6): 653-666, https://doi.org/10.1016/j.pnsc.2018.11.002.

Fuel cells operate much like batteries, except that the energy is supplied continuously by a fuel. Depending on the type of fuel cell, the fuel can be hydrogen or a hydrocarbon. Currently, fuel cell technology fills an important niche in the portable energy segment, providing reliable power in situations where the challenges associated with storing and accessing the fuel do not present a problem. Hydrogen, for example, can be made from natural gas or by separating water into its components. If made at a distance from the fuel cell, it must be transported, typically under pressure. Hydrogen is highly flammable, so safe handling procedures are necessary.[43]

The U.S. government in general and USAF in particular have invested heavily in portable energy technologies. Because there is broad commercial use of such technologies, including for the electric vehicle market, there is additionally significant investment in the commercial sector.[44]

Finding 15: Portable energy technologies are advancing in capabilities from both commercial and government research and development (R&D) investments.

Energy Dependence and Demand

Dependence on commercial power and alternative energy sources will certainly grow in the coming years and decades.[45] Commercial energy use planning typically has a 10- to 15-year horizon, which takes into account the time needed for real estate acquisition, permits, construction, and other items that support the power utilities, as well as local, city, or county growth plans. Military installations should be engaged with commercial energy providers to ensure that planning includes known expansion or increases in energy demands for their tenant organizations.[46] Except in wartime conditions, military installation expansion intentions are well known years in advance, which should allow for sufficient planning time with commercial energy providers. The units that deploy to the tactical edge originate at these installations and can be assumed to deploy with doctrinal energy support infrastructures, as well as with an initial supply of energy.

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[43] See Lawrence Livermore National Laboratory (LLNL), 2021, *Strategic Latency Unleashed: The Role of Technology in a Revisionist Global Order and the Implications for Special Operations Forces*, https://cgsr.llnl.gov/research/book.

[44] See LLNL, 2021, *Strategic Latency Unleashed: The Role of Technology in a Revisionist Global Order and the Implications for Special Operations Forces*, https://cgsr.llnl.gov/research/book.

[45] See International Energy Agency, 2020, *Renewables 2020*, Paris, https://www.iea.org/reports/renewables-2020; U.S. Energy Information Administration, 2021, "Short-Term Energy Outlook," https://www.eia.gov/outlooks/steo/report/electricity.php.

[46] See Department of the Air Force, 2021, *Installation Energy Strategic Plan 2021*, January 1, https://www.af.mil/Portals/1/documents/2021SAF/01_Jan/AF_Installation_Energy_Strategic_Plan_15JAN2021.pdf.

A factor that must be considered in military planning is the rapidly increasing energy demand from large data processing companies such as Amazon Web Services (AWS), Microsoft Azure, Google, Facebook, and others. These and other companies are building (and will continue to build or expand) very large data centers that are significant consumers of electric power.[47] If these data centers are located near military installations, either fixed or deployed, there can be a benefit in that the local utilities will plan and install upgraded facilities, which could result in added capacity for the military users. There can also be a resource competition issue should the local power utilities be unable to provide the additional facilities in a timely manner, or if they are not aware of the military installation's growing needs and do not plan adequately for them. Other issues may emerge, especially with respect to the construction of new generation facilities or transmission lines, both of which require decades of planning, hearings, permitting, and property or right of way acquisition.

> **Finding 16:** The initial deployment of a unit to the tactical edge will include energy that originates from the fixed installations, including energy from commercial energy provider partners.

Support for Machine Learning and Artificial Intelligence

Machine learning (ML) and AI are the terms used to refer to a set of algorithms and analysis methodologies that enable an automated ability to derive useful patterns from data sets, either as de novo discoveries or as rule matching for encountered situations.[48] For extremely complex situations, the ability to harness automation to quickly discern patterns is very valuable. Some common uses for ML include product recommendations, event alerts, and predictive medicine.[49]

The application of ML and AI to military operations is increasing in value as the amount of data collected, processed, and used at the tactical edge increases in both volume and type. Ubiquitous sensing from both fixed and mobile devices, such as unmanned aerial vehicles (UAVs), provides a wealth of data in audio, image, video, and signal formats. Time delays from pushing the data to back-end proces-

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[47] See Energy Innovation, 2020, "How Much Energy Do Data Centers Really Use?" March 17, https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use/; R. Battish, 2015, "Parameters to Consider in the Data Center Location Decision," AreaDevelopment, https://www.areadevelopment.com/data-centers/Data-Centers-Q1-2015/data-center-location-decision-parameters-46734866.shtml.

[48] See I.H. Witten and E. Frank, 2005, *Data Mining: Practical Machine Learning Tools and Techniques* (2nd edition), Morgan Kaufman Publishers, Waltham, MA.

[49] See Educba, 2021, "Uses of Machine Learning," https://www.educba.com/uses-of-machine-learning/.

sors, even when communications capabilities support that transfer, can adversely affect the ability to act in a timely manner on the resultant intelligence data. Adopting ML capabilities at the tactical edge ameliorates this problem by enabling near-real-time analysis of the data in order to discover important situational aspects.[50]

Energy needs associated with ML and AI can be extensive. First, the data being analyzed must be transferred from the source systems to the ML or AI platform. This process includes storing the data in the system, creating metadata for each data artifact, and cleaning the data to ensure that it is error-free and in a format that is process-friendly. Next, the applications execute the analysis of the data, possibly against previously collected and analyzed data, which means that computer processors operate on the data, moving portions of it in and out of memory as the processing continues. An important distinction exists between data processing for training as opposed to inference, in that training can be very expensive in terms of energy, while inference can be relatively cheap, depending on the application and only if engineered appropriately.[51] Last, the results of the ML operations need to be formatted and output for action. During each of these phases, there may be some or minimal human interaction. For any human interaction, there needs to be an interface that is human-friendly, such as a display or a keyboard. Each of these interfaces requires energy.[52]

Finding 17: Tactical-edge operational needs are driving the adoption of advanced computational capabilities, such as AI and ML. There are significant energy considerations associated with AI and ML that derive from the sensitivity of electronic components, the human-machine interface requirements, and the increased integration of sensors.

Power for User Interfaces

While USAF facility computing systems will need reliable power in the continental United States (CONUS) and outside the continental United States (OCONUS), the users of the information also need energy support because they will need to be able to view and interact with the data and processes through

[50] See Defense Systems Staff, 2020, "Automated Analytics for the Tactical Edge," Defense Systems, September 16, https://defensesystems.com/articles/2020/09/16/socom-automated-analytics.aspx.

[51] See R. Toews, 2020, "Deep Learning's Carbon Emissions Problem," *Forbes*, June 17, https://www.forbes.com/sites/robtoews/2020/06/17/deep-learnings-climate-change-problem/?sh=1b516f8f6b43.

[52] See W. Knight, 2020, "AI Can Do Great Things—If It Doesn't Burn the Planet," *WIRED*, January 21, https://www.wired.com/story/ai-great-things-burn-planet/; B. Bailey, 2019, "Power Is Limiting Machine Learning Deployments," SemiEngineering, July 25, https://semiengineering.com/power-limitations-of-machine-learning/.

peripherals such as keyboards, mice, earphones, microphones, and displays.[53] This implies reliable power at the human consumption end, which could be inside an aircraft or could be in a forward-deployed command post. As an example, large displays (or thousands of smaller body-worn displays) and the computers that will create the high-resolution images cumulatively require significant power resources.

For fixed systems such as those in a building, power for computers and displays is obtained from the utility infrastructure and typically consists of very small percentages of the energy used and available. Mobile systems, however, typically rely on battery power, or can draw power from a vehicle or platform that has internal power generation. The number of displays, tablets, keyboards, and other human-machine interfaces will increase, and the supply of batteries, fuel cells, or other forms of portable electric power will also increase. This will require additional storage, transportation, and disposal as the number of systems grows. Experience over the past decade shows that rechargeable batteries are not as useful as once thought, owing to the requirement to recharge them in places where recharging is not available or is difficult. Additionally, rechargeable batteries require actual activity to recharge (someone needs to move the battery to the recharging station, monitor the recharging, and then swap it out) and may present a fire hazard.[54] In fast-paced operational environments, use of nonrechargeable batteries may be preferred, even though that incurs a resupply cost.

Integrated Operations

In order to synergize operational capabilities, increase the speed at which operations can be conducted, and increase the flexibility of military options, the U.S. military has developed the concept of Joint All-Domain Operations (JADO). The intent of this approach is to harmonize and coordinate activities across all services and weapons platforms. In order to achieve these goals, significant communications and data exchange between services and units, particularly forward-deployed units, is necessary. There will be significant energy needed to support the communications and data exchange. As the planning for JADO is still in its early stages, the amount of energy needed at the tactical edge to support such operations is yet to be discovered.[55]

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[53] See G. Torbet, 2019, "How Much Energy Does Your PC Use? (And 8 Ways to Cut It Down)," MUO, December 18, https://www.muo.com/tag/much-energy-pc-use-8-ways-cut/.

[54] See S. Witman, 2019, "Are Rechargable Batteries Better Than Alkaline? Most of the Time," *New York Times*, June 6, https://www.nytimes.com/2019/06/06/smarter-living/wirecutter/are-rechargeable-batteries-better-than-alkaline.html.

[55] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872.

Finding 18: The energy needs associated with JADO for tactical-edge data operations will be significant but are as of yet not totally understood.

Effect on Operational Readiness

The Department of Defense doctrinally defines "operational readiness" as "The capability of a unit/formation, ship, weapon system, or equipment to perform the missions or functions for which it is organized or designed." Each of the services uses varying approaches toward measuring and reporting readiness, but all are required to conform with directives from the Chairman of the Joint Chiefs of Staff. The latest Air Force guidance is in AFI 10-201, 22 December 2020.[56] There are two distinct measured areas of readiness: resource readiness and capability readiness. These are defined in AFI 10-201 as

- "Resource readiness is a commander's objective measurement of the unit's resources and training to execute the mission for which it is organized and designed."
- "Capability readiness is a commander's subjective assessment of the unit's ability to accomplish its designed mission essential tasks (METs) based on the unit's full spectrum mission and the unit's ability to perform assigned missions."

The preceding discussion associated with energy dependencies for data-driven capabilities at the tactical edge implies that there may be readiness effects arising from both energy assurance and data assurance. Without energy, data-driven systems cannot operate. Without data, systems cannot see, hear, or speak.

Compounding these issues, it is currently not a requirement that data dependencies or needs be included in weapon systems specifications.[57] Because data dependencies and needs are not specified, it follows that the energy required for both direct data dependencies and indirect data dependencies for weapon systems readiness and operational capabilities, particularly when deployed, may not be well understood.

Finding 19: Resource readiness is affected when the unit does not have the resources needed to execute the mission.

[56] See Secretary of the Air Force, 2020, Air Force Instruction 10-201, December 22, https://static.e-publishing.af.mil/production/1/af_a3/publication/afi10-201/afi10-201.pdf.

[57] Conversations with AFRL personnel on October 2020 and Jeff Stanley, June 24, 2020, Appendix B.

Finding 20: Capability readiness is affected when the unit does not have the data needed to support the full-spectrum mission.

Finding 21: In determining the requirements for new systems, be that combat or combat support, the USAF has not directed the need for energy minimization, energy consumption monitoring, or power generation as part of the system requirements.

There are significant research efforts under way in many different technological areas that are focused on more effective and efficient use of energy. These include reducing energy usage for computation, both in software construction and in hardware components, as well as developing more efficient computational approaches to structuring the storage and movement of data within systems.

The challenge of delivering energy to deployed forces is complicated by logistics, which tend to favor simplicity over complexity and large users over small users. At the tactical edge, small users may have a larger role in data collection, analysis, and communication under the JADO concepts, which would make them a dependency for the operational readiness of the larger units.

Finding 22: Delivering energy to small units becomes a critical need for the overall system.

Energy Consumption Reduction Architectures

Perhaps the largest opportunities for energy efficiency gains in data-driven operations will be in the combination of algorithms and data system architecture design choices. There is an increasing trend toward edge computing and disaggregation, which is a data architecture with different requirements from a model of cloud-based or otherwise centralized computing centers.[58] In parallel with the trend toward edge computing, however, there is also a trend toward optimizing energy efficiency of computing hardware by specializing to computing chip platforms tailored to neural network machine learning (such as Google's tensor processing units [TPUs][59] and

[58] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872, presentations by Mukhopadhyay, M. Linderman, Benigni.

[59] "Tensor Processing Units (TPUs) are Google's custom-developed application-specific integrated circuits (ASICs) used to accelerate machine learning workloads." See Google, 2021, "Cloud Tensor Processing Units (TPUs)," https://cloud.google.com/tpu/docs/tpus.

many emerging neuromorphic[60] platforms).[61] These combined trends raise these questions:

- How long and under which operational use cases will neural network-based ML remain the dominant paradigm?
- How, in what time scales, and under which preprocessing, compression, and data fusion models do the data required for training and inference in ML algorithms flow across a disaggregated network?
- When is a data architecture constrained by energy costs versus bandwidth limitations to move the data to where they need to be processed?

Industry ML deployments are increasingly using custom computer chips to accelerate model training algorithms. While these chips show performance gains in both processing time and energy requirements for commercial cloud deep-learning applications, there is concern within the Air Force that mission-specific applications will require further processor development to realize similar gains. DoD and intelligence community (IC) use cases, including fast decryption of files and cyber-hardening features for use in contested environments, do not yet have an off-the-shelf computer chip solution from industry. Investigations into synaptic or neuromorphic computing platforms (such as Blue Raven[62]) or low cost, size, weight, and power high-power computing (C-SWAP HPC; such as Agile Condor[63]) are showing potential benefits for edge deployment of ML algorithms for sensor data processing. High-power computing (HPC) that can be deployed on edge platforms may have particular advantages in those use cases where, for example, graph- and logic-based algorithms are preferred over neural network-based algorithms.

A key question for the neural network-based algorithm paradigm is whether the training data requirements and retraining requirements during operations are practical to meet in the desired mission applications. Algorithm advances that can

[60] "Neuromorphic computing research emulates the neural structure of the human brain." See Intel, 2021, "Neuromorphic Computing," https://www.intel.com/content/www/us/en/research/neuromorphic-computing.html.

[61] NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief,* The National Academies Press, Washington, DC, https://doi.org/10.17226/25872, presentations by Crisman, Carol-Jean Wu, Sherief Reda.

[62] Blue Raven is the project name for "the world's largest neuromorphic digital synaptic super computer." See J. O'Brien, 2018, "AFRL, IBM Unveil World's Largest Neuromorphic Digital Synaptic Super Computer," Wright-Patterson AFB, July 24, https://www.wpafb.af.mil/News/Article-Display/Article/1582310/afrl-ibm-unveil-worlds-largest-neuromorphic-digital-synaptic-super-computer/.

[63] "The Agile Condor high-performance embedded computing (HPEC) architecture offers sensor-agnostic, on-board, real-time data processing to deliver actionable intelligence to the warfighter." See SRC, 2021, "Agile Condor High Performance Embedded Computing," https://www.srcinc.com/products/intel-collection-and-analysis/agile-condor-high-performance-embeded-computing.html.

perform with less training data would have potential advantages both in the number of application areas where they could be deployed and in the potential energy requirements for training the algorithms. While less training data may be advantageous for reducing computing and energy requirements, such reductions could be either confounded or enhanced depending on the suitability of the computing and communications platforms for the chosen algorithms. Without further specification of the data flows, algorithms, and computing platforms within an architecture plan, it is difficult to make assessments about energy needs. The committee has not seen the desired level of detail in any data architecture plan.

Finding 23: There is a trend toward optimizing energy efficiency of computing hardware by specializing to computing chip platforms tailored to neural network machine learning.

Finding 24: Mission-specific applications require further processor development to realize similar gains in reducing processing time and energy requirements.

Finding 25: Algorithm advances that can perform with less training data would have potential advantages both in the number of application areas where they could be deployed and in the potential energy requirements for training the algorithms.

Energy-Efficient Computation

The growing demand for computing capabilities, particularly at the tactical edge, has forced the design community to consider all aspects of a fielded product, including size, weight, environmental factors, and energy usage. Energy, a scarce and expensive resource, is becoming a critical design constraint. Software engineers, hardware manufacturers, and system designers are exploring new techniques to reduce the energy consumption of computing devices. One way to reduce energy consumption of a computing device is through the design of software and algorithms that are energy consumption aware. In a given scenario, the goal is to design energy-efficient computational algorithms that reduce energy consumption without sacrificing performance. Research in this area includes both theoretical inquiry and application-level exploration.

