Photovoltaic battery system developed by Office of Naval Research can provide continuous power to troops in field

U.S. Navy (John F. Williams)

Scalable Energy Networks

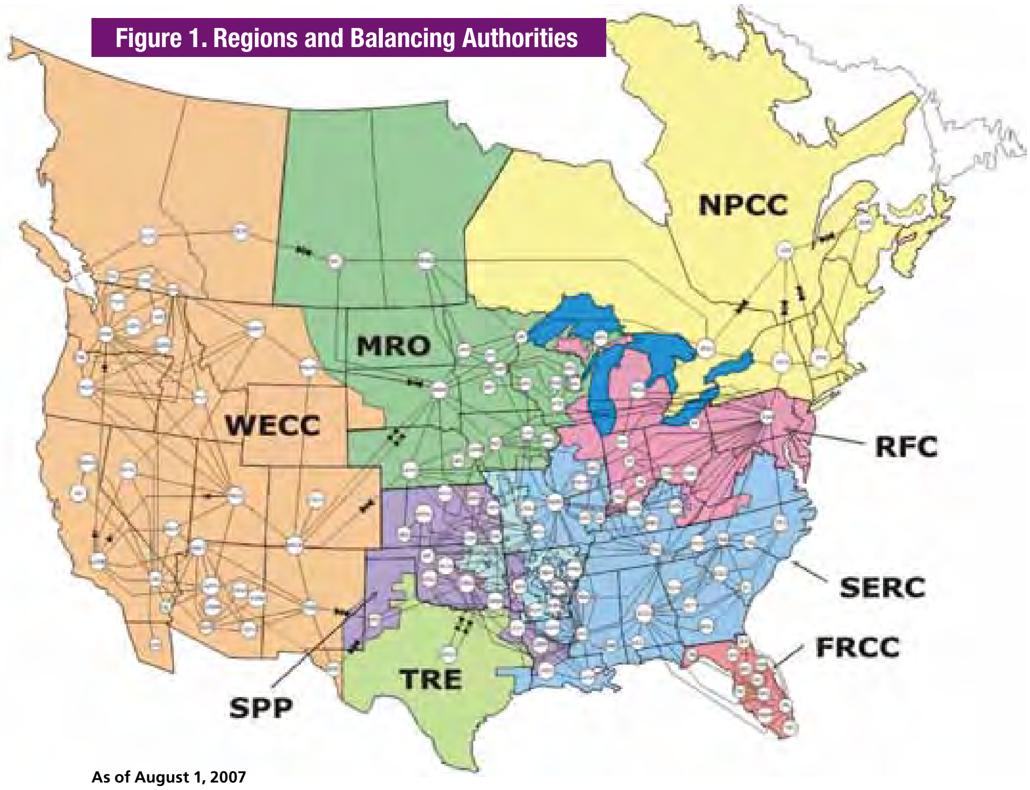
to Promote Energy Security

By PAUL E. ROEGE

In an age of fluctuating energy prices and environmental concerns, engineers and scientists are locked into a worldwide race to improve energy technologies. Through hard work and investment, these innovators are creating more efficient photovoltaic cells, responsive energy management software, and wireless energy transmission devices. Some of the greatest potential gains, however, remain to be harvested through energy system integration and networking, which ultimately will transform all forms of energy into a fungible commodity. Consider current challenges of converting energy and synchronizing sources with loads—for example, capturing solar energy to provide hot water and heat at night, or supplying transportation fuel. We need a paradigm shift that dissolves existing boundaries and enables us to manage energy seamlessly and interchangeably.

Modern information networks enable data conversion, distribution, and access through flexible hardware/software components that readily integrate into an endless variety of applications. This network approach has evolved rapidly in recent years, and may offer a useful example for energy systems. Two decades ago, only a few imagined the capability to check out a book or rent movies online; today, school children routinely download entire movies onto their telephones with high-resolution screens that are too small for older adults even to watch.