Theoretical work[64] has shown that algorithms for sleep states, power-down mechanisms, dynamic speed scaling, temperature management, and energy-

[64] See E. Demaine et al., 2016, "Energy-Efficient Algorithms," *Proceedings of the 2016 ACM Conference on Innovations in Theorectical Computer Science*, pp. 321–332, Association for Computing Machinery (ACM), New York, NY.

minimizing scheduling can have a very significant effect on energy consumption. Power-down mechanisms have been developed[65] that conserve energy by switching a device into low-power modes. The process of dynamic speed scaling in variable-speed processors can save energy by utilizing the full speed and frequency capabilities of a processor and utilizing low speeds whenever possible.[66] Experiments to understand energy consumption for algorithms have been performed[67] for popular vector operations, matrix operations, sorting, and graph algorithms. Energy consumption for a given algorithm depends on the extent to which that algorithm can exhibit memory parallelism for a given data layout in the random access memory (RAM) with variations up to 100 percent for many popular algorithms.[68]

In addition, fundamental work[69] has explored energy complexity of algorithms based on Landauer's principle, which gives a lower bound on the amount of energy a system must dissipate if it destroys information. This approach lays a theoretical foundation for a new field of semi-reversible computing and provides a framework for the investigation of algorithms. Using this theoretical framework, energy-aware algorithms for control logic, memory allocation, garbage collection, comparison sort, insertion sort, counting sort, breadth-first search, Bellman-Ford, Floyd-Warshall, matrix all-pairs shortest paths, Adelson-Velsky and Landis (AVL) trees, binary heaps, and dynamic arrays have been developed.[70]

Besides theoretical research on operating system-level algorithms, there is also a substantial body of literature on methods to save energy during computation. Many data-rich applications for computing at the edge exist, and the number of use

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[65] See S. Albers, 2010, Energy-efficient algorithms, *Communications of the Association for Computing Machinery* 53(5):86–96.

[66] See S. Irani et al., 2007, Algorithms for power savings, *ACM Transactions on Algorithms* 3(4); S. Irani et al., 2003, Online strategies for dynamic power management in systems with multiple power-saving states, *ACM Transactions on Embedded Computing Systems* 2(3).

[67] See S. Albers and H. Fujiwara, 2007, Energy-efficient algorithms for flow time minimization, *ACM Transactions on Algorithms* 3(4):Article 49 (November), http://doi.acm.org/10.1145/1290672.1290686; C. Ambühl, 2005, "An Optimal Bound for the MST Algorithm to Compute Energy Efficient Broadcast Trees in Wireless Networks," *ICALP '05: Proceedings of the 32nd International Conference on Automata, Languages and Programming*, pp. 1139–1150, ACM, New York, NY; M. Li and F.F. Yao, 2005, An efficient algorithm for computing optimal discrete voltage schedules, *SIAM Journal on Computing* 35(3).

[68] See S. Albers and H. Fujiwara, 2007, Energy-efficient algorithms for flow time minimization, *ACM Transactions on Algorithms* 3(4):Article 49 (November), http://doi.acm.org/10.1145/1290672.1290686; C. Ambühl, 2005, "An Optimal Bound for the MST Algorithm to Compute Energy Efficient Broadcast Trees in Wireless Networks," *ICALP '05: Proceedings of the 32nd International Conference on Automata, Languages and Programming*, pp. 1139–1150, ACM, New York, NY; M. Li and F.F. Yao, 2005. An efficient algorithm for computing optimal discrete voltage schedules, *SIAM Journal on Computing* 35(3).

[69] See E. Demaine et al., 2016, "Energy-Efficient Algorithms," *Proceedings of the 2016 ACM Conference on Innovations in Theorectical Computer Science*, pp. 321–332, ACM, New York, NY.

[70] See E. Demaine et al., 2016, "Energy-Efficient Algorithms," *Proceedings of the 2016 ACM Conference on Innovations in Theorectical Computer Science*, pp. 321–332, ACM, New York, NY.

cases is growing. This includes signal and image processing, deep neural networks, computer vision, and machine learning. These applications have special needs for on-board processing: size, weight, and power (SWaP) constraints and hard real-time constraints.[71]

There are three key design principles for energy-efficient embedded processing of data-rich applications: (1) hardware accelerators, (2) approximate design and synthesis, and (3) software/hardware co-design.

Hardware acceleration with custom processing circuits eliminates many loads and stores, and executes all possible concurrent operations simultaneously. Custom accelerators can be used in embedded field programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs). In terms of hardware for data-intensive processing, accelerators provide the best energy efficiency for data-rich applications, followed by graphics processing units (GPUs).[72]

Many data-rich applications in machine learning, signal processing, computer vision, and cognitive computing have inherent error resiliency: noisy inputs, approximate algorithms, and loose constraint on output. Approximate computation can be leveraged to trade off accuracy for hardware resources (e.g., design area, power, latency). The benefits of approximations in embedded accelerators include a large fraction of energy spent in arithmetic units, customization of the data path down to individual bits, and reduced internal memory and memory bandwidth.[73]

[71] See L. Benini et al., 2000, A survey of design techniques for system-level dynamic power management, *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 8(3):299–316; S. Irani et al., 2007, Algorithms for power savings, *ACM Transactions on Algorithms* 3(4); K. Pruhs et al., 2008, Speed scaling of tasks with precedence constraints, *Theory of Computing Systems* 43(1); S. Roy et al., 2014, "Energy Aware Algorithmic Engineering," *MASCOTS '14: Proceedings of the 2014 IEEE 22nd International Symposium on Modelling, Analysis & Simulation of Computer and Telecommunication Systems*, pp. 321–330, IEEE, Piscataway, NJ.

[72] See S. Albers and F. Müller, 2007, "Speed Scaling on Parallel Processors," *SPAA '07: Proceedings of the Nineteenth Annual ACM Symposium on Parallel Algorithms and Architectures*, pp. 289–298, ACM, New York, NY; J. Augustine et al. 2004, "Optimal Power-Down Strategies," *45th Annual IEEE Symposium on Foundations of Computer Science*, pp. 530–539, IEEE, Piscataway, NJ; N. Bansal et al., 2007, Speed scaling to manage energy and temperature, *Journal of the ACM* 54(1):Article 3 (March); K. Pruhs et al., 2008, Speed scaling of tasks with precedence constraints, *Theory of Computing Systems* 43(1).

[73] See S. Albers and H. Fujiwara, 2007, Energy-efficient algorithms for flow time minimization, *ACM Transactions on Algorithms* 3(4):Article 49 (November), http://doi.acm.org/10.1145/1290672.1290686; E. Demaine et al., 2016, "Energy-Efficient Algorithms," *Proceedings of the 2016 ACM Conference on Innovations in Theorectical Computer Science*, pp. 321–332, ACM, New York, NY; M. Flammini et al., 2004, "Improved Approximation Results for the Minimum Energy Broadcasting Problem," *Proceedings of the 2004 Joint Workshop on Foundations of Mobile Computing*, pp. 85–91, ACM, New York, NY; S. Roy et al., 2014, "Energy Aware Algorithmic Engineering," *MASCOTS '14: Proceedings of the 2014 IEEE 22nd International Symposium on Modelling, Analysis & Simulation of Computer and Telecommunication Systems*, pp. 321–330, IEEE, Piscataway, NJ.

Software and hardware co-design for embedded data-rich systems involved integrated design of the accelerator, approximation techniques, and computation algorithms employed. Examples show 2–3 × reduction in power consumption of accelerators with 2–8 percent reduction in accuracy.[74]

A substantial amount of research has been performed to create energy consumption-aware algorithms at the operating system level and the application level, and it appears this line of work has great potential for reducing energy needs for computing at the tactical edge, but there is still more research that needs to be performed to yield practical and deployed energy-aware algorithms. Needed research includes theoretical work on the application-level side, particularly applications that will be used in computing at the edge such as neural networks and deep learning. In addition, practical algorithm prototypes need to be tested in comprehensive campaigns, structured around operational concept use cases, for energy analysis and best practices.

Finding 26: Clever algorithm design can yield orders of magnitude of energy savings for computer energy consumption.

Further, this body of knowledge suggests pathways in research that can expand fundamental ideas surrounding energy-aware numerical algorithms and research on practical and prototyped algorithms for energy-aware computations.

Computing Hardware

Air Force systems operating at the tactical edge increasingly use highly capable computing hardware that process distributed sensor system data with sophisticated algorithms.[75] Using these sophisticated algorithms to analyze large amounts of data requires considerable computational capacity. In some circumstances, most processing takes place in back-end systems, where the data is moved from the edge to off-premise support locations. In other circumstances, time constraints and operational security considerations require that the time-sensitive processing take place in near real time at the tactical edge. These edge computing systems have special

[74] See S. Irani et al., 2003, Online strategies for dynamic power management in systems with multiple power-saving states, *ACM Transactions on Embedded Computing Systems* 2(3); K. Pruhs et al., 2008, Speed scaling of tasks with precedence constraints, *Theory of Computing Systems* 43(1); S. Roy et al., 2014, "Energy Aware Algorithmic Engineering," *MASCOTS '14: Proceedings of the 2014 IEEE 22nd International Symposium on Modelling, Analysis & Simulation of Computer and Telecommunication Systems*, pp. 321–330, IEEE, Piscataway, NJ.

[75] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872.

needs for on-board algorithm execution, which include both hard real-time processing and SWaP constraints. For this reason, when possible, supporting and direct computation for devices and platforms at the edge is done off-premise. However, when data-driven decisions must be made instantaneously, this analysis must be done at the edge using field-deployed data centers and platform processors. This is especially important in situations with limited connectivity or inadequate time to transfer the data back and forth from back-end servers. This has led to the growing trend of deploying advanced machine learning methods to the tactical edge.[76]

There are a variety of hardware systems relevant for edge-deployed computational systems. To optimize within SWaP constraints, the current trend is to specialize computing hardware to specific applications.[77] Because the algorithms used at the tactical edge are complex and may require large parallel matrix multiplications, heterogenous computer architectures are used for tactical-edge devices. Hardware specialization within heterogeneous computing systems with custom processing circuits results in the elimination of many loads and stores, in addition to executing all possible concurrent operations simultaneously. In terms of hardware for data-intensive processing, heterogeneous computing systems provide the best energy efficiency for data rich applications.[78] Box 2.1 discusses the current state of machine learning hardware in more detail.

Finding 27: Operational constraints, such as communication capability and speed requirements for data-driven decisions, cause situations where advanced data processing must take place at the tactical edge. Deploying these types of capabilities to the tactical edge requires an architectural approach that optimizes design constraints to minimize power usage while delivering very fast processing on-premise.

Software

As the development and availability of high-capacity data storage devices has continued to increase the amount of data that can be collected and stored, the

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[76] Conversations with USMC Major Aaron Stone on September 2020, Appendix B.

[77] See M. Iriarte, 2018, "UAS SWaP Constraints Driving RF and Microwave Designs," Military Embedded Systems, April 23, https://militaryembedded.com/unmanned/isr/uas-driving-and-microwave-designs.

[78] See M. Hallock et al., 2016. "Evaluation of Emerging Energy-Efficient Heterogeneous Computing Platforms for Biomolecular and Cellular Stimulation Workloads," University of Illinois, Urbana-Champaign, https://www.ks.uiuc.edu/~johns/files/ipdps2016/papers/hcw2016-08-ArmGPU-final.pdf; and Z. Cheng et al., 2017, "Rethinking Energy-Efficiency of Heterogeneous Computing for CNN-Based Mobile Applications," *2017 IEEE International Symposium on Parallel and Distributed Processing with Applications and 2017 IEEE International Conference on Ubiquitous Computing and Communications (ISPA/IUCC)*, pp. 454–458, doi: 10.1109/ISPA/IUCC.2017.00074.

BOX 2.1
Machine Learning Hardware

There is a particularly rich set of offerings for machine learning (ML) detailed in Konstantinidis.[1] These include the following:

- Coral System-on-Module: This hardware offering is a fully integrated system for ML applications that includes CPU, GPU, and edge tensor processing unit. The unit is capable of performing 4 trillion operations (tera-operations) per second (TOPS).
- Intel Neural Compute Stick 2: This hardware offering has a form factor like a standard USB thumb drive and is built on the latest Intel Movidius Myriad X Vision Processing Unit (VPU), which is a system-on-chip system with a dedicated Neural Compute Engine for accelerating ML computation.
- NVIDIA Jetson TX2: This system is an embedded system on a chip used for deploying computer vision and ML algorithms.
- RISC-V GAP8: This system is an ultra-low power, eight-core, Reduced Instruction Set Computer (RISC)-V-based processor optimized to execute algorithms used for image and audio recognition.
- ARM Ethos N-77: This system is a multicore neural processing unit (NPU), part of the ARM Ethos. It delivers up to 4 TOPs of performance and supports several algorithms used for image/speech/sound recognition.
- ECM3531: This system is an ASIC based on the ARM Cortex-M3 architecture that is able to perform ML algorithms in very few milliwatts.

As is always the case for computer hardware, system capability is very rapidly evolving, with currently cutting-edge hardware often being obsolete within a year.

[1] See F. Konstantinidis, 2020, "Why and How to Run Machine Learning Algorithms on Edge Devices," *The Robot Report*, February 23.

software development community has been challenged to develop approaches to data access and usage that are fast enough to avoid frustrating users and to meet the capabilities of the hardware. There are energy trade-offs in how software accomplishes the various steps that support task execution.[79]

[79] See J. Michanan et al., 2014, Understanding the power-performance tradeoff through pareto analysis of live performance data, *Journal of the ACM* 54(1):Article 3, 1–39, https://doi.org/10.1145/1206035.1206038; S. Akramullah, 2014, "Performance, Power, and Quality Tradeoff Analysis," *Digital Video Concepts, Methods, and Metrics*, Apress, Berkeley, CA, https://doi.org/10.1007/978-1-4302-6713-3_8; ScaleFocus, 2019, "Top 13 Reasons to Modernize Your Legacy Systems," March 6, https://www.scalefocus.com/insights/business/top-13-reasons-to-modernize-your-legacy-systems; R. Mack, 2020, "How Utilities Can Rewire Customer Engagement by Replacing Legacy Systems," Veracity, March 11, https://veracityit.com/2020/03/11/utilities-legacy-systems/.

An increased amount of data manipulated for complex analyses implies the need for many computation cycles.[80] There are better and worse ways to approach computational strategy. Some computational approaches are energy hogs, while others are energy efficient. There is an entire research field associated with identifying energy-efficient computational approaches, which encompass both hardware and software aspects. To date, "researchers have proved mathematically that relatively simple hardware modifications could cut in half the energy consumed in running today's standard software procedures."[81] The implications of efficient computing cascade to the energy needed for cooling as well: fewer computational cycles generate less heat.

Finding 28: Modifying how computational systems execute instructions can reduce energy usage of the system.

Finding 29: Reducing the energy used in computation also reduces the amount of heat generated, which not only affects the amount of energy needed for environmental controls but also affects the operational heat signature of deployed units.

For small data users, such as home computer users, the amount of energy consumed by software processes may not be noticeable. However, as individuals come to rely on mobile devices, which are battery powered, software processes that run down batteries quickly become a market differentiator. Legacy software on more modern devices are typical sources of power drain; concomitantly, advanced software installed on older computational systems (if possible at all) can overwhelm system resources (such as RAM) and drain power supplies. Keeping many programs in active memory is also implicated in draining power from devices. Activities that are inherently resource-intensive, such as mining bitcoins, can overwhelm regional power grids and may serve as a warning of what is to come.[82] Further, the use of device software that relies on cloud-based software processes rely on communication between the device and the cloud, which requires extensive use of communications software. For example, voice-activated capabili-

[80] See T. Brown and D. Hernandez, 2020, "AI and Efficiency," OpenAI Blog, May 5, https://openai.com/blog/ai-and-efficiency/.

[81] See N.W. Stauffer, 2013, "Energy-Efficient Computing: Enabling Smaller, Lighter, Faster computers," MIT Energy Institute News, June 20, http://energy.mit.edu/news/energy-efficient-computing/.

[82] See P. Roberts, 2018, "This Is What Happens When Bitcoin Miners Take Over Your Town: Eastern Washington Had Cheap Power and Tons of Space. Then the Suitcases of Cash Started Arriving," Politico, March/April, https://www.politico.com/magazine/story/2018/03/09/bitcoin-mining-energy-prices-smalltown-feature-217230.

ties typically require back-end cloud-based computational support for interpretation of the voice commands.[83] The integration of many small end users' devices (the IoT phenomenon) magnifies this issue. Very large data users are strongly motivated to implement software that minimizes energy consumption. This desire has spurred a dynamic research area in how to construct software to minimize energy consumption.

Finding 30: There is a relationship between the software use profiles and the hardware architecture of small devices that affects battery life between charges.

There are some straightforward approaches to reducing energy use by software components, such as reducing the amount and frequency of data logged during operation, removing unneeded data from actively searched repositories, and eliminating data format translations during software execution. Every unneeded process consumes energy, so a first step is to reduce the number of operations that are needed. Beyond that, research into reversible energy computing is yielding results that are impacting the approaches to developing software programs. "Existing work shows that the use of parallel and approximate programming, source code analyzers, efficient data structures, coding practices, and specific programming languages can significantly increase energy efficiency. Moreover, the utilization of energy monitoring tools and benchmarks can provide insights for the software practitioners and raise energy-awareness during the development phase."[84]

Big Data

The plan for "AI to the Edge" means that data sets will be needed at the edge. As noted in the section "Energy Consumption Reduction Architectures" above, the choices of applications and engineering solutions that depend on big data can greatly affect energy requirements for tactical-edge computing support. The next-generation tactical-edge information collection, processing, and usage is conceptually based on what can be referred to as "big data," which is intended to feed machine learning support to operations. There are both practical and operational considerations for the use of big data machine learning solutions at the tactical edge. The practical aspect includes the problem of training the machine learning application: training takes a great deal of data, time, and energy, which makes it problematic in a fast-paced tactical environment. The operational aspect includes

[83] See V. Sharma, 2017, "How Do Digital Voice Assistants (e.g., Alexa, Siri) Work?" USC Marshall, October 17, https://www.marshall.usc.edu/blog/how-do-digital-voice-assistants-eg-alexa-siri-work.

[84] See S. Georgiou et al., 2019, Software development lifecycle for energy efficiency: Techniques and tools, *ACM Computing Surveys* 52(4).

the challenge of performing the machine learning training at the back end and then performing inference based only on that training at the tactical edge: because the inference is based on historical data, an adversary need only change its tactics and processes to reduce the utility of the output.

A conventional definition of big data is that it is based on velocity, volume, variety, veracity, and value.[85] A critical value proposition in big data analytics is the discovery of subtle patterns and hidden correlations that are not obvious. The ability to use the sheer volume of data to make qualitatively different discoveries is an important part of the big data environment. The increased number and variety of data collection at the tactical edge provides all of these aspects. It is one thing to collect a rich data set; it is a very different thing to access it from the tactical edge. A huge lesson learned from global business operations that "follow the sun" is that you do not want to be pushing entire data sets over networks from time zone to time zone: it would take the entire work cycle to update the baseline.[86] This creates a challenge: sending the sheer volume of data collected to back-end processors is tactically difficult in that it requires significant bandwidth, but processing the data locally removes the context of prior knowledge that is available at the back end and requires significant processing infrastructure at the tactical edge. A middle-ground solution that deploys advanced IT infrastructure with tactical-edge operators can address this issue, but that also implies advanced energy support for those cutting-edge technologies.

Big data processing consumes a lot of energy.[87] The energy needs are not just for the computational devices but also for environmental control. Because of the huge energy consumption needs, the details of implementation are important: energy losses over transmission lines can figure quite significantly in the requirements calculations. That is why very large data centers are located as close as possible to power generation facilities.[88]

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[85] See Big Data, 2020, "The Five V's of Big Data," BBVA, May 26, https://www.bbva.com/en/five-vs-big-data/.

[86] The problem with moving data over networks is so problematic that actual trucks are used to move large amounts of data. See, for example, this very real service: "AWS Snowmobile is an Exabyte-scale data transfer service used to move extremely large amounts of data to AWS. You can transfer up to 100PB per Snowmobile, a 45-foot long ruggedized shipping container, pulled by a semi-trailer truck. … Transferring data with Snowmobile is more secure, fast and cost effective." See AWS, 2019, "AWS Snowmobile Overview," https://aws.amazon.com/snowmobile/.

[87] See R. Danilak, 2017, "Why Energy Is a Big and Rapidly Growing Problem for Data Centers," *Forbes*, December 15, https://www.forbes.com/sites/forbestechcouncil/2017/12/15/why-energy-is-a-big-and-rapidly-growing-problem-for-data-centers/?sh=714d0c155a30.

[88] See F. Boshell and S. Ratka, 2020, "The Nexus Between Data Centers Efficiency and Renewables: A Role Model for the Energy Transition," Energypost, June 26, https://energypost.eu/the-nexus-between-data-centres-efficiency-and-renewables-a-role-model-for-the-energy-transition/.

Finding 31: Collecting rich data at the tactical edge means that some capability for big data processing exists at the tactical edge. Big data processing at the tactical edge requires adequate energy.

Finding 32: Dependence on conventional cloud computing solutions is not a viable solution for every tactical situation and therefore cannot be the sole solution to the data-driven operational problems. The development of portable data centers may provide an intermediate solution.

Data Variety

The types of data being collected, stored, and analyzed is increasingly varied in format. The formats include video, audio, textual, and other sensory systems (such as telemetry). Mixing all these types of data into a comprehensive analytical framework requires advanced approaches to data integration and meaning extraction. Research on how to do this quickly and energy efficiently touches on storage approaches, searching algorithms, and display efficiencies (such as background refresh options). Data in forms other than textual (such as video, audio, or analog signals) increases communication bandwidth needs, both locally and externally, which increases energy needed for communication infrastructure.

Concomitantly, fusing data in multiple formats from a variety of sources is not a trivial undertaking. The term "data fusion" refers to combining distinct data sets to obtain unified analytic results. With appropriate methods of data fusion, information from distinct edge sensors may be combined to produce inferences that exploit modality or geographic diversities that are qualitatively improved over any single edge analysis alone. The whole is greater than the sum of its parts. The fusion process must be engineered to allow for the time aspects associated with various data (some data phenomena occur frequently, while others occur rarely or periodically), the precision (or lack thereof) of different data types, and the reliability of various data sources. Poorly engineered fusion approaches use excessive computing cycles, which increases the energy needed.

Finding 33: Variety in data types increases communication bandwidth needs, which increases energy needed for communication.

Finding 34: Data fusion that integrates many different types of data requires careful consideration and engineering to minimize energy used in the fusion process.

INFRASTRUCTURE AND ENTERPRISE NEEDS

A system is an integrated set of capabilities. For one part of a system to operate as designed, any dependencies in other parts of the system must be considered. For tactical-edge advanced computing, the following components will make the overall system work better or worse: architecture design, software and hardware energy efficiencies, and manpower support.

Architecture Design

There is a growing trend toward edge computing and disaggregated data architectures, which have different infrastructure (including energy) requirements from architecture models of centralized cloud or command and control (C2) centers where data is aggregated for processing. Part of the reason for the move to edge computing is that it is common to produce large volumes of data at the tactical edge that cannot be backhauled to a central computing facility within a time frame that meets mission requirements.[89] Leaving time aside, the communications infrastructure is also often not in place to move large volumes of data that are generated on a regular or continual basis. Data triage is a viable solution to data transfer bottlenecks, but it does not address the stated need for more data-driven operations.[90] Instead, volumes and rates of data processing at the edge are expected to continue increasing, with associated increases in energy demands. The pressing questions are: (1) What algorithms will be run to meet which mission needs? (2) What data are needed where to support such algorithms? (3) What energy and communications infrastructure requirements does this imply? The answers to these questions are given by a data architecture design.

As noted previously, for most data-centric algorithms it is important to separate the operations of "training" versus "inference." During training, models are fit to the available data. During inference, fitted models are used to analyze new data. In a recent analysis by the company OpenAI, the computational power requirements to train state-of-the-art AI algorithms have been doubling every 3 to 4 months since 2012—seven times faster than Moore's law.[91] With such trends in mind, the (often implicit) architecture model for training AI systems is to aggregate training data in a large, centralized computing center, followed by deployment of the trained model to the edge. Such a data architecture may be appropriate when

[89] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872, presentation by Col. Benigni.

[90] See Conversation with Frank Konieczny, July 2020, Appendix B.

[91] See T. Brown and D. Hernandez, 2020, "AI and Efficiency," OpenAI Blog, May 5, https://openai.com/blog/ai-and-efficiency/.

the necessary training data can be aggregated offline and when the trained models can be trusted to maintain relevance in the deployed domain. On the other hand, when data must be aggregated from or otherwise shared across edge networks over limited bandwidths or when the models require frequent retraining, other data architecture designs may be required.

Because training AI models is the most demanding part of the computation in terms of energy requirements, the data architecture may become a dominant factor in determining energy needs for data-driven operations. In addition, current activities to optimize the energy efficiency of computing hardware is leading to specialization of computing chips for performing AI inference. These specialized computing platforms are showing promise for reducing SWaP requirements but are not addressing the architecture questions of when (re-)training of such AI systems may be needed and how the training data is made available.[92]

Finding 35: The data architecture may become a dominant factor in determining energy needs for data-driven operation.

Data fusion as an aspect of data architecture design is worth calling out. When mission applications may be enhanced or even reliant on edge node data fusion capabilities, data processing and communications requirements must be set at the system or architecture level. This is a complicated and difficult problem that is easy to overlook. However, without a system-level requirements process for data exploitation, the delivered architecture may fail to meet the promise of data-driven operations and at the same time become overengineered into isolated edge node or centralized processing models.

Finding 36: A system-level requirements process for data acquisition, communications, and processing is likely required to achieve the desired data-driven operations capabilities.

Manpower

One critical part of the infrastructure that is often overlooked is that of people. In the field of energy, particularly as it applies to energy needed to operate dispersed data centers, the Air Force has a shortage of qualified personnel, which is exacerbated by the reality of competition with the civilian sector for the available

[92] See Defense Advanced Research Projects Agency, 2021, "AI Next Campaign," https://www.darpa.mil/work-with-us/ai-next-campaign.

talent pool.[93] In the past, the Air Force has treated energy as a commodity and then outsourced both the planning and execution of this to the contractors.[94] As energy becomes more critical to mission success, this specialty field needs to become a core field within the Air Force. There are several concerns. First, in order to contract for, and supervise, contractors, the Air Force needs in-house experts. Second, the energy needs for deployed units and weapons systems are different based on mission profiles, operational needs, and component elements, which implies a need for specific expertise on a deployable basis.

Critical skill sets needed are balancing load power, controlling microgrids, battery maintenance and sustainment, maintaining a low signature, and the ability to stand up and take down the power sources quickly across the operational and tactical battle space. Additionally, the Air Force must have the expertise to power not just the data center but also the networks associated with moving the data from place to place as needed. This is, in and of itself, a specialty area where power may need to be turned on and off, in an instant. Last, within the field of research and development, it is likely that the Air Force will have unique requirements for the power consumption of chips, which large commercial providers do not have. Therefore, this scientific skill set, for minimizing chip power consumption, needs to be considered as an investment within the Air Force science and technology (S&T) enterprise.

At a national or strategic level, the number of electrical engineers entering the career field, including the subset who are interested in and capable of attaining security clearances, is not growing as fast as industry or the Air Force needs.[95] A career in electric power is not viewed as being as lucrative as a career in computer science, programming, or application development. This impacts both the Air Force and industry, and competition for trained and experienced electrical engineers may drive the available pool more toward industry than toward government or military service. Furthermore, as the average age of experienced electrical engineers increases, the awareness of new technologies and new threats diminishes.

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[93] See C. Murray, 2000, "Engineer Shortage Called Danger to Military Readiness," *EETimes*, September 21, https://www.eetimes.com/engineer-shortage-called-danger-to-military-readiness/#; R. Wilson, 2016, "EuMW: Skills Shortage Is Sector's Biggest Challenge," *Electronics Weekly*, October 4, https://www.electronicsweekly.com/market-sectors/military-aerospace-electronics/eumw-skills-shortage-sectors-biggest-challenge-2016-10/; L. Frenzel, 2013, "Is There Really a Shortage of Engineers?" Electronic Design, September 16, https://www.electronicdesign.com/community-home/article/21798513/is-there-really-a-shortage-of-engineers; M. Lapedus, 2019, "Engineering Talent Shortage Now Top Risk Factor," Semiengineering, February 25, https://semiengineering.com/engineering-talent-shortage-now-top-risk-factor/.

[94] See Air Force Civil Engineer Center, 2017, "Energy Flight Plan 2017–2036," https://www.afcec.af.mil/Portals/17/documents/Energy/AFEnergyFlightPlan2017.pdf?ver=2019-12-16-105948-090.

[95] See M. Lapedus, 2019 "Engineering Talent Shortage Now Top Risk Factor," Semiengineering, February 25, https://semiengineering.com/engineering-talent-shortage-now-top-risk-factor/.

However, there may be unexpected continued resilience in new power facilities owing to the tendency of these engineers to use designs that rely more on physical switches, relays, protective systems, and human control, and less on automation and computer control.

Finding 37: There is a need for deployable personnel to set up, manage, maintain, and optimize the energy support for tactical-edge computational systems.

Finding 38: There is a shortage of trained personnel in electrical engineering and data center support operations.

Finding 39: Owing to the design needs of tactical edge computational systems, it is likely that there will be a need for S&T investment.

The current assumption that data-driven operations will rely on large data centers has falsely led the Air Force to assume that its current methods of providing energy to large operational installations, using contracted power and labor, is sufficient. With the need to perform the compute and store functions dispersed across the tactical, operational, and strategic level of warfare, the manpower skill sets needed for this change in energy patterns is significant and is a barrier to the successful implementation of data-driven operations.

The Air Force must have the organic manpower in order to learn how its needs differ from the commercial sector, to determine what organic intellectual property meets its needs, to manage contractors who will implement solutions, and to make the trade-offs needed between operational needs and energy needs. Simply stated, without the organic manpower that understands the entire spectrum of energy needs, the Air Force may never achieve a solution that strengthens its operational goals and instead will subject itself to substantial tactical, operational, and strategic risk. For the purpose of this discussion, the term "manpower" includes recruiting, educating, training, contractor/military blend, and incentives for education.

Finding 40: The USAF does not have the organic manpower to manage, lead, supervise, or solve the challenges associated with the design, operation, and management of energy consumption associated with data-driven operations.

Research

There is a gap today between current technologies for data collection and exploitation and stated aspirations such as intelligent automated decision support and real-time collaborative autonomy (as in the "kill mesh" described by Air Force Warfighting Integration Capability [AFWIC] and the "mosaic warfare" concept from Defense Advanced Research Projects Agency Strategic Technology Office [DARPA STO]). The National Security Commission on Artificial Intelligence (NSCAI) in its interim report identified a need for AI-enabled autonomous operations to include predictive analysis, decision support systems, unmanned platforms, robotics, and weapons.[96] While individual algorithms and platforms exist today for each of these capabilities, an enterprise architecture integrating such capabilities has yet to be demonstrated.

Finding 41: There is a gap between current technologies and planned capabilities for collaborative data-driven decisions.

Innovative Approaches to Energy

There are several important aspects regarding innovation in energy sourcing, storage, and logistics. These include distributing energy resources, utilizing alternative energy sources in innovative ways, and being clever in the storage and usage of energy in order to minimize loss and maximize the use of available resources.

Distributed Energy Resources

Distributed Energy Resources (DER) are an important element in an overall energy architecture. The traditional model of electricity infrastructure is to generate power where it is cheapest or has the smallest impact, move the electricity via transmission lines to substations close to the user, then distribute the electricity from those substations to the users. DER technologies are typically used with solar, wind, or other "renewable" sources and can either be connected to a larger power grid or in a microgrid[97] configuration.[98] Renewable energy technologies have matured significantly in the past several decades and have achieved significant market penetration.[99] They have also emerged as an important technology

[96] See National Security Commission on Artificial Intelligence, 2019, *Interim Report: November 2019*, https://www.nscai.gov/whitepaper/interim-report-november-2019/.

[97] Microgrids are a key component for improving power reliability and quality, efficiency, and providing grid-independence to users. See M. Smith and D. Ton, 2016, "The U.S. Department of Energy's Microgrid Initiative," U.S. Department of Energy, Washington, DC.

[98] DER is defined as "any resource on the distribution system that produces electricity and is not otherwise included in the formal NERC definition of the Bulk Electric System (BES)." See North American Electric Reliability Corporation, 2017, "Distributed Energy Resources," February, https://www.nerc.com/comm/other/essntlrlbltysrvcstskfrcdl/distributed_energy_resources_report.pdf.

[99] See National Renewable Energy Laboratory, 2021, "Renewable Electricity Futures Study," https://www.nrel.gov/analysis/re-futures.html.

for disaster and emergency relief operations.[100] There are efforts under way to establish the utility of renewable energy-based DER in garrison via microgrids, such as at Scott Air Force Base in Illinois, where solar and other systems are being integrated to increase resiliency.[101] Renewable energy for deployed military units is seen as advantageous owing to the historic poor performance of diesel generators, which have an expected probability of performance of 80 percent at initial start and reducing after that with extended operations[102] and with the challenges associated with deploying to areas with extensive lack of infrastructure.[103]

Finding 42: DER based on renewable sources, such as wind and solar power, has become a viable technology for deployed microgrids.

Finding 43: DER at the tactical edge have been in the form of diesel generators, batteries, and other forms of local electric power generation. The use of renewable energy sources such as solar, wind, or thermal has been limited owing to the cost of deployment and the fact that they are generally not "hardened" against physical damage during conflict.