Figure 1. Regions and Balancing Authorities



As of August 1, 2007

Key: FRCC: Florida Reliability Coordinating Council, Inc.; MRO: Midwest Reliability Organization; NPCC: Northeast Power Coordinating Council; RFC: Reliability First Corporation; SERC: SERC Reliability Corporation; SPP: Southwest Power Pool; TRE: Texas Regional Entity; WECC: Western Electricity Coordinating Council

Imagine replacing today's taxonomy of discrete energy components and machines with a pervasive, integrated architecture, akin to modern information systems. Energy would be collected, stored, converted, redistributed, and used in a plug-and-play manner. Transcending even the latest concepts for smart electrical distribution grids or devices, this construct would encompass all forms of energy—electrical, chemical, thermal, or kinetic—enabling seamless conversion and exchange. Such *scalable energy networks* could help mitigate some of our most urgent energy challenges, such as operational instability and vulnerability of the domestic power grid, especially considering the incipient proliferation of dynamic influences such as distributed *micro-generation*[1] (for example, roof-mounted solar panels) and plug-in electric/hybrid vehicles.

The imperative extends to our national security when one considers American Soldiers who defend us by patrolling rugged, remote areas of the world while carrying tens of pounds of batteries;[2] combat vehicles with insufficient capability to power onboard systems in an extended silent watch mode; and combat forces diverted to secure resupply convoys, largely delivering water and fuel.[3]

Colonel Paul E. Roege, USA, is Special Assistant to the Director for Energy in the U.S. Army Capabilities Integration Center at the U.S. Army Training and Doctrine Command.

Historical Context

Energy concepts have evolved over the centuries, but have not achieved a maturity level that provides for the flexible architectures and seamless integration such as those that have transformed information and knowledge. Since the industrial revolution, energy systems such as vehicles, lighting, and manufacturing equipment have reflected a steady progression of performance, efficiency, and reliability improvements, benefitting largely from advancements in materials and manufacturing. Unlike modern notions of information as a ubiquitous and fluid medium, however, we still conceive of energy in terms of basic components:

- sources: oil reservoirs, coal mines, wind, geothermal wells, nuclear fuel
- storage: batteries, fuel tanks, thermal mass, flywheels
- conversion: boilers, generators, compressors, transformers, battery chargers
- distribution: pumps, pipes, switches, cables
- applications: lighting, automobiles, personal electronic devices.

> *some of the most dramatic recent advances in energy performance reflec integration of information and energy*

With increased public awareness and an apparent inflection point in both the importance of (and global competition for) energy, the time has come to advance holistic and systematic energy concepts, using an analogy of modern information networks.

Some of the most dramatic recent advances in energy performance reflect integration of information and energy—manifested, for example, in digital systems that control modern automobile engines and home heating/air conditioning systems. The North American electrical grid, often termed the world's largest machine, illustrates the challenges inherent in connecting and synchronizing diverse energy sources and loads (see figure 1). Hundreds of utilities coordinate with independent system operators and regional transmission authorities,[4] using state-of-the-art sensors, modeling, communications, and information-driven control technologies to manage the dynamic balance of electrical power across the continent.[5] As Eric Lerner and others point out, the expanse, complexity, and dynamic nature of the grid demand extensive systems modeling and control to manage it in a reliable manner, seeking to avoid such contingencies as the massive East Coast power outage of 2003.[6]

Given the challenges of integrating and synchronizing real-time electrical power, it might seem impossible to implement practical energy networks that somehow connect the energy in our automobiles, iPods, furnaces, and bath water. Given the right perspective, however, these complicating factors of time and physics may actually contribute the additional degrees of freedom needed to take that leap. Consider today's flexible, resilient information networks woven with strands of satellite communications, fiber optics, 4G—and even copper wire. These information architectures leverage asynchronicity and diversity through buffers, redundant pathways, and backup storage functions to enable nearly seamless access to knowledge and communications upon which we have come to rely.

Network Thinking

In *The Rise of the Network Society*, Manuel Castells describes how the information technology revolution has transformed personal relationships and business processes, and has driven globalization.[7] We once thought of information as static data—books, file cabinets, and libraries. In contrast, the words *information technology* evoke images of dynamic processes and tools that enhance both capabilities and lifestyles. In the 21st century, a typical American household *needs* cable television, Internet service, cellular telephones—even *smart* appliances. Personal electronic devices have become adaptive tools that not only enable multimedia communications, but also perform any number of other tasks ranging from home shopping to metal detection. With a few keystrokes, consumers can customize their telephones simply by selecting any of the hundreds of thousands of programs or applications available from friends, vendors, or app stores, such as the iPhone Store or Android Market.