Innovative Storage Concepts and Resiliency

Beyond DER innovations, there is potential for innovative approaches to using electric vehicles for storage and reuse of generated power at the tactical edge. DoD is in the process of electrifying its nontactical fleet of vehicles[104] and the U.S. government recently committed to an all-electric fleet of vehicles,[105] making the

[100] See Federal Emergency Management Agency, 2020, "Integrated Sustainability into Recovery," July 22, https://www.fema.gov/emergency-managers/national-preparedness/frameworks/community-recovery-management-toolkit/recovery-planning/integrating-sustainability.

[101] See Office of Energy Efficiency and Renewable Energy, 2020, "2020 Assisting Federal Facilities with Energy Conservation Technologies (AFFECT) Federal Agency Call Funding Recipients," https://www.energy.gov/eere/femp/2020-assisting-federal-facilities-energy-conservation-technologies-affect-federal-agency.

[102] See NASEM, 2020, *Energy Challenges and Opportunities for Future Data-Driven Operations in the United States Air Force: Proceedings of a Workshop—in Brief*, The National Academies Press, Washington, DC, https://doi.org/10.17226/25872.

[103] See V. Miyagi, 1996, "National Guard in Disaster Relief Operations—Hurricane Iniki (6 September–6 November 1992)—A Case Study," University of Pittsburgh, March 25, https://apps.dtic.mil/dtic/tr/fulltext/u2/a310669.pdf.

[104] See C. Marnay et al., 2013, "Los Angeles Air Force Base Vehicle to Grid Pilot Project," Lawrence Berkeley National Laboratory, https://eta-publications.lbl.gov/sites/default/files/lbnl-6154e.pdf.

[105] See R. Meyer, 2021, "The Weekly Planet: Why Biden Is Buying 645,000 New Cars," *The Atlantic*, January 26, https://www.theatlantic.com/science/archive/2021/01/weekly-planet-why-biden-is-buying-645000-new-cars/617828/.

concept of vehicle-to-grid (V2G)[106] power sharing potential an interesting option to explore. In the V2G concept, battery-equipped vehicles are used for power storage when not in use, which enables the potential for using those batteries as a source of energy for other equipment. A V2G solution can assist in bulk energy storage (particularly from deployed renewable energy generation capabilities), power frequency and fluctuation regulation, and holding operational reserves. Advances in stable large batteries, such as the Tesla PowerWall, can also be part of this potential solution space.

Resiliency in power supplies at the tactical edge, as well as any other contested or compromised location, is a critical component for continued operational capability. This may include concepts such as isolating microgrids from each other or creating self-sufficient microgrids as required on emergency bases. The reliance on traditional energy sources, such as diesel generators, can imbue vulnerabilities into the system that can be ameliorated with alternative energy sourcing and storage. Having multiple energy sources with versatile storage capabilities can be an advantage.[107]

There are several ways to think about increasing the resiliency of energy systems in order to minimize effects from direct or indirect attacks, including those resulting from natural phenomena such as weather. One of the first options is to harden the system, simply to minimize effects. How the energy systems at the tactical edge can be hardened is an interesting challenge, because by definition the systems must be deployable, which implies that they are movable, relatively lightweight, and potentially stand-alone. There has been some research into replacing petroleum-based fuels with alternatives, such as liquefied natural gas (LNG) or batteries, which reduces the size and weight of the energy component while improving reliability of the system.[108]

Another way to improve resiliency is to design systems that can be quickly restored following outages or systems that can react to and isolate the effects of attacks, through a self-aware triage capacity. In other words, to design systems

[106] See D. Steward, 2021, "Critical Elements of Vehicle-to-Grid (V2G) Economics," National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy17osti/69017.pdf; W. Kempton and J. Tomić, 2004, "Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large Scale Renewable Energy," University of Delaware, November 12, http://www1.udel.edu/V2G/KempTom-V2G-Implementation05.PDF.

[107] See National Renewable Energy Laboratory, 2018, "Valuing the Resilience Provided by Solar and Battery Energy Storage Systems," March, https://www.energy.gov/sites/prod/files/2018/03/f49/Valuing-Resilience.pdf.

[108] See Conversations with AFRL on October 2020, Appendix B.

that are self-aware to the point where they can react to insults or attacks by taking themselves off-line in order to protect the rest of the system.[109]

Innovation in storage and reuse of energy is another way to improve resiliency. For example, enlisting unused capabilities, such as the batteries in dormant vehicles, as storage devices for generated electricity, can create a significant alternative bank of energy resources. The V2G concept, discussed previously, is an example of such a solution.[110] Such innovative approaches make the most out of the components onsite, thereby augmenting conventional capabilities and increasing the resiliency of power systems.

Finding 44: Innovating integration of multiple-source energy generation and storage capability can increase resiliency at the tactical edge.

Finding 45: The increasing use of electric vehicles combined with deployed energy generation systems creates the potential for the innovative system integration of those two elements into a V2G capability.

POTENTIAL THREATS

Throughout the history of competition between adversaries, energy sources have been among the preferred targets: deny energy to your adversary and they lose some or all ability to operate. Therefore, understanding the types and potential of threats to energy sources throughout the supply chain is important.

The Threat Ecosystem

Threats come in many flavors, including those yet to be imagined. When considering the ecosystem of problems that might arise with regard to the availability of energy at the tactical edge to power data-driven operations, one must consider all aspects of how energy is made available. There are two particular dimensions that bear analysis: the supply chain for energy and the system of systems that manage the energy usage at the tactical edge. The supply chain of energy includes the encapsulation of energy into a transportable medium, the transportation of the stored energy, the receipt of the energy, and the integration of the energy into the tactical-edge environment. Figure 2.3 shows a generalized view of the energy

[109] See B. Carrier, 2019, "Incident Response KPIs: SPEED Is Critical. Here Are Five Reasons Why," Cyber Triage, April 9, https://www.cybertriage.com/2019/incident-response-kpis-time-is-critical-here-are-five-reasons-why/; J. James and M. Koopmans, 2013, Automated network triage, *Digital Investigation* 10(2):129–137.

[110] See University of Delaware, 2021, "What Is V2G?" http://www1.udel.edu/V2G/.

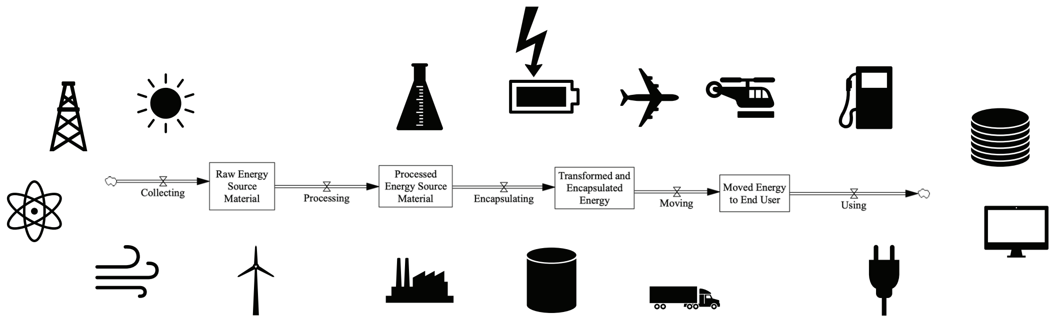

FIGURE 2.3 A generalized view of the energy supply chain.

supply chain in more detail. The management of energy use at the tactical edge includes the systems for converting stored energy to usable energy, the infrastructure through which energy flows from source to user, the administration of scarce resources, and the communications of energy requirements for both future and current operations.

Transforming a source of energy into a usable form of energy is an important first step in the supply chain. Nonrenewable sources, such as coal or oil, can be extracted from various sources, such as mines or underground reservoirs, but are not readily usable without processing. In this process, impurities are removed, and the product is refined to a usable state for its intended purpose. Energy from renewable sources, such as wind and solar, must be captured and then transformed into storable energy, such as in batteries, stored water, or molten salt. Threats to energy supplies during these transformation processes include both physical and logical attacks on the processes. It is unlikely that nonrenewable sources would ever be processed and transformed at or near the tactical edge, so this is not a primary consideration for those types of energy sources. For example, drilling for oil requires significant infrastructure, so it is unlikely that an oil extraction and refining capability would ever be associated with tactical deployments. A possible exception could be small nuclear generators, given the extraction and refinement of the nuclear energy prior to the deployment of the small nuclear generators. However, for renewable energy, it is quite likely that collection, processing, and transformation could be near or at the tactical edge.

Moving energy, once it has been transformed into storable energy, is necessary in order to get it to the end user. When the energy is in transit, it is a likely target: if energy can be denied to an end user, it cannot be used. Moving nonrenewable energy to end users, the "last mile," is a recognized challenge. While the security of supply convoys has always been a priority, studies recently have established "a strong relationship between fuel consumption and casualty rates owing to fuel and water convoy protection."[111] It follows, therefore, that reducing the dependency on energy supply convoys or shortening the distance between energy source and energy use may have some benefits in terms of reducing casualty rates. On the other hand, exposing the energy source and processing systems to attack also has drawbacks in that if the collection and processing mechanisms are destroyed, then all energy from that source is denied. Last, what has not been seriously contemplated is the potential scale of the distributed energy need and how to distribute, in a potentially clandestine manner, energy across the battlefield in tiny packets.

Finding 46: The transportation of energy to the tactical edge is a recognized target for adversaries.

Receiving and integrating energy into end user systems can present some challenges as well. Energy sources that are highly volatile require special handling and use. Lithium-ion batteries, for example, can explode under certain storage environments as well as when subjected to shocks. For example, there have been "several incidents where Tesla batteries appeared to spontaneously burst into flames—sometimes while driving, other times while the car was parked."[112] The volatility of hydrocarbon fuel sources is well known and requires special storage.

Attacks on the energy supply and use can stem from physical attack, such as explosives, or from logical attacks, such as compromising control systems. Malicious software is regularly implicated in battery life reduction in handheld devices, such as smart phones, and could in the future be specifically designed to drain energy from such systems.[113] The vulnerability of systems to attack varies at each stage in the system and is limited only by the limitations of the adversary. Another attack vector—a compromise of the technology supply system—was used in conjunction with the SolarWinds incident in late 2020.[114] The technology supply chain is different from the energy supply chain discussed above. Rather than disrupting

[111] See Army Technology, 2020, "Casualty Costs of Fuel and Water Resupply Convoys in Afghanistan and Iraq," February 7, https://www.army-technology.com/features/feature77200/.

[112] See R. Mitchell, 2019, "Federal Safety Agency Launches Probe of Tesla Battery Fires," *Los Angeles Times*, November 1, https://www.latimes.com/business/story/2019-11-01/federal-safety-agency-launches-investigation-of-tesla-battery-fires.

[113] See I. Morris, 2018, "Android Virus May Be Draining Your Battery and You Should Remove it NOW," *Mirror*, December 17, https://www.mirror.co.uk/tech/android-virus-draining-your-battery-13744925; D. Riley, 2019, "New Android Malware Drains Batteries and Uses Data in Ad Fraud Scam," Silicon Angle, February 21, https://siliconangle.com/2019/02/21/new-android-malware-drains-batteries-uses-data-ad-fraud-scam/.

[114] See FireEye, 2020, "Highly Evasive Attacker Leverages SolarWinds Supply Chain to Compromise Multiple Global Victims with SUNBURST Backdoor," December 13, https://www.fireeye.com/blog/threat-research/2020/12/evasive-attacker-leverages-solarwinds-supply-chain-compromises-with-sunburst-backdoor.html.

parts of the flow of energy, an attacker that can successfully compromise a technical system used widely by energy managers could potentially disrupt energy flow. In the SolarWinds incident, tens of thousands of businesses were impacted when updates to the Orion system (a popular network and asset management tool) contained hidden malicious code that gave the attackers virtually unrestricted access to the victims' networks.

Cyberattacks on Energy Grid Operations

Availability of commercial power has not traditionally been a concern for CONUS installations. Utilities are regulated at the state and federal level and must adhere to reliability standards that ensure near 100 percent availability. While outages caused by natural events (weather, seismic activity, forest fires, etc.) are infrequent, they are not rare. Weather and seasonal impacts can often be anticipated and planned for. A different type of outage—mandatory "rolling blackouts" as seen in California in 2020[115]—will be a factor in planning for future commercial power availability. Other factors such as policies that reduce or eliminate electricity generation by fossil or nuclear fuels may also reduce available commercial power. Renewable energy (wind, solar, etc.) may not provide the steady base load of commercial power needed by military installations.

Fortunately, there have been no cyberattacks on the North American electric grid that resulted in a loss of power or loss of control. All grid operators are required by regulation to report any cyber incident that impacts their operations, and over the past several years there have been very few reports of cyberattacks. However, two incidents are worth noting.

In 2019, a control center in the western part of the United States lost communications with several remote power generation sites. The loss was intermittent, lasting a few minutes before communications were restored, then failing again for a few minutes. An investigation revealed that the utility's Internet-facing firewalls were rebooting in response to malicious actors attempting to exploit a known vulnerability in that specific type of firewall. Patching the firewalls with updated software corrected the issue. While the generation and transmission of electricity was not disrupted, the utility did not have full control over its assets for about 10 hours. There is no evidence that this incident was a targeted attack, and in fact the attackers may have been scanning the Internet looking for vulnerable firewalls

[115] See J.D. Morris, 2020, "PG&E Error at Power Plant May Help Explain California's Rolling Blackouts," *San Francisco Chronicle*, September 14, https://www.sfchronicle.com/business/article/PG-E-error-at-power-plant-may-help-explain-15567028.php; PG&E, 2021, "Learn About Public Safety Power Shutoff (PSPS) Events," https://www.pge.com/en_US/residential/outages/public-safety-power-shuttoff/learn-about-psps.page.

and were unaware that they had successfully degraded the operations of an electric utility.

In 2015, Ukraine suffered distribution outages resulting from a successful cyberattack. Three power distribution substations were disabled via unauthorized remote access into a utility control center. An extensive investigation by U.S. and Ukrainian experts revealed that the attackers had successfully obtained usernames and passwords of the utility's employees 6 months prior to the attack via phishing e-mails. A second similar attack on parts of Ukraine's electrical grid occurred in 2016. In 2020, the U.S. government publicly identified the attackers as members of the Russian military.

The electric grid functions at three main layers—generation, transmission, and distribution. Disruptions in any of these layers can cause loss of power to military installations and other customers. Historically, the most frequent causes of power disruptions at the generation and transmission layers are related to weather or natural events. At the distribution level, an outage is more likely to be caused by either lightning or animals such as squirrels, birds, or snakes getting in the wires and causing a short, which trips a breaker. Cyberattacks against the grid are a constant threat, but to date the number of successful attacks that resulted in power loss to a customer are exceptionally low.

Finding 47: The reality of cyberattacks against energy infrastructure is that the number and severity of attacks are growing. Even if not aimed directly at the energy infrastructure, the effects of a cyberattack may affect it adversely.

3

Recommendations

SUMMARY LIST OF FINDINGS

The following findings and conclusions are used as the basis for the recommendations that follow. While each of these findings is derived from different analyses, they form the basis for multiple recommendations. These findings are taken directly from the discussion in Chapter 2 and are replicated here for the reader's convenience. For contextual discussion, please refer to the appropriate section.

Finding 1: The explosion of data creation, sharing, and use, including data analytics to support near-real-time decision making, will drive an increase in demand for energy.

Finding 2: The increase in demand for energy will influence the energy supply chain and accompanying logistics.

Finding 3: Cloud computing enables highly distributed and mobile information technology (IT) that is very powerful.

Finding 4: Back-end data centers require an enormous amount of energy, are fixed sites, and are potentially a target during wartime, both physically and virtually.

Finding 5: The integration of smart devices into the tactical edge is resulting in a very large increase in data generated at the tactical edge. As the amount of data being produced increases, the bandwidth required to transmit it back to off-premise computational centers will also increase.

Finding 6: Reliance on communications between tactical-edge centers and off-premise data centers is a vulnerability that could be exploited by an adversary.

Finding 7: The reversal of data flows to and from the tactical edge will force the movement of computational devices to the tactical edge, which will profoundly affect the energy supply chain requirements.

Finding 8: Movement of electricity to power data-driven operations at the tactical edge is a critical need that is more complicated than moving petroleum products.

Finding 9: Highly distributed small devices require energy to operate. The form of that energy can pose challenges unless the supply of energy is logistics-friendly.

Finding 10: Small devices spread across a deployed force may need to have separately powered transmission capabilities.

Finding 11: Storing energy in environmentally appropriate ways and keeping the devices operational through managing the environmental characteristics is a necessary and important analytical element.

Finding 12: Adversaries will target both data capabilities and communications, including the energy used to power such capabilities.

Finding 13: The energy needs for deployed forces operating within the Joint All-Domain Operations (JADO) construct will require solutions that are not likely to come from the commercial sector.

Finding 14: There will be energy needs associated with the proliferation of smart devices, artificial intelligence (AI) applications, and unmanned systems.

Finding 15: Portable energy technologies are advancing in capabilities from both commercial and government research and development (R&D) investments.

Finding 16: The initial deployment of a unit to the tactical edge will include energy that originates from the fixed installations, including energy from commercial energy provider partners.

Finding 17: Tactical-edge operational needs are driving the adoption of advanced computational capabilities, such as artificial intelligence (AI) and machine learning (ML). There are significant energy considerations associated with AI and ML that derive from the sensitivity of electronic components, the human-machine interface requirements, and the increased integration of sensors.

Finding 18: The energy needs associated with Joint All-Domain Operations (JADO) for tactical-edge data operations will be significant but are as of yet not totally understood.

Finding 19: Resource readiness is affected when the unit does not have the resources needed to execute the mission.

Finding 20: Capability readiness is affected when the unit does not have the data needed to support the full-spectrum mission.

Finding 21: In determining the requirements for new systems, be that combat or combat support, the U.S. Air Force (USAF) has not directed the need for energy minimization, energy consumption monitoring, or power generation as part of the system requirements.

Finding 22: Delivering energy to small units becomes a critical need for the overall system.

Finding 23: There is a trend toward optimizing energy efficiency of computing hardware by specializing to computing chip platforms tailored to neural network machine learning.

Finding 24: Mission-specific applications require further processor development to realize similar gains in reducing processing time and energy requirements.

Finding 25: Algorithm advances that can perform with less training data would have potential advantages both in the number of application areas where they could be deployed and in the potential energy requirements for training the algorithms.

Finding 26: Clever algorithm design can yield orders of magnitude of energy savings for computer energy consumption.

Finding 27: Operational constraints, such as communication capability and speed requirements for data-driven decisions, cause situations where advanced data processing must take place at the tactical edge. Deploying these types of capabilities to the tactical edge requires an architectural approach that optimizes design constraints to minimize power usage while delivering very fast processing on-premise.

Finding 28: Modifying how computational systems execute instructions can reduce energy usage of the system.

Finding 29: Reducing the energy used in computation also reduces the amount of heat generated, which not only affects the amount of energy needed for environmental controls but also affects the operational heat signature of deployed units.

Finding 30: There is a relationship between the software use profiles and the hardware architecture of small devices that affects battery life between charges.

Finding 31: Collecting rich data at the tactical edge means that some capability for big data processing exists at the tactical edge. Big data processing at the tactical edge requires adequate energy.

Finding 32: Dependence on conventional cloud computing solutions is not a viable solution for every tactical situation and therefore cannot be the sole solution to the data-driven operational problems. The development of portable data centers may provide an intermediate solution.

Finding 33: Variety in data types increases communication bandwidth needs, which increases energy needed for communication.

Finding 34: Data fusion that integrates many different types of data requires careful consideration and engineering to minimize energy used in the fusion process.

Finding 35: The data architecture may become a dominant factor in determining energy needs for data-driven operation.

Finding 36: A system-level requirements process for data acquisition, communications, and processing is likely required to achieve the desired data-driven operations capabilities.

Finding 37: There is a need for deployable personnel to set up, manage, maintain, and optimize the energy support for tactical-edge computational systems.

Finding 38: There is a shortage of trained personnel in electrical engineering and data center support operations.

Finding 39: Owing to the design needs of tactical-edge computational systems, it is likely that there will be a need for science and technology (S&T) investment.

Finding 40: The U.S. Air Force does not have the organic manpower to manage, lead, supervise, or solve the challenges associated with the design, operation, and management of energy consumption associated with data-driven operations.

Finding 41: There is a gap between current technologies and planned capabilities for collaborative data-driven decisions.

Finding 42: Distributed Energy Resources (DER) based on renewable sources, such as wind and solar power, have become a viable technology for deployed microgrids.

Finding 43: Distributed Energy Resources (DER) at the tactical edge have been in the form of diesel generators, batteries, and other forms of local electric power generation. The use of renewable energy sources such as solar, wind, or thermal has been limited owing to the cost of deployment and the fact that they are generally not "hardened" against physical damage during conflict.

Finding 44: Innovating integration of multiple-source energy generation and storage capability can increase resiliency at the tactical edge.

Finding 45: The increasing use of electric vehicles combined with deployed energy generation systems creates the potential for the innovative system integration of those two elements into a vehicle-to-grid (V2G) capability.

Finding 46: The transportation of energy to the tactical edge is a recognized target for adversaries.

Finding 47: The reality of cyberattacks against energy infrastructure is that the number and severity of attacks are growing. Even if not aimed directly at the energy infrastructure, the effects of a cyberattack may affect it adversely.

CONCLUSIONS

Based on the preceding findings, the committee reached additional conclusions separate from the actual findings and that informed the development of the recommendations.

The reliance on actionable data at the tactical edge combined with communications vulnerabilities will require that some capability for on-premise computational support be located at the tactical edge. The Air Force must design a forward-looking strategy for energy supply to the tactical edge computing devices that anticipates advances in technologies. As JADO planning continues, specific focus on energy needs for on-premise data support to deployed units and weapon systems must be considered. The energy needs for these devices should be included explicitly in requirement specifications and the deployment planning efforts. The need to power transmission capabilities associated with an abundance of small devices spread across deployed forces requires supply chain consideration over and above the power issues associated with the devices themselves.

Solutions to the energy supply challenges must be designed to reduce risk to the force and to the mission. The USAF should actively engage with start-ups, research groups, and others working on next-generation products and services that support the broad energy market in order to provide funding for solutions with protection built in. The programmatic challenges associated with designing, budgeting for, developing, acquiring, and operating robust and reliable systems with fewer exploitable vulnerabilities will require significant leadership engagement. Providing appropriate environmental controls for both energy storage and device usage is likely to require more energy, not less.

The ability of a unit to deploy to the tactical edge with appropriate energy supplies is dependent at deployment on the originating installation's ability to provide adequate deployable energy resources. Therefore, the energy needs analysis of the deployed unit at the tactical edge must include the initial energy deployment stock from the originating installation. The energy needs for tactical deployed AI and ML capabilities must be part of the logistics support planning for deployment. Opting for devices that use interchangeable power sources (e.g., battery size) or the same type of power source are two of many possible solutions.

Lack of adequate energy at the tactical edge to power computational and communications devices reduces the readiness of a unit to execute the mission. The use of alternative methods for energy delivery, such as using small unmanned aerial vehicle (UAVs) to deliver batteries to tactical edge units, should be considered and analyzed.

In assessing energy needs associated with tactical edge use of ML applications, data architecture plans must take into account the details of data flows, algorithms, and computing platforms. Energy-aware software algorithms will require rethinking both software algorithms and the hardware they are paired with. Currently, these two aspects of a computational system are largely decoupled. There has also been research focused on the application side of energy-aware numerical algorithms, particular centered on various forms of neural networks. The largest energy savings are realized when an integrated approach is used that includes the intended application, computer hardware, and software algorithm design.

The design of on-premise tactical-edge computational support is a challenge that is probably not met by off-the-shelf systems. There are variations in use cases that will impact requirements for systems. These variations in use cases, and the associated data and algorithmic processing requirements, will need to be enumerated. There is no obvious technical solution that would meet all conceivable use cases, particularly considering constraints associated with size, weight, power, ruggedness, and environmental resilience.

When planning information architectures for deployable units, the fit between small device hardware and software is an important part of energy needs analyses. Data architectures for tactical-edge computing should be a consideration for energy logistics analyses. An enterprise architecture should be developed that demonstrates the ability to support the planned needs.

There must be organic manpower within the Air Force to lead and manage the energy consumption that is needed for data-driven operations. The manpower needs for current and future energy support to the tactical-edge computing infrastructure require immediate analysis and planning in order to support future operational capabilities.

As the demand for more computer systems increases, DER may be a viable solution to meeting a military installation's future increasing electric power needs without increasing the amount of commercial power brought into the installation. Additional R&D is necessary to develop deployable DER capabilities beyond diesel generators and batteries that focus on renewable energy sources. The potential contribution of V2G approaches may assist in the management of available energy and operational reserves in deployed tactical-edge units. Diversifying energy generation and sources can contribute to resiliency consideration.

Reducing the number, signature, and exposure of energy supply convoys may have some benefits in terms of reducing casualty rates but does raise the issue of how energy will be provided to the tactical edge. Protecting the supply chain of energy in order to ensure adequate and on-demand energy availability at the tactical edge must include cybersecurity of the entire energy supply chain.

RECOMMENDATIONS

The committee consulted with technical experts in academia, government, and industry to identify challenges and issues associated with energy needs at the tactical edge as well as any potential for solutions to be considered in the future to help address these challenges. These include manpower, research, and expertise requirements needed for the future energy environment.

Energy Needs and Readiness

The core of these recommendations falls under the issue of how much energy will be needed for functionality of data processing and support to combat operations at the tactical edge. Fundamentally, the answer to this question is not currently comprehensively known. Plans are under way for advanced operational capabilities, including dynamic basing and JADO. It stands to reason that an obvious recommendation would be that the energy needs associated with data processing to support these missions be systematically analyzed and documented.

Recommendation 1: The U.S. Air Force must include energy needs in readiness reporting metrics for all weapons systems.

Concomitant to a comprehensive analysis of the energy needs associated with data processing at the tactical edge, it is important to understand the impacts of energy availability to these functions and what the impact would be to larger mission functions and weapons systems should the energy needs not be met, either at all or in a timely manner. The impact on operations associated with a temporary or sustained loss of power to data capabilities at the tactical edge must be understood, ranging from logistics to management to enabling effects on target. The ability of units to execute mission requirements can be greatly undermined by the inability to collect, process, analyze, and communicate critical data, thereby impacting both unit and mission readiness.

Recommendation 2: In the emerging data-driven operational environment, the U.S. Air Force resource and capability readiness assessments should include the availability of adequate and appropriate energy to data capabilities at the tactical edge.

Pull-the-Plug Exercises in Field Tests

Field exercises and training often assume that power is available at all times and for any demand requirement. This is also a standard assumption for communications systems, networks, and other support infrastructures. In a forward-deployed situation or in a contested battle space, it should be expected that power and other infrastructures will be targets of attack and therefore will not be continuously available or will be intermittent. Losses may stem from existing poor commercial infrastructure or enemy denial, lack of maintenance, lack of fuel, or human error. To simulate a realistic future environment, the USAF must include a "lights out" situation in training and exercises. These pull-the-plug exercises for tactical units and dynamic basing can reveal dependencies associated with expectations of data availability to the tactical-edge missions.

Recommendation 3: The U.S. Air Force should conduct pull-the-plug exercises for all realistic field exercises, and the effect on tactical-edge data expectations should be documented and relayed to the mission plan developers.

Recommendation 4: The results of pull-the-plug exercises on tactical-edge data capabilities should be used to revise and update mission readiness assessments.

Energy Needs as Explicit Requirements for All Systems

At present, energy needs for computational support, either on-premise or off-premise, are not defined in any major weapons system or mission profile. The use of both advanced information technology (IT) capabilities, such as AI, and massively distributed small devices and communications nodes, impact the energy needs at the tactical edge and have implications for the operational readiness of both missions and weapon systems. These energy needs must be defined as requirements for all missions and systems.

Recommendation 5: The U.S. Air Force should include energy needs associated with data expectations, both for support and internal to the mission or system, as explicit requirements for all missions and systems. The terms and conditions for contracts should include language that requires specific and complete descriptions of energy needs, types, and compatibility with logistics support.

Recommendation 6: The U.S. Air Force should explicitly address energy minimization, power consumption monitoring, and energy generation for the tactical-edge information environment, including all small devices and Internet of Things capabilities.

Manpower

The manpower skill sets needed to support the energy needs associated with the compute/store functions dispersed across the tactical, operational, and strategic level of warfare, is significant and is a barrier to the successful implementation of data-driven operations. The U.S. Air Force does not have the organic manpower to manage, lead, supervise, or solve the challenges of energy consumption tied to data-driven operations. Without the organic manpower that understands the entire spectrum of energy needs, the Air Force may never achieve a solution that strengthens its operational goals and instead will subject itself to substantial tactical, operational, and strategic risk. This manpower challenge includes recruiting, educating, training, optimizing the contractor/military blend, and incentives for education.

Recommendation 7: The U.S. Air Force should establish a manpower program to recruit, educate, assign, and train both military and civilian personnel to address energy challenges associated with data-driven operations.

Recommendation 8: The U.S. Air Force should incentivize energy engineers, particularly specialists such as antenna and radio frequency engineers.

Energy Resilience

The challenge of delivering energy to deployed forces is complicated by logistics, which tend to favor simplicity over complexity and large users over small users. At the tactical edge, small users may have a larger role in data collection, analysis, and communication under the JADO concepts, which would make them a dependency for the operational readiness of the larger units.

Recommendation 9: The U.S. Air Force should develop an economic benefit model exploring the utility, opportunity costs, risks, and benefits for different energy delivery modes.

The increasing use of electric-powered vehicles provides an opportunity to explore alternative methods of harvesting, storing, and reusing power.

Recommendation 10: The U.S. Air Force should explore the options associated with vehicle-to-grid (V2G) implementations in tactical field exercises.

Recommendation 11: The U.S. Air Force should consider the logistics tail for energy types and methods of delivery from the perspective of cost-efficiency of energy delivery and operational costs associated with single energy sourcing (e.g., using drones to deliver batteries to small users, as opposed to conventional fuel convoys).

Interoperability

While technology interoperability of deployed American forces in foreign countries is a well understood problem, these issues must be a specified consideration when developing or procuring new power sources or distribution systems. Ideally, new systems should automatically adapt and interoperate with a foreign environment with little or no mechanical switching or reconfiguration.

Recommendation 12: The U.S. Air Force should consider interoperability with foreign nation power systems and partner military forces (e.g., the North Atlantic Treaty Organization) when designing power systems (more than transformers), including standardization of certain elements and "plug and play" capability.

Research

As data-driven operations become more critical to operating concepts, the energy implications should be explicitly part of the planning process, including research on how to reduce energy usage, energy source exposure to hostile activity, and improving energy resiliency.

Recommendation 13: The U.S. Air Force should invest in future research in both product and process technologies associated with reducing energy usage, minimizing energy logistics risk, and improving energy resiliencies associated with data operations at the tactical edge.

Algorithms and application space to reduce energy consumption have been shown to be very promising. Research has been performed to create energy consumption-aware algorithms at the operating system level and the application level, and it appears that this line of work has great potential for reducing energy needs for computing systems operating at the tactical edge. While it is known that clever algorithm design can yield energy savings, there is still more research that needs to be performed to yield practical and deployed energy-aware algorithms. Needed research includes conversion of theoretical algorithms to practical deployable software. In addition, further research is needed on the role of approximation techniques to reduce energy usage while not compromising accuracy.

Recommendation 14: The U.S. Air Force should invest in research into using energy-aware algorithms in practical deployable software.

Recommendation 15: The U.S. Air Force should invest in the development of approximation techniques in software algorithms that are effective in energy reduction without compromising accuracy to unacceptable levels.

Recommendation 16: The U.S. Air Force should conduct experimental campaigns in realistic scenarios, including variety of systems and deployment characteristics of tactical-edge units, to guide the research directions and implementation potentials.

PRIORITIZATION

While all of the recommendations made are important, there are different time horizons associated with each. The committee has identified some that are most important for near-term consideration and others that are longer term needs. The prioritization of these recommendations is based on what can be done quickly, what can make a significant difference quickly, and what actions take longer to establish and get operational. For example, it takes a long time to establish a research effort: funding must be identified, research priorities must be agreed on, and relationships with researchers need to be established. Other things can happen much more quickly. For example, changing the readiness reporting can be done relatively quickly, as well as instituting pull-the-plug exercises.

- In the near term, Recommendation 1, Recommendation 2, Recommendation 3, Recommendation 4, Recommendation 5, Recommendation 8, and Recommendation 16 are priorities.
- The recommendations that should be mid-term priorities are Recommendation 7, Recommendation 6, Recommendation 9, Recommendation 10, Recommendation 11, and Recommendation 12.
- In the long term, Recommendation 13, Recommendation 14, and Recommendation 15 should be prioritized.

CONCLUDING THOUGHTS

The data infrastructure is evolving so quickly and being integrated so tightly in so many aspects of warfighting operations that it is of an importance equivalent to a major weapon system. But it is infinitely more complex than a single major weapon system. Small issues, such as energy supply to small handheld devices at the tactical edge, have the potential to serve as single points of failure with outsized consequences to overall capability. Early consideration of the entirety of the system and interactions can pay great benefits in the long run.

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Appendixes

A

Statement of Task

The Air Force Studies Board at the National Academies of Sciences, Engineering, and Medicine will establish an ad hoc committee to investigate energy challenges and opportunities for future data-driven operations in the U.S. Air Force (USAF).

The committee will develop a report that will:

1. Investigate the current state of Air Force planning, research and development, and expectations related to energy usage for military operations in the 2030 time frame.
2. Investigate potential threats to energy assurance and access based on recent events and assumptions of future energy dependencies that should inform Air Force/government planning for energy generation, storage, and use.
3. Investigate and describe current research and state of the art in energy efficient computation including hardware, software, and big data.
4. Investigate and describe the energy needs for advanced weapons platforms including static infrastructure that provides support to machine learning, artificial intelligence, and integrated operations.
5. Recommend manpower, research, and expertise requirements needed for the future energy environment.