In the industrial sector, automotive engineers can now reproduce a classic car using automated information systems to manage the process from end-to-end. A laptop computer running off-the-shelf photogrammetry software uses laser scanners to capture every surface contour and dimension.[8] Computer-aided design and manufacturing systems, coupled with modern manufacturing equipment, can quickly reproduce the car body with remarkable fidelity. At the customer's option, the design team can produce under-the-hood systems that mimic the original or, alternatively, customize the drive train and suspension for state-of-the-art performance.

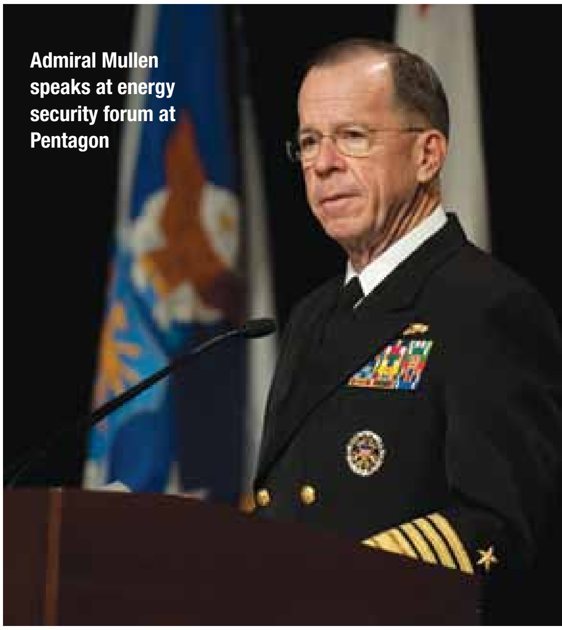
Scalable Energy Networks

In the new reality, scalable energy networks will enable energy to be managed safely, efficiently, and interchangeably. Flexible, ad hoc networks will produce, store, convert, prioritize, allocate, and distribute/redistribute energy as needed. Through integrated architectures, industrial and home systems will gradually incorporate more closed cycles—for example, capturing energy from renewable sources (wind, sun) or waste heat (stove, dryer exhaust) and storing it in thermal mass (concrete floor) or chemical/electrochemical energy (fuel, batteries).

Intelligent systems will monitor energy flows, anticipate usage patterns, and manage buffers, improving energy use in work tasks, home lives, and leisure activities. Much as we configure preferences and applications on today's personal computers, future work processes will integrate indicators, options, and settings, enabling the energy network to balance parameters such as reliability, speed, and economy—all consistent with our needs. Separate charge indicators, fuel gauges, and thermometers will give way to intuitive, composite icons, accompanied by selection options. To appreciate the nature of this ergonomic shift, one need only contrast the intuitive functionality of today's Web search engines—helpful to the point of annoyance—to the challenge of programming a home thermostat based, at best, upon interpretation of household energy bills.

In a constrained or dynamic situation, the scalable energy network concept could provide a critical edge. Consider, for example, a small Army unit ordered to search a particular neighborhood. The platoon would convoy from its forward operating base, then dismount and patrol the community using various devices, including weapons, sensors, radios, and electronic translators. Such networks might allow vehicles and Soldier-carried devices to be charged at the base camp, drawing power from the local grid, if available. During the movement phase, all systems would share vehicle power, with energy priority allocated to propulsion, sensors, and communications systems. During the subsequent dismounted search, Soldier batteries would continue to charge when within range of a vehicle-mounted wireless energy hotspot, while radars sleep to conserve energy in favor of infrared search devices and translators. By providing interoperability, flexible configuration, and intelligent/transparent energy management schema, the energy network would support critical mission tasks. Energy-sharing and management capabilities would simultaneously enhance performance, reduce operational delays, and improve resource efficiency.

The network concept is not revolutionary in the sense that nearly every machine comprises a combination of energy components such as springs, wheels, batteries, and displays. Yet most Americans see no irony as rail cars ferry coal across America, parallelling but independent of the fuel tanker fleets, power grids, and pipelines that collectively power our country. Moreover, many systems are vulnerable to disruptions in any one of several energy sources. Winter power outages, for example, remind us of the unpleasant truth that a typical oil or gas furnace will not heat the house without power for electrical valves, switches, and fans—no consolation that the car in the garage has a full tank of gasoline and a charged battery. In contrast, by enriching connectivity and increasing liquidity of energy resources, the scalable energy network concept would enable not only more efficient design, but would also replace compound failure modes with increased resilience.