The committee will also plan and convene a multiday workshop to inform its deliberations about what steps and plans the USAF is taking and/or should be considering now to successfully develop, deploy, and sustain the weapons systems needed to compete in an emerging information-rich environment. The workshop will investigate energy demands for weapons systems from the airbase to the battle space, including information requirements and needs associated with capture, curation, storage, exploitation, and transmission of energy to enable the deployment and operation of data-reliant systems.

B

Meeting Agendas

WORKSHOP: APRIL 27–29, 2020

Day One—April 27, 2020

1000–1030 ET	Introduction and Opening Remarks: Dr. Julie Ryan, Committee Chair
1030–1115 ET	Current Air Force Activities: Maj. Mary Kuconis, A2/6, and Other A2/6 Participants
1115–1200 ET	Current Air Force Activities: Lt. Col. Will Woodward, Deputy Chief, Innovative Solutions, Air Force Warfighting Integration Capability (AFWIC)
1200–1215 ET	Break
1215–1300 ET	Speaker: Mr. Mark Correll, Deputy Assistant Secretary of the Air Force for Environment, Safety, and Infrastructure (SAF/IEE)
1300–1345 ET	Lunch Break
1345–1430 ET	Speaker: Mr. Tim Tetreault, Program Manager for Energy and Water, Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP)
1430–1515 ET	Speaker: Prof. Willett Kempton, University of Delaware, "Impact of Changing Energy Resource Mix on the Power Grid"
1515–1530 ET	Break

1530–1615 ET	Speaker: Prof. Eric Wachsman, University of Maryland, "Electrochemical Energy Conversion and Storage Devices"
1615–1700 ET	Speaker: Mr. Asim Hussain, Bloom Energy, "Exploring Power Security with Microgrids"
1700–1730 ET	Discussion and Day 1 Wrap-Up
1730 ET	Adjourn

Day Two—April 28, 2020

1000–1030 ET	Introduction, Recap of Day 1, and Discussion
1030–1115 ET	Speaker: Dr. Jill Crisman, Technical Director for Artificial Intelligence, Office of the Undersecretary of Defense—Research and Engineering
1115–1200 ET	Speaker: Gen. Paul Kern, U.S. Army (Retired)
1200–1215 ET	Break
1215–1300 ET	Speaker: Mr. James Murphy, Senior Systems Engineer, Idaho National Laboratory, and Mr. Chris Dieckman, Systems Engineering Lead, Idaho National Laboratory
1300–1345 ET	Lunch Break
1345–1430 ET	Speaker: Dr. Mark Linderman, Senior Scientist, Command and Control Decision Support, Information Directorate, Air Force Research Laboratory, Rome, NY
1430–1515 ET	Speaker: Dr. Anu Narayanan, RAND Corporation
1515–1530 ET	Break
1530–1600 ET	Speaker: Prof. Saibal Mukhopadhyay, Georgia Institute of Technology
1600–1630 ET	Speaker: Prof. Carole-Jean Wu, Arizona State University
1630–1700 ET	Speaker: Prof. Sherief Reda, Brown University
1700–1730 ET	Discussion and Day 2 Wrap-Up
1730 ET	Adjourn

Day Three—April 29, 2020

1000–1030 ET	Discussion and Day 2 Recap
1030–1115 ET	Speaker: Col. Matt Benigni, JSOC
1115–1200 ET	Speakers: Dr. Nikhil Krishnan, C3.ai Group Vice President, Products, and Mr. Udit Garg, C3.ai Senior Director, Products
1200–1215 ET	Break
1215–1300 ET	Speaker: Mr. Anoop Mavath, Amazon Web Services
1300–1345 ET	Lunch Break

1345–1415 ET	Speaker: Mr. Marty Edwards, Vice President Operational Technology Security, Tenable
1415–1445 ET	Speaker: Mr. Sam Chanoski, Director, Intelligence, Electricity Information Sharing, and Analysis Center, North American Electric Reliability Corporation
1445–1515 ET	Speaker: Mr. Perry Pederson, Technical Advisor for Embedded and ICS Security, Pacific Northwest National Laboratory
1515–1530 ET	Break
1530–1600 ET	Speaker: Mr. Ernie Hayden, Founder, 443 Consulting
1600–1630 ET	Speaker: Mr. Chris Sistrunk, Technical Manager ICS/PT, FireEye
1630–1715 ET	Discussion and Workshop Wrap-Up
1715 ET	Adjourn

DATA GATHERING SESSION #1

June 3, 2020

1400 ET	Welcome and Introductions
1405–1500 ET	Speaker: Col. Drew Cukor, USMC, Chief, Algorithmic Cross Function Team, ISR Operations Directorate, Offices of the Undersecretary of Defense for Intelligence
1500–1545 ET	Speaker: Dr. Jordan Eccles, SAF/IEN Data Collection/Analysis Lead
1545–1600 ET	Break
1600–1630 ET	Sponsor's Remarks and Discussion: Mr. Ed Oshiba, Director of Resource Integration, Deputy Chief of Staff for Logistics, Engineering, and Force Protection, HQ USAF
1630–1730 ET	Committee Discussion: Report Scope, Future Meeting Dates

DATA GATHERING SESSION #2

June 24, 2020

1500 ET	Welcome and Introductions
1505–1600 ET	Speaker: Mr. Jeff Stanley, Former Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering (SAF/AQR), Original Project Sponsor
1600–1630 ET	Committee Discussion

DATA GATHERING SESSION #3

July 1, 2020

1500 ET	Welcome and Introductions
1505–1600 ET	Speaker: Mr. Frank Konieczny, Air Force Chief Technology Officer, Office of the Deputy Chief Information Officer, Office of the Secretary of the Air Force, “5G Experimentation and 5G at the Edge”
1600–1630 ET	Committee Discussion

DATA GATHERING SESSION #4

September 9, 2020

1500–1600 ET	Speaker: Maj. Aaron Stone, USMC, “Expeditionary Energy and Energy at the Tactical Edge”
1600–1700 ET	Committee Planning/Discussion

DATA GATHERING SESSION #5

September 29, 2020

1100–1200 ET	Speaker: Col. Doug “Cinco” DeMaio (Retired), Former Vice Commander of the Curtis E. Lemay Center for Doctrine Development
1200–1250 ET	Speaker: Dr. Douglas Doudas, Lead, Air Force Research Laboratory (AFRL) Energy Office, and Mr. Bud Boulter, Advanced Power Technology Office (AFRL/RXSC)
1250–1300 ET	Committee Discussion and Wrap-Up

DATA GATHERING SESSION #6

October 21, 2020

1500–1600 ET	Speaker: Dr. Douglas Dudis, Lead, AFRL Energy Office
1600–1700 ET	Committee Discussion and Report Planning; Review of Writing So Far; Making New Writing Assignments; Planning Future Meetings

C

Workshop Proceedings in Brief

ENERGY CHALLENGES AND OPPORTUNITIES FOR FUTURE DATA-DRIVEN OPERATIONS IN THE UNITED STATES AIR FORCE: PROCEEDINGS OF A WORKSHOP—IN BRIEF

On April 27–29, 2020, the National Academies of Sciences, Engineering, and Medicine's Air Force Studies Board (AFSB) convened a virtual workshop on U.S. Air Force (USAF) data-driven operations' energy challenges as part of a broader study focused on this topic. The goals of the study are as follows:

1. Investigate the current state of Air Force planning, research and development, and expectations related to energy usage for military operations in the 2030 time frame.
2. Investigate potential threats to energy assurance and access based on recent events and assumptions of future energy dependencies that should inform Air Force/government planning for energy generation, storage, and use.
3. Investigate and describe current research and state of the art in energy efficient computation including hardware, software, and big data.
4. Investigate and describe the energy needs for advanced weapons platforms, including static infrastructure, that provide support to machine learning, artificial intelligence, and integrated operations.
5. Recommend manpower, research, and expertise requirements needed for the future energy environment.

The data gathered at the workshop, focusing on items 1 to 4 above, will assist the committee in forming the recommendations for a final report that will address all five items. During the workshop, committee members heard from a wide range of subject experts from government, industry, and academia to inform them about what steps and plans the USAF is taking and/or should be considering now to successfully develop, deploy, and sustain the weapons systems needed to compete in an emerging information-rich environment. The information summarized here reflects the knowledge and opinions of individual workshop participants and should not be viewed as a consensus of the workshop participants, the AFSB, or the National Academies. The purpose of the workshop was to begin investigating energy demands for weapons systems, from the airbase to the battle space, including information requirements and needs associated with capture, curation, storage, exploitation, and transmission of energy to enable the deployment and operation of data reliant systems.

CURRENT AIR FORCE AND DEPARTMENT OF DEFENSE ACTIVITIES

The Joint All-Domain Command and Control (JADC2) Operational Environment

Dr. Julie Ryan (Committee Chair) convened the workshop and introduced the first speaker, Maj. Mary Kuconis (Intelligence, Surveillance, Reconnaissance and Cyber Effects Operations (A2/6)[1]). Kuconis discussed her office's current efforts in infrastructure modernization, especially in relation to Joint All-Domain Command and Control (JADC2) and the Advanced Battle Management System (ABMS).[2]

Kuconis explained that A2/6 contributes to ABMS by updating the information technology (IT) infrastructure in order to develop the sensing grid. Kuconis's team is focusing on research, development, and experiments to develop reference architectures, guidance, and policies in order to realize the vision of this sensing grid. Most of their time is currently spent on cataloging data sets, curating data, getting access to the right data, and merging data sets.

Her team is conducting cost-benefit analyses in terms of resources and operational benefits in determining which old infrastructures should be migrated into a digital cloud environment. Instead of hosting data servers on the premises, Kuconis

[1] U.S. Air Force, Sensitive Compartmented Information Security and Intelligence, Surveillance, and Reconnaissance Systems Cyber-security and Governance, Air Force Manual 14-403, September 3, 2019, https://fas.org/irp/doddir/usaf/afman14-403.pdf.

[2] M. Dwyer, "Making the Most of the Air Force's Investment in Joint All Domain Command and Control," Commentary, Center for Strategic and International Studies, March 6, 2020, https://www.csis.org/analysis/making-most-air-forces-investment-joint-all-domain-command-and-control.

said that moving to the cloud might be cheaper and easier to scale if need be. When that is not feasible, they are assessing the ability to move data centers onto forward-operating bases and data analytics tools onto aircraft for more immediate data analysis capabilities during field operations. They are also testing the feasibility of hybrid storage of data for larger data analytics loads, such as when assessing imagery data. Kuconis said that their data reference architecture will help manage large data sets in different data centers or on premise at the edge to get necessary data to operators who will use that data, because it is too complicated to keep all of the data in one big data center.

Air Force Warfighting Integration Capability (AFWIC)

Lt. Col. Charles Bris-Bois (Air Force Warfare Integration Capability (AFWIC)) discussed how AFWIC is starting to organize cross functionally across the USAF and developing the future USAF rapidly.[3] Bris-Bois mentioned how their innovative solutions division is researching and writing opportunity concepts on cutting-edge technologies from academia, industry, laboratories, and federally funded research and development centers to try and predict what is going to have an impact in 2030 and beyond. Those concepts are then given to groups at the Air Force Research Laboratory (AFRL) and rapid-incubation arms forces to develop those technologies for USAF applications.

When discussing a technology perspective to addressing energy needs of forward-operating bases, Bris-Bois said that one of the design choices could be to move more operations to long-range air superiority, so that fewer forward-operating bases will be needed. He noted that one challenge of operating dynamic bases on the edge is to ensure that it is more expensive for potential adversaries to fire missiles at that base than it is for the Department of Defense (DoD) to defend it. He pointed out that cost-effective base defense will require a lot of energy, and the USAF has not figured out exactly how to manage that electric power requirement yet. AFWIC is actively searching for alternative technologies that are going to allow the USAF to agilely push energy to the edge, store it, transport it, and manage that power in a way that is not easily attacked or disrupted by adversaries.

Dr. Dorothy Robyn (planning committee member) asked about the support for micro-nuclear technology within DoD, and Captain Brandon Hua (AFWIC) gave a vignette of how AFWIC is looking at bringing that power to the edge. Hua explained that AFWIC is giving more attention to zero-gamma isotopes, where the half-life is only 3 months and no gamma rays are emitted. In answer to a question from Robyn, Hua clarified that AFWIC is doing preliminary research on

[3] U.S. Air Force, Air Force Warfighting Integration Capability, "About Us," https://www.afwic.af.mil/About-Us/.

scientific possibilities on this technology, and it is not at the official research and development (R&D) phase or prototype phase yet. Robyn and Bris-Bois noted that other countries will need to be consulted when deploying nuclear technologies in forward-operating bases in those areas.

Air Force Installation Energy

Robyn introduced Mr. Mark Correll (Air Force Deputy Assistant Secretary for Environment, Safety, and Infrastructure (SAF/IEE)). Correll's office is in the process of completing an installation energy plan that will discuss how robust, resilient, redundant, responsive, and resourceful each installation is in managing its energy infrastructure.

When Robyn asked if data centers have more demanding needs for energy than other fixed installations, Correll said, "Yes, and no." The data center itself is susceptible because it needs very reliable power, such as properly working heating, ventilation, and air conditioning (HVAC) systems, in order to function. However, from a mission-assurance perspective, redundancy does not just mean how many generators are backing up one data center but also how many data centers are in the system. If one data center goes down, the mission can be transferred to another data center. Correll said that the system can take more risk if there is greater power resiliency.

In answer to a question from Dr. Subhash Singhal (planning committee member), Correll said that the USAF is only in the power generation business if it has to be; when there is an energy requirement on a base, a contractor or some other group is brought on board to supply the power that the USAF needs. In answer to a question from Robyn, Correll said that for the USAF to adopt more microgrids,[4] the operators have to be invested and really want it, because microgrids are difficult to install and manage.

Environmental Security Technology Certification Program (ESTCP) Installation Energy and Water

Mr. Tim Tetreault (Program Manager for Energy and Water, Strategic Environmental Research and Development Program (SERDP) & Environmental Security Technology Certification Program (ESTCP)[5]) began by saying how energy demands are increasing requirements both for reliability and quality across the board, specifically as it relates to data centers and other sensitive electronic devices.

[4] U.S. Department of Energy, "How Microgrids Work," June 17, 2014, https://www.energy.gov/articles/how-microgrids-work.

[5] See the Strategic Environmental Research and Development Program website at https://www.serdp-estcp.org/.

Tetrault said that there is pressure for the USAF to provide more energy infrastructure in the event that the commercial grid cannot supply USAF needs for extended periods of time.

Tetrault explained that ESTCP provides data and information for installation, management guidance, regulatory bodies, and technology developers. Every mission on every installation relies on electric power, either directly or indirectly, and is dependent on the reliable delivery of electric power. The ESTCP seeks to identify high-impact technologies and solutions, and then through the execution of demonstration projects, provide DoD stakeholders with a better understanding of critical issues and the benefits of specific solutions.

Microgrids are an area of active research, and the Tinker Air Force Base (AFB) experiment Correll mentioned was actually cofounded with ESTCP. Microgrids offer a networked design, so there is no one point of failure. They can also operate both in parallel with the grid and islanded to provide emergency backup power. Tetreault said that ESTCP is looking into integrated design approaches to reduce the complicated engineering and up-front costs that go into developing and installing microgrids. He completed his talk by emphasizing the importance of pull-the-plug exercises, where energy grids are tested in real life by shutting off different sections to verify how the systems will react in an emergency.

ENERGY SOURCES: NOW AND IN THE FUTURE

The Impact of Changing Energy Resource Mix on the Power Grid

Dr. Deniz Ozkan (planning committee member) introduced Prof. Willett Kempton (Department of Electrical and Computer Engineering, University of Delaware) as the Cofounder and Associate Director of the Center for Research in Wind (CReW) and who is affiliated with the College of Earth, Ocean, and Environment.

Kempton discussed the requirements for integrating variable generation[6] into the grid, such as the role of transmission, energy storage, and the need for large-scale resources. The scale is important because clean, low-cost resources that are too small will not have a significant impact on the overall system. Systems where all the power in a grid comes from one energy source are intermittent and unreliable, because even a very well run thermal plant has 5 percent unscheduled outages, Kempton said. And so, while the problem of power source reliability is not new, the problem of variable generation is new.

[6] National Renewable Energy Laboratory, "Variable Renewable Generation Can Provide Balancing Control to the Electric Power System," NREL/FS-5500-57820, September 2013, https://www.nrel.gov/docs/fy13osti/57820.pdf.

Large power sources that could contribute to solid grid systems, Kempton continued, include land-based and offshore near-surface winds, mid-altitude and high-altitude winds, ocean thermal gradients and ocean saline gradients, ocean currents, and rooftop solar. Some of these technologies are still being developed but will be applicable within the 2030 time frame, and some of these are only viable regionally, but where they do occur they have high potential (the steady winds of the Great Plains, and the steady sunlight of the Southwestern States, for instance). The implementation of these technologies in a grid system requires an understanding of how these sources fluctuate by season as well as accurate weather forecasting. Maj. Gen. John Ferrari (planning committee member) asked which technology would be the most mobile, and thus most available to forward-operating bases and field operations, and Kempton said that solar is the most mobile.

Electrochemical Energy Conversion and Storage Devices

Singhal introduced Prof. Eric Wachsman (University of Maryland) and the topic of electrochemical energy conversion and storage devices, such as fuel cells, batteries, and hydrogen. Wachsman studies solid ion-conducting materials and electrocatalysts and the development of solid-state batteries, fuel cells, ion transport membrane reactors, and gas sensors. Wachsman said that the high-temperature requirements of solid-oxide fuel cells puts constraints on the operation of the fuel cell—specifically, lifetime, reliability, and cost. In addition, most of the cost of the solid-oxide fuel cell is not the fuel itself, but its other components, so using simple stainless steel materials could lower the cost.

Wachsman said that with less insulation, there is lower mass, volume, and cost. The higher the operating temperature, the lower the thermal mismatch between when the fuel cell is started up and when it is operating. However, efficiency decreases as temperature increases. And so, if the fuel cell operates at a lower temperature, then the theoretical efficiency of the fuel cell increases.

When speaking to the importance of cooling in the goals of the study, Wachsman said that heat can be used in a variety of different ways, such as for an absorption chiller to provide cooling. Ferrari asked where the USAF should invest in this area, and Wachsman recommended the high-temperature capability of solid-state batteries or solid-oxide fuel cells that combine cooling and power, especially for the potential usage in data centers.

Exploring Power Security with Microgrids

Singhal introduced the next speaker, Mr. Asim Hussain (Vice President of Commercial Strategy and Customer Experience, Bloom Energy),[7] who discussed solid-oxide fuel-cell-based microgrids and the power security implications of microgrid technology. Bloom Energy was founded with a mission to make clean, reliable, and affordable energy. They work toward this using a solid-oxide fuel cell and by deploying Bloom Energy servers. They are currently deployed across four countries with about 450 megawatts in 10 U.S. states.

Hussain mentioned how Bloom Energy had a system in Delaware in 2012 during Hurricane Sandy that was powering a substation where they kept 60,000 electricity customers functioning in partnership with local utilities. He said they have tried to use solid-oxide fuel-cell technology as a building block and build a modular and scalable system that incorporates many capabilities into its model. Bloom Energy has different tiered solutions based on how much disruption the customers' missions can stand. At each site, they take the load curve projections to figure out how much total power they need to provide and what the peak power looks like, so they determine if they need to supplement with batteries—to essentially charge the batteries during the off-peak hours and dispatch them during the peak hours, such that the system follows the load curve as closely as possible. In a worst case scenario, they would provide a diesel or other type of backup generator. Hussain explained that there is an economy of scale during the installation phase based on the configuration that the customer wants versus what is the facility's reliability requirement.

ENERGY AND ARTIFICIAL INTELLIGENCE

Dr. Jill Crisman (Technical Director for Artificial Intelligence in the Office of the Undersecretary of Defense for Research and Engineering) spoke about artificial intelligence (AI), machine learning, and ubiquitous computing sensing. Crisman said that there is a growing realization in media and across the country that AI consumes a large amount of resources. She noted that determining how to stop data centers from using all of the world's electricity is a serious AI concern that should not be just a DoD problem.

Crisman explained an AI algorithm competition in which the winners release their data and code at the end, showing that the models they made could be trained on different data sets by removing just the top layer of their models. Crisman said that training just the top layers of an AI algorithm is more energy efficient because

[7] Bloom Energy, "Resiliency: AlwaysON Microgrids," https://www.bloomenergy.com/solutions/advanced-applications/microgrid.

it requires less data and uses less power during the training process. This allows users to deploy the same network to solve different problems, which is called transfer learning.

Crisman mentioned how helpful open AI is for training different data sets and finding existing available resources. She used AlphaGo as an example of a popular AI algorithm that consumes a lot of computing power in order to win at games of Go. Since 2012, the computing power needed to run new algorithms has been doubling about every 3.4 months.

Crisman also explained that one of the things that enabled AI was the exponential growth in actual data, because AI learns from the data. Data gathering is growing very rapidly around the world, and she projected that if DoD starts saving more and more of its data for training AI algorithms, a similar type of increase in data growth will be observed. Crisman said that commercial industry is handling this data inflow by keeping available the data that people access all the time, and archiving the data that is rarely accessed, taking it off of some of their cloud platforms, and potentially destroying data that is never really accessed.

PREVIOUS STUDIES

Defense Science Board Study on Energy Systems for Forward-Operating Bases

Gen. Paul Kern (U.S. Army, retired) was asked to speak because of the 2016 Defense Science Board (DSB) report[8] on which he was chair and which recommends that DoD consider micro-nuclear reactor technology to power forward-operating bases. Bris-Bois and Hua had previously mentioned they were researching micro-nuclear reactor capabilities for field operations in part due to this 2016 DSB report's recommendations.

Kern explained that the focus of that study was pointing out the energy demand for operations on those bases and discussing how to get the energy needed to meet those demands. He pointed out that 90 percent of the demand at the time of their study was for two things: fuel and water. He said that the demand for bandwidth was not addressed in the study, but it is clearly one of the demand structures that is growing. He projected that possible future engagements in near-peer-type battles will result in demands for energy in smaller locations. Those installments will consolidate for tactical operations, move on, and then redistribute again so they don't become targets themselves.

[8] Defense Science Board, Task Force on Energy Systems for Forward/Remote Operating Bases: Final Report, prepared for the Department of Defense, Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, 2016, https://dsb.cto.mil/reports/2010s/Energy_Systems_for_Forward_Remote_Operating_Bases.pdf.

Experience Evaluating USAF Mission Assurance and Resilience

Mr. James Murphy (Idaho National Laboratory) is a senior system engineer and chemist who focuses on model-based systems engineering technology development and decision analysis techniques for the Department of Energy (DOE) and the Department of Homeland Security (DHS). He is currently involved in the DEEPR (Decomposition for Energy Assurance and Electrical Power Resilience) project, which is a mission thread analysis technique with associated metrics to dynamically evaluate USAF's mission assurance effectiveness when subject to various installation threats that impact enabling assets and energy systems.

He was asked to demonstrate a useful approach to mission threat analysis with a focus on helping the USAF value resiliency and help it consider options for improving resiliency beyond the typical "adding a generator" approach that it had experienced so much. They found that the civil engineering, the communications squadron, and the installation support elements could all help Murphy's team to understand how energy got to the facilities and how those utilities then fed the facilities at the transformers. Through this information gathering, Murphy's team allowed these different groups to see how their work was tied to other teams' successes through seeing how the different energy-dependent elements of the facility were all connected.

This DEEPR model focused on task enablers in order to strengthen mission resilience. Task enablers are what enables the mission operators to perform the important things necessary to achieve outcomes, and the mission resilience was measured by trying to understand how well the facility can stand up to different threat-informed scenarios.

RAND Project Air Force Research for the USAF on Energy Resiliency

Dr. Anu Narayanan (Engineer, RAND) focuses her research on the intersection of critical infrastructure systems, particularly energy systems and national security. Narayanan has been the lead on RAND's extensive work for the USAF on installation energy issues ranging from valuing electric power resilience to strategies for deterring a tax on the power grid. She is an expert in probabilistic risk assessment scenarios and capabilities-based planning and systems analysis, and she recently finished a report on adaptive basing.

Narayanan described how RAND's Project Air Force (PAF)[9] group fits within the item 2 of the goals of the study, with its focus on potential threats to energy assurance and the implications of USAF's dependence on energy today and in the future. The USAF tasked RAND with coming up with a systematic and defensible

[9] RAND Corporation, "Making a Difference with the Air Force," https://www.rand.org/paf.html.

approach for deciding where and how much to spend on electric power resilience, and part of that is figuring out where there are problems and then deciding what to do about them. There is a need to be strategic about where these investments are made, because there is no such thing as risk elimination. The point is to have something defensible, she said.

PERVASIVE ADVANCED DATA USES

Dr. Mark Linderman (Senior Scientist for Command and Control Decision Support and the Information Directorate, AFRL) serves as the principal scientific authority and independent researcher in the field of command and control, and supporting technologies, including information sharing, data fusion, machine learning, performance optimization techniques, and systems resiliency.

Linderman noted that at the tactical edge, "we do not seem to measure things in gigawatts as often as we do in watts." Sometimes at the tactical edge, some small advantages can have outsized effects. Because the USAF burns about 2.5 billion gallons of gas a year, efforts to make missions more effective to reduce the number of times aircraft need to reengage a target or reassess some intelligence, surveillance, and reconnaissance can save a lot of money and resources. Deploying aircraft and other weapon and surveillance technologies around the globe is a logistical nightmare, which is why the USAF is the only service that can project power globally, although it is expensive and very energy intensive, in order to accomplish those missions.

He then discussed what his team has been doing over the years to try and get this high-performance computing up and into the field and how that generates revolutionary capability. Linderman explained that the constraints of these systems are their size, power, and weight loaded onto airborne systems and even more so into satellite-based systems. For his team, the generation of power is not as big a problem as getting rid of the heat that comes off that system, which prioritizes computational efficiency in order to get the best decision making in the shortest amount of time to prevent overheating.

ENERGY-EFFICIENT COMPUTATIONAL APPROACHES

Artificial Intelligence for Autonomous Systems: Algorithm and Hardware Perspectives

Dr. Mark Costello (planning committee member) said that the next group of speakers is focused on energy-efficient computational approaches, and for the next several speakers he wanted to explore basic computational algorithms that are designed for energy efficiency, try to understand what the state of the art is in this area, and then discuss the potential of future research. Costello introduced Dr. Saibal Mukhopadhyay (Professor, School of Electrical and Computer Engineering, Georgia Institute of Technology), whose research is on low-power, variation-tolerant, and reliable very-large-scale integration (VLSI) systems, memory design for VLSI applications, and ultra-low-power and fault-tolerant nanoelectronics technology circuits and computing platforms.

Mukhopadhyay said that energy-efficient AI is a challenge that needs to be solved by looking at algorithms and hardware together. Resiliency is an important factor when you start porting this algorithm to the edge, which has a direct consequence in terms of energy efficiency. Making things resilient more often than not comes at the cost of energy and performance. He discussed the Defense Advanced Research Projects Agency's (DARPA's) ReImagine Program[10] and how his team is trying to make AI algorithms more computationally efficient, which includes making algorithms less complicated and reliant on less data inputs.

A Discussion with Carole-Jean Wu

Dr. Carole-Jean Wu (Associate Professor, School of Electrical Computer and Energy Engineering, Arizona State University; Research Scientist, Facebook AI Infrastructure Research Team) focuses on high-performance and energy-efficient computer architectures through hardware heterogeneity, energy harvesting techniques for emerging computing devices, and understanding inference at the edge. She mentioned working on the system infrastructure development challenges specifically for machine learning in the cloud. She described energy-efficient computation, including hardware, software, and big data.

She first discussed the energy challenges and opportunities from the angle of high performance and system design, and then mobile and edge deployment challenges and how this focuses on machine learning inference. Wu said that we need to pay more attention to advanced energy and cooling management solutions because of ultra-high-performance requirements coming from highly parallel heterogeneous computing systems. In addition to improving the systems, performance, and energy efficiency, we start to see large-scale long running programs such as machine learning training or applications in the high-performance computing domain to have significant environmental impact, Wu said.

[10] W. Mason, "Reconfigurable Imaging (ReImagine)," Defense Advanced Research Projects Agency, https://www.darpa.mil/ program/reconfigurable-imaging.

Embedded Systems for Data-Rich Processing

Dr. Sherief Reda (Professor, School of Engineering, Brown University) researches hardware systems with a focus on energy-efficient computing, embedded systems, design automation of integrated circuits, and computer architecture. Reda pointed out that we've seen a class of applications that rely on a lot of data in their processing, which includes signal and image processing, computer vision, deep neural network, and machine learning in general, and they're all characterized by massive amounts of data that need to be processed in order to get results.

Reda used the example of a missile traveling at supersonic speeds, whether you want to track it or you're tracking something from it. He noted that a difference in microseconds in processing could mean that you're off-target, which is why hardware time constraints are important in this context. He then mentioned that custom accelerators could be used, and they've been used in embedded Field Programmable Gate Arrays (FPGAs) or Application Specific Integrated Circuits (ASICs), and ASICs provide an additional energy improvement advantage over FPGAs at the expense of cost. Reda said that "when you couple approximations and embedded accelerators, you get high energy, more benefit than you would if you applied approximations in the central processing unit (CPU) or graphics processing unit (GPU)." He advised focusing on acceleration, approximation, and then software and hardware codesign to maximize the efficiency of the system.

DATA INFRASTRUCTURE ENERGY NEEDS

Energy and Remote AI Architecture

Maj. Gen. John Ferrari (planning committee member) introduced the next three speakers. Col. Matt Benigni (Joint Special Operations Command (JSOC)) uses big data at the edge, and JSOC is usually the group that implements future technologies on the field first, Ferrari said. Benigni talked about the tipping point happening on the battlefield, which is important because time horizons and projecting forward what the USAF might need is changing. Over the past 3 years, Benigni said that he traveled to a number of U.S.-deployed locations in order to work directly with operators, sometimes for extended amounts of time.

Benigni mentioned that he has observed the "flipping of the paradigm" this past year, in which the Internet of Things (IoT) is collecting more data than the systems can analyze. They collected more data within the tactical bubble than what's collected outside of it; the tactical bubble is the geographical space between the forward-operating base and the objective. This paradigm shift stresses USAF's architecture in that it will no longer have the ability to backhaul that volume of information in a timely manner.

A Discussion with Nikhil Krishnan and Udit Garg

C3.ai has positioned itself to use software and AI to manage the IoT at the edge, and the energy management team discussed how it's using its software and data to do energy management around the world to make better decisions. Ferrari said that Tom Siebel's (C3.ai founder's) *Digital Transformation* book[11] outlines the coming evolution in IoT technology, and introduced the speakers Dr. Nikhil Krishnan (Group Vice President, C3.ai) and Mr. Udit Garg (Senior Director, C3.ai).

Krishnan said that C3.ai provides a platform that abstracts away the complexity of the underlying cloud services, whether that is run on Amazon, Microsoft, or another cloud provider. They accomplish this through a model-driven architecture that uses conceptual domain models (C3 models) that allows developers and data scientists to operate on the business objects that they understand. Garg noted that IT infrastructure, data centers, and IoT devices are extremely important for DoD operations, and they are seeing this via the idea of digital transformation, digital tooling, and how digital applications are becoming increasingly mission critical. C3.ai uses AI to analyze USAF bases as though they were mini-cities to optimize energy management and operations. For instance, if the system does maximum conversion efficiency on the plant feeding an Air Force base, then the team can identify losses in the facility's heating and cooling network.

A Discussion with Anoop Mavath and Rob Nolan

Amazon Web Services (AWS) is a practitioner that deploys, manages, and decommissions data centers, and the effect of minimizing the electromagnetic, thermal, and visual footprint is important because force protection and mission protection is important to military operations. Mr. Anoop Mavath (Director of Infrastructure Products, AWS) and Mr. Rob Nolan (AWS) spoke about designing, deploying, operating, and decommissioning data center infrastructures. Ferrari noted that what's important on the battlefield is minimizing detection and maximizing protective measures.

Mavath began by saying he generally looks at data center design considerations under the premises of needing to operate remotely, such as on forward-operating bases mentioned in the study's goals. He discussed the requirements that need to be established before setting up a remote data center, such as mobility requirements, how fast it needs to be deployed, and how fast it needs to be decommissioned, especially since all data centers carry a lot of critical information. AWS has a

[11] T.M. Siebel, *Digital Transformation: Survive and Thrive in an Era of Mass Extinction*, Rosetta Books, New York, N.Y., 2019.

number of "plug and play" data center configurations that can be used at the edge, wherein front-end set-up costs, time, and personnel training can be minimized.

ENERGY SUPPLY CHAIN, INFRASTUCTURE, AND ECOSYSTEM ISSUES

A Discussion with Marty Edwards

Mr. Marc Sachs (planning committee member) introduced Mr. Marty Edwards (Vice President of Operational Technology Security, Tenable[12]) and a globally recognized operational technology and an industrial control system (ICS) expert. Edwards said that when he worked in homeland security, his team would conduct facility assessments, and the number one finding was improper, inappropriate, or inadequate segmentation of networks.

Through Tenable's asset identification and vulnerability management tools, his teams notice interconnections that customers did not even know existed. Tracking and managing everything that goes into a network is challenging, especially on a complex type of installation such as a military base. Edwards also explained Tenable's Vulnerability Priority Rating (VPR) mechanism that ingests threat feeds from a variety of providers in order to use machine learning around the threat environment.