Admiral Mullen speaks at energy security forum at Pentagon

U.S. Navy (Chad J. McNeeley)

Component Technologies

How might we transform traditionally rigid energy systems architectures into the sort of flexible, resilient, and useful information networks that have essentially flattened the world? As a first step, consider apparent parallels between information and energy system components (see table).

Sources. Networks ultimately require energy captured or extracted from some source, whether coal combustion, nuclear

in a constrained or dynamic situation, the scalable energy network concept could provide a critical edge


U.S. Air Force (Quinton Russ)

Airmen prepare to run fiber optic cables to improve connectivity at Camp Herat, Afghanistan

fission, wind turbines, photovoltaic panels, or waste heat. Compare this function to data collection through keyboards, microphones, sensors, database searches, and Web crawlers. Scalable energy network designers will stress alignment of source and application characteristics, such as voltage, temperature, or entropy to the respective process interface (for example, mating solar or waste heat sources with domestic water heating).

Storage. We store energy in respective forms and quantities to support applications and to optimize network functions. Just as we configure caches, buffers, and hard drives to archive documents, enrich video displays, and optimize complex calculations, so we use capacitors, batteries, fuel tanks, and thermal mass to start automobiles, maintain building temperatures, and run solar-powered lights at night.

Conversion. Nearly every process involves energy conversion from one form to another. Winding a watch converts motion to spring tension; car engines burn fuel to produce motion. In general, energy conversion accounts for most system efficiency losses. With many of today's thermodynamic processes, such as internal combustion engines, operating at 10 to 30 percent efficiency, and theoretical constraints (depending upon the process) below 50 percent, energy practitioners appropriately are pursuing incremental improvements and alternatives. Considering the room for improvement, success could bring *disruptive* overall process improvements—just as information systems processes have been transformed by conversion process migration from ancient storytelling traditions and primitive painting to electronic processors, Web crawlers, and intelligent speech recognition routines.

Distribution. To be useful, networks must efficiently move and manage energy among collection, storage, and conversion nodes. Maturing information technology concepts have driven a proliferation of transfer technologies, such as portable media, wired and wireless protocols, and management functions integrated into routers and switches. Today's energy distribution technologies remain segregated by the respective media, such as fuel, electricity, and batteries. A scalable network approach might lead to new or improved media-specific technologies, such as free-space transmission (wireless "energy beaming"), as well as development of hybrid systems that would simultaneously manage multiple forms of energy.

Applications. Energy brings the motion, heat, or signal propagation to vehicles, homes, and radios. While many information applications have become virtually indistinguishable from the tools that we use to conduct business—witness the transparent integration of Internet search, GPS location, and communication functions into a smart phone—energy applications remain relatively discrete. Automobiles, stoves, and lights each embody energy to perform singular functions, although plug-in hybrid vehicles, for example, reflect a trend toward synergistic integration of energy technologies to improve flexibility and efficiency. In this example, the vehicles may someday serve an additional function as distributed energy buffers for the electrical grid. Will we eventually use our "smart Joule" device to draw from the most readily available and inexpensive energy source, selecting among energy "hotspot" providers to warm our hands or power our laptop, or will such a device be unnecessary as the energy network is seamlessly integrated into vehicles, homes, and information systems?

many information applications have become virtually indistinguishable from the tools that we use to conduct business

Table. Parallels Between Information and Energy System Components

Function	Information examples	Energy examples
Sources	Observation, printed media, sound, Web sites, databases, sensor/camera, transducer	Motion (induction), piezoelectric, waste/solar heat, photovoltaic, wind, petroleum, nuclear
Storage	Book, optical media (CD/DVD), flash media hard drive	Thermal mass, flywheel inductor, battery, fuel tank
Conversion	Keyboard, scanner, printer, modem, interface card, optical drive	Fire, light, generator, fuel cell, battery charger, motor, compressor
Distribution	Mail, telephone, email, wireless, infrared, 4G, microwave, twisted pair, router, switch	Wire (AC/DC), pipeline, tanker, truck (fuel, batteries), microwave, laser, transformer, breaker, switch
Application	Word processor, online shopping, entertainment, engine controller, computer-aided design, radar	Heating/cooling/lighting, entertainment systems, transportation, power tools, radar

System Integration

Individual technology improvements are necessary but not sufficient to enable scalable energy networks—just as information networks are more than a collection of processors, drives, and routers. Implementation requires construction of holistic models and taxonomies, definition of protocols and standards, and development of fusion concepts.