A Discussion with Sam Chanoski

Mr. Sam Chanoski (Director of Intelligence, Information Sharing and Analysis Center) said he works with private-sector organizations to exchange and analyze all source intelligence in the context of the electric sector. He said that energy is injected into a system from resources that create or store energy, and he noted that the limiting factor in scaling energy is due to hydroelectric pump storage capacity, since batteries are useful but not as available at a utility scale. Furthermore, depending on the location of where energy is injected into the system, it flows into a complicated and dense network topology with different injection points from various resources with different operating capabilities.

Chanoski discussed how government and military facilities, because they do not want to ever experience outages, require a different design approach to combining outside-the-fence and inside-the-fence operations on an installation. Outside the fence refers to engineering with local utilities and construction plans, while inside the fence refers to energy storage, backup power, batteries, monitoring, awareness, and understanding of how these systems interact from a system of systems perspective on the installation's property. More stringent pre-contingency

[12] Tenable, Inc., "Our Vision," https://www.tenable.com/about-tenable/about-us.

operating criteria at the utilities will operate the bulk of the power system and its dense network as well.

Cyber Resilient Hardware Controller

Mr. Perry Pederson (Pacific Northwest National Laboratory) is a technical advisor and cybersecurity researcher in the development and execution of a national strategy to improve cybersecurity for the US critical infrastructure. Pederson spent his talk describing a project he is working on, in collaboration with colleagues at Idaho National Laboratory and Oak Ridge National Laboratory, which rethinks the concept of digital by trying to accomplish cyber-secure safety measures in microchips through hardware metrics rather than software malware adjustments. His prototype FPGA development board uses tools like Verilog, a hardware description language, to physically burn in deterministic behavior to chips that have advantages against bad-acting or corrupt software. "If you're printing your own logic you're almost baking the security in, and it's visible security," Pederson said.

Substation Physical Security Initiatives

Mr. Ernie Hayden (443 Consulting) was introduced as a highly experienced and seasoned technical consultant, author, speaker, strategist, and thought leader with extensive experience in the power utility industry with a background in informational security and industrial controls. Hayden spoke to the physical security threat assessment of facilities, such as direct attack, power-line damage, vandalism, and severe weather. He said that a utility has to do an initial risk assessment to identify whether a substation is a critical facility or not; how critical the facility is determines the standards for managing its physical security measures.

Electric Sector Threats

Mr. Chris Sistrunk (Technical Director, ICS/IoT Security Consulting Team, Mandiant, FireEye) was awarded the Energy Sector Security Professional of the Year distinction in 2014 and is a senior member of the Institute of Electrical and Electronics Engineers (IEEE). Sistrunk mentioned ICS security topics, electric sector threats and risks, and incident response and forensic assessments. He said that many things can threaten a system, such as old programs and platforms, data theft, and hacktivism.[13] He also discussed the case study of the blackout that occurred

[13] IT Pro Team, "What Is Hacktivism?," ITPro.co.uk, August 9, 2018, https://www.itpro.co.uk/hacking/30203/what-is-hacktivism.

during the 2013 Super Bowl, which was caused by relay misoperations.[14] Sistrunk said that there were some other contributing factors that caused that blackout, but the main reason was a defect in the design of that relay.

Sistrunk said that when his team is assessing facilities, they look at fences, tree cover, and storm drainage tendencies. He suggested that the USAF should consider where its substations are, what the threat environment is like, and what visibility might be needed on local power companies and the substation itself. This includes training personnel in physical security of facilities and looking for how a bad actor might exploit vulnerabilities. "You may have a gaping hole in your physical security, even though your cybersecurity may be top notch," Sistrunk stressed.

A Discussion with Art Conklin

Dr. Art Conklin's (Professor and Director, Center for Information Security Research and Education, College of Technology, University of Houston) research interests include the use of systems theory to explore information security, specifically in cyber-physical systems and critical infrastructures. Conklin said that science, engineering, and business are all reliant on technology, and each sector tries to manage technology in different ways. He explained that he looks at the management of technology from a systems perspective, such as assessing needs for electricity, communications, etc., on a base or for a utility and recognizing that these elements are all connected.

Conklin used an example from the response effort after Hurricane Ike hit Houston, when the city filed and successfully received over a billion dollars' worth of bond funding. Two weeks later, the financial collapse of 2008 happened, and had the hurricane been 2 weeks later, Conklin said, Houston would not have recovered from the hurricane without a federal intervention, because the bond market would have been unavailable. "It wasn't a matter of was the utility available, it wasn't a matter of was the hardware available, we had workers, but literally the financial markets," Conklin noted.

DISCUSSION AND CONCLUSION

When reflecting on the workshop's discussions with the other workshop participants, Ryan said that there is an uncertainty about the power needs for operations and how to logistically deliver that power to the edge. The USAF is conducting experiments and testing different technologies, and the logistics-under-attack issue

[14] North American Electric Reliability Corporation, Analysis of System Protection Misoperations, December 2015, https://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/2015_Analysis_of_System_Protection_Misoperations_Final.pdf.

impacts the agility of energy at the edge. The challenges discussed during the workshop included the following: the trade-offs between on premise systems and the cloud, back-end computing, computing on dedicated storage, data as a service, software as a service, and how to manage these elements. Ferrari stressed that if military operations are going to be data driven, then it is important to manage the movement of that data and the energy requirement for the chain of fiber, cellular, Wi-Fi, and satellites. Cell towers, fiber cables, etc., all need energy, and the movement and transmission of that data is important to the mission at the edge.

DISCLAIMER: The Proceedings of a Workshop—in Brief has been prepared by Catherine Puma as a factual summary of what occurred at the meeting. She was assisted by Ryan Murphy. The committee's role was limited to planning the event. The statements made are those of the individual workshop participants and do not necessarily represent the views of all participants, the planning committee, or the National Academies. This Proceedings of a Workshop—in Brief was reviewed in draft form by Mark Costello, Georgia Institute of Technology, and David Van Wie, Johns Hopkins University Applied Physics Laboratory, to ensure that it meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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Acronyms

AFRL	Air Force Research Laboratory
AFSB	Air Force Studies Board
AFWIC	Air Force Warfighting Integration Capability
AI	artificial intelligence
ASIC	application-specific integrated circuit
AVL	Adelson-Velsky and Landis
AWS	Amazon Web Services
C2	command and control
CONUS	continental United States
COVID-19	SARS-CoV-2
CPU	central processing unit
CReW	Center for Research in Wind
C-SWAP HPC	cost, size, weight, and power high-power computing
DARPA	Defense Advanced Research Projects Agency
DARPA STO	Defense Advanced Research Projects Agency Strategic Technology Office
DEEPR	Decomposition for Energy Assurance and Electrical Power Resilience
DER	Distributed Energy Resource(s)
DHS	Department of Homeland Security
DoD	Department of Defense

DOE	Department of Energy
DOI	digital object identifier
DSB	Defense Science Board
ENIAC	electronic numerical integrator computer
ESPC	Energy Savings Performance Contract
ESTCP	Environmental Security Technology Certification Program
FPGA	field-programmable gate array
GPU	graphics processing unit
HPC	high-power computing
HPEC	high-performance embedded computing
HVAC	heating, ventilation, and air conditioning
IC	intelligence community
ICS	industrial control system
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IT	information technology
JADC2	Joint All-Domain Command and Control
JADO	Joint All-Domain Operations
JSOC	Joint Special Operations Command
JTS-CND	Joint Task Force on Computer Network Defense
LLNL	Lawrence Livermore National Laboratory
LNG	liquefied natural gas
MET	mission-essential task
MIoT	Military Internet of Things
ML	machine learning
MUO	Make Use Of
NATO	North Atlantic Treaty Organization
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NPU	neural processing unit
NSCAI	National Security Commission on Artificial Intelligence

OCONUS	outside the continental United States
PC	personal computer
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RAM	random access memory
RF	radio frequency
RISC	Reduced Instruction Set Computer
S&T	science and technology
SAF/AQR	Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering
SAF/IEE	Deputy Assistant Secretary of the Air Force for Environment, Safety, and Infrastructure
SERDP	Strategic Environmental Research and Development Program
SOCOM	Special Operations Command
SWaP	size, weight, and power
TOPS	tera-operations per second
TPU	tensor processing unit
UAV	unmanned aerial vehicle
UESC	Utility Energy Service Contract
USAF	U.S. Air Force
US-CERT	U.S. Computer Emergency Response Team
V2G	vehicle-to-grid
VLSI	very-large-scale integration
VPR	Vulnerability Priority Rating
VPU	vision processing unit

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Committee Member Biographical Information

JULIE J.C.H. RYAN, *Chair,* is the chief executive officer at Wyndrose Technical Group. Dr. Ryan was previously professor for systems management at the National Defense University; a visiting scholar for the National Institute of Standards and Technology (NIST); and associate professor of engineering management and systems engineering, 2009–2016, and department chair, 2010–2012, at George Washington University. She holds a B.S. degree in humanities from the U.S. Air Force Academy, an M.L.S. in technology from Eastern Michigan University, and a D.Sc. in engineering management from George Washington University. Dr. Ryan began her career as an intelligence officer, serving the U.S. Air Force (USAF) and the U.S. Defense Intelligence Agency (DIA), working in a series of increasingly responsible positions throughout her distinguished career. Her areas of interest are in information security and information warfare research.

MARK F. COSTELLO is the William R.T. Oakes Professor and chair of the School of Aerospace Engineering at Georgia Institute of Technology (Georgia Tech), where he is responsible for leadership of the school, as well as all administration and financial management of the department. Previously, Dr. Costello was posted at the Tactical Technology Office at the Defense Advanced Research Projects Agency (DARPA), where he served as a program manager. Prior to joining DARPA, Dr. Costello served as the David Lewis Professor of Autonomy in the Schools of Aerospace Engineering and Mechanical Engineering at Georgia Tech, where he taught in the areas of dynamics, controls, and design. His research team is noted for creating innovative new technologies, such as robotic landing gear for rotorcraft, bleed air control of parafoils, and direct impact control of smart projectiles. This research has led to formation of start-up companies. He founded and serves as the CEO of Earthly Dynamics Corporation, a company that develops and fields new guided airdrop system technology. He also co-founded the Persimia Corporation, which provides Web-based environmental impact assessment analysis tools for wind energy system installations. Dr. Costello received his B.S. in aerospace engineering from Pennsylvania State University, and his M.S. and Ph.D. in aerospace engineering from Georgia Tech.

MAJ. GEN. JOHN FERARRI (retired) is currently chief administrative officer at QOMPLX, a start-up company focused on democratizing advanced data science methodologies and massively scalable analytics that until now have been restricted to only the largest corporations. Mr. Ferrari joined QOMPLX after a 32-year career in the U.S. Army, having retired as a Major General in 2019. Over the course of his military career, he ran business operations, implemented data analytics, and executed financial management activities within the Department of Defense (DoD). Mr. Ferrari's operational experiences include Operation Desert Storm, Operation Iraqi Freedom, and Operation Enduring Freedom. He has served in various U.S. Cavalry units, including the 2nd and 3rd Cavalry. Mr. Ferrari has extensive institutional experience, including Army Materiel Command, White Sands Missile Range, the Executive Office of the President, the Joint Staff, and the Army Staff. His last assignment in the Army was as the Director of Program Analysis and Evaluations, where he oversaw the strategic resources of the Army, as well as led the Army's operations research systems analysis functional area.

DENIZ OZKAN is the Americas Valuation lead at Shell New Energies Offshore Wind Team and is currently working on the Mayflower Offshore Wind Project in Massachusetts. Dr. Ozkan is an energy investment analysis expert with extensive technical knowledge. Before joining Shell, she was the director of analysis, research, and systems engineering at Atlantic Grid Development, an offshore transmission development project, where she was leading techno-economic studies, including system design optimization and investment analysis. Dr. Ozkan has a Ph.D. in engineering management/economics, finance, and cost engineering from George Washington University, where she taught engineering economy courses for 6 years. She has conducted more than 13 years of research in the fields of renewable energy, power markets, transmission planning, and integrated system analysis and written articles and technical reports on the integrated design of energy systems, including her dissertation, "Financial Analysis and Cost Optimization of Offshore Wind Energy Under Uncertainty and in Deregulated Power Markets."

MARCUS (MARC) SACHS is the chief security officer of Pattern Computer, a start-up in the machine learning (ML) and artificial intelligence (AI) field, where he is responsible for overall corporate security policy and strategy. Mr. Sachs is also a partner at RIDGE-LANE Limited Partners in the technology practice. Mr. Sachs retired from the U.S. Army after serving a distinguished 20-year career as a Corps of Engineers and Systems Automation Officer. His final assignment was with the DoD Joint Task Force on Computer Network Defense (JTF-CND), established in 1998 to defend the department's computer networks from foreign intrusions. Following his military retirement, Mr. Sachs was appointed by President George W. Bush to serve concurrently on the staff of the National Security Council and on the staff of the President's Critical Infrastructure Protection Board. Mr. Sachs later joined the National Cyber Security Division of the U.S. Department of Homeland Security (DHS) as the department's first Cyber Director, where he was responsible for developing the implementation plan for the National Strategy to Secure Cyberspace. While at the White House and DHS, he proposed and developed the concept and early design for the U.S. Computer Emergency Response Team (US-CERT). Since leaving military and public service, Mr. Sachs's private sector experience includes serving as the deputy director of SRI International's Computer Science Laboratory, as the vice president for national security policy at Verizon Communications, and as the senior vice president and chief security officer of the North American Electric Reliability Corporation, where he directed the rebuilding of the Electricity Information Sharing and Analysis Center (E-ISAC). Mr. Sachs was the director of the SysAdmin, Audit, Network, Security (SANS) Internet Storm Center from 2003 to 2010 and has co-authored several books on information security. He holds degrees in civil engineering, computer science, and technology commercialization and is a licensed professional engineer in the Commonwealth of Virginia.

MICHAEL SCHNEIDER is group leader in astronomy and astrophysics analytics at the Lawrence Livermore National Laboratory (LLNL). Dr. Schneider has more than 10 years of experience in the application of statistical and numerical methods to the analysis of large data sets. He wrote his Ph.D. thesis on simulation frameworks for the future Large Synoptic Survey Telescope (LSST) under the direction of the founding director of the project. Dr. Schneider moved to a postdoctoral position in the United Kingdom in 2008, working on simulations of galaxy formation on high-performance computing resources for application to the Pan-STARRS 1 sky survey. He then moved back to the United States in 2010 to start a science program in dark energy at LLNL targeted for the LSST. Over the past 9 years at LLNL, Dr. Schneider has built a new team at the laboratory in data analytics for astronomy. He now also leads a large interdisciplinary research team at LLNL focused on development of novel machine learning and quantum computing algorithms. Dr. Schneider has served on a variety of U.S. government agency review teams to help plan the next generation of data exploitation approaches for upcoming synoptic sky surveys. From 2015 to 2018, he led the Weak Gravitational Lensing working group in the LSST Dark Energy Science Collaboration. At LLNL, he now serves on the Data Science Institute Governing Council. Dr. Schneider earned his B.S. in physics from the University of Illinois, Urbana-Champaign, and his Ph.D. in physics from the University of California, Davis.

SUBHASH C. SINGHAL retired as a Battelle fellow and director of fuel cells at Pacific Northwest National Laboratory in 2013. From 2000 to 2013, Dr. Singhal provided senior technical, managerial, and commercialization leadership to the laboratory's extensive fuel cell and clean energy programs. Previously, he worked for more than 29 years at the Westinghouse Electric Corporation, initially as a scientist and later as manager of fuel cell technology. While at Westinghouse, which became part of Siemens, Dr. Singhal conducted and/or managed major research, development, and demonstration programs on advanced materials and energy systems, including steam and gas turbines, coal gasification, and fuel cells. From 1984 to 2000, as manager of fuel cell technology, he was responsible for the development of solid oxide fuel cells for stationary power generation. In this role, he led an internationally recognized group in fuel cell technology and brought these cells from a few-watt laboratory curiosity to fully integrated 200-kilowatt power generation systems. Dr. Singhal has authored 100 scientific publications, edited 21 books, received 13 patents, and given more than 340 plenary, keynote, and invited presentations worldwide. Dr. Singhal is the recognized world leader in solid oxide fuel cells for power generation. He has served on the advisory boards of the Department of Materials Science and Engineering at the University of Florida; Florida Institute for Sustainable Energy; Division of Materials Science and Engineering at Boston University; Materials Research Science and Engineering Center at the University of Maryland; Center on Nanostructuring for Efficient Energy Conversion at Stanford University; and the Fuel Cell Institute at the National University of Malaysia. Dr. Singhal is a member of the National Academy of Engineering; a founding member and past president of the Washington State Academy of Sciences; and a fellow of the American Ceramic Society, Electrochemical Society, ASM International, and American Association for the Advancement of Science.