Holistic Models. Everyone has a different view of energy. For some, the word evokes an image of sustainable resources; others are concerned about power grid vulnerabilities. Many of us consider automobile fuel economy or computer battery life in major purchasing decisions. In order to be useful, a holistic energy model must somehow relate these diverse perspectives, capturing system interactions and collective performance. Lest this seem an impossible task, consider Stanford University's Global Climate and Energy Project, which has published a series of flow charts depicting global energy and carbon flows or "exergy."[9] These diagrams demonstrate that energy in various forms can be mapped and tracked through conversion and storage processes, further capturing interactions with other systems such as carbon cycles.

Taxonomies. Scalable energy networks would comprise essentially the same components as traditional energy systems. However, the information network example suggests that conversion, distribution, and interfaces increase in importance with network scale, interconnectivity, and dynamic operation. In that context, the information technology community has developed taxonomies, protocols, and standards that enable structured and interoperable system design and operation. The Open Systems Interconnection (OSI) model—now captured in International Organization for Standardization/International Electrotechnical Commission Standard 7498–1[10]—defines a layered overall taxonomy for information systems.

energy applications remain relatively discrete

The Army's "Power and Energy Strategy White Paper," which considers energy implications to various dynamic military situations and complex performance demands, proposes a similarly layered taxonomy (figure 2).[11] Although this construct does not directly parallel the OSI model, the taxonomy does transcend component technologies in a similar manner, providing a prospective basis for systems analysis and definition of various protocols.

Figure 2. Energy Taxonomy

Mission Integration/Energy Informed Operations
- Awareness/understanding – concept of operations, systems analysis
- Planning tools – mission planning, sustainment planning, support architecture
- Execution integration – decision aids, measures of effectiveness

Energy/Power/Water Management
- Monitoring/SA – meter, sensors, metric, visualization
- Power management – manual or automated
- Demand reduction – control, discipline, recycling

Hardware/Software System Integration
- Shared components
- Design optimization – synergies, trades
- Networks/"smartgrids"

Energy Technology
- Storage – tankage, batteries, capacitors
- Conversion – engines, fuel cells, generators
- Delivery – pumps, distribution infrastructure, rechargers, pulsed power
- Use – air conditioners, water production, transportation, computers
- Delivery – pumps, distribution infrastructure, rechargers, pulsed power

Energy Source
- Logistics fuel
- Renewables/waste-to-energy
- Local grid
- Nuclear

Protocols and Standards. Energy-related technical standards already exist, having been established by various professional organizations such as the American Petroleum Institute, Institute of Electrical and Electronics Engineers, and National Fire Protection Association. Motorists choose among diesel fuel or gasoline at various octane levels when they refuel, while international travelers encounter differences between customary U.S. (120 volt/60 hertz) power and European (240 volt/50 hertz) standards.

Scalable energy networks would require an expanded suite of interface standards and system protocols to ensure compatibility and to facilitate system management. While it may seem difficult to imagine standards relevant to diverse forms of energy, consider the variety of information devices and systems we now routinely connect through a plug-and-play approach, thanks to interface standards (USB 2.0, 801.11 series Wi-fi) and protocols such as Internet Protocol, hypertext transfer protocol, and Domain Name System.

Fusion Concepts. As energy and information technologies evolve, each naturally embraces the other in greater degrees—ultimately, the information and energy networks seem inseparable. Information network components use energy, while intelligent energy systems thrive on information. Faster

Marines provide security for convoy delivering supplies to Forward Operating Base Nolay, Afghanistan

U.S. Marine Corps (Brian A. Lautenslager)

U.S. Navy

Microbial fuel cells, which convert decomposed marine organisms into electrical energy, provide clean, efficient alternative to batteries and fuels

processors needed to improve energy management require more power, increasing the cooling load. In their ultimate manifestation, scalable energy networks will essentially fuse energy and information.

Process Integration

Energy is only useful when it supports real-world needs. To that end, we should examine various energy use cases, seeking effective ways to weave these new capabilities into the work process. Going beyond the basic power meter and preference settings, race car teams have long integrated energy into work processes. Winning NASCAR crews evaluate driving conditions and the competitive situation to inform decisions such as speed and refueling stops.

Process integration does not sprout overnight. Early in the information age, computers were only useful to those who learned to program; early packaged applications had characteristically rigid, logical structures. Batch programs ran from start to finish, and even commercial word processing packages required the operator to insert special codes into the text to accomplish various formatting options, such as bold or underline. Later, object-oriented programming evolved to enable such advanced concepts as drag-and-drop and plug-and-play. Still, users were largely bound to functions and procedures defined by the engineer.

in their ultimate manifestation, scalable energy networks will essentially fuse energy and information

Today, the proliferation of widgets and apps provides a high degree of flexibility to infuse information into our work, social lives, and entertainment pursuits. Who will design tomorrow's energy apps?

Manuel Castells asserts that information network integration has fundamentally changed our world. Without the benefit of special training or grand design, we now configure smart phones that, in turn, reconfigure our human interactions and daily routines. Correspondingly, smart energy systems might influence the ways we juggle cooking, working, and vacationing. We already use basic awareness tools, such as broadcast traffic reports, real-time miles-per-gallon displays, and charge status indicators to inform our commute, driving habits, and the need to recharge telephones. Energy-informed travel management systems would automatically recommend routes, travel time, and speed, based on predicted energy use and fuel prices en route. Future home appliances and heating and cooling systems will optimize temperature settings and timing and select from available energy sources, based on individual preferences and schedules, real-time energy prices, and weather forecast.

Next Steps

Scalable energy networks offer prospects of not only overall energy efficiency improvement but also increased system flexibility, which could be used to reduce vulnerabilities and better balance considerations such as resources and sustainability. To advance the concept, a three-pronged strategy is offered:

- Investigate holistic models at the conceptual level. Academic institutions and think tanks could organize workshops and referee papers, integrating diverse, multidisciplined views.
- Perform diverse systems analyses. Design and analyze integrated systems for real-world use and explore interactions among various energy and information technologies to expose compatibilities, synergies, critical nodes, and important interface controls.
- Guide component technology development. System performance will always depend on sound component technologies. Industry and government sponsors should draw on insights from the above analyses as they craft technology investment strategies.

This will be a long-term, iterative process, but the energy stakes are high. Nearly anyone can contribute to energy security, whether as a researcher, leader, voter, communicator, or early technology adopter. **JFQ**

NOTES

[1] Alex Salkever, "Too Green, Too Soon? Renewables Weaken Electrical Grid," *Daily Finance*, April 6, 2010, available at <www.dailyfinance.com/story/too-green-too-soon-renewable-power-may-destablize-electrical-g/19426714/>.

[2] *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan (Apr-May 2003)* (Fort Leavenworth, KS: Center for U.S. Army Lessons Learned, 2003).

[3] Defense Science Board, *"More Fight—Less Fuel": Report of the Defense Science Board Task Force on DOD Energy Strategy* (Washington, DC: Department of Defense, February 2008), available at <www.acq.osd.mil/dsb/reports/ADA477619.pdf>.

[4] See <www.isorto.org/site/c.jhKQIZPBImE/b.2603295/k.BEAD/Home.htm>.

[5] Department of Homeland Security, Science and Technology Directorate, "National Power Grid Simulation Capability: Needs and Issues," National Power Grid Simulator Workshop, Argonne, IL, December 9–10, 2008, available at <www.anl.gov/ese/pdfs/PowerGridBrochure.pdf>.

[6] Eric J. Lerner, "What's wrong with the electric grid?" *The Industrial Physicist* (October/November 2003).

[7] Manuel Castells, *The Information Age*, vol. 1, *Economy*, 2d ed. (Malden, MA: Blackwell Publishers, 2000).

[8] See, for example, <www.menci.com/index.php?page=shop.product_details&category_id=11&flypage=shop>.

[9] Stanford University Global Climate and Energy Project, "Global Exergy and Carbon Flow Charts," available at <http://gcep.stanford.edu/research/exergy/flowchart.html>.

[10] IOS/IEC 7491-1, *Information Systems—Open Systems Interconnection—Basic Reference Model: the basic model* (Geneva: International Standards Organization, 1994).

[11] U.S. Army Capabilities Integration Center, "Power and Energy Strategy White Paper" (Fort Monroe, VA: U.S. Army Capabilities Integration Center, 2010).