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Chapter 2: Energy Sectors and Systems
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Issues and RDD&D Opportunities

Energy systems are becoming increasingly interconnected and complex. Integrated energy systems present both opportunities for performance improvement as well as risks to operability and security. The size and scope of these opportunities and risks are just beginning to be understood.

This chapter addresses both the key issues of energy sectors and their associated energy systems and a spectrum of research, development, demonstration, and deployment (RDD&D) opportunities including energy systems integration and complex system science.

Key issues:

- Three layers of increasing integration and complexity are discussed here:
    - Number, variability, and communication of devices connected to the electric grid
    - Cross-talk between sectors of the energy system (e.g., fuels/electricity, electricity/buildings)
    - Coupling of energy systems to non-energy systems (e.g., Internet, water)
- Information and communications technologies are driving the interconnection of energy systems.
- Integration can improve system cost and efficiency by optimizing the utilization of assets and resources.
- Integration can also increase the risks of unintended consequences and cascading failure.

Opportunities:

- Identify and address market barriers to adopting integrated systems, including high capital costs and complexity of operations
- Develop methods of quantifying uncertainty in large energy systems and calculating networked risks
- Develop co-simulation models of the interdependencies between and among 1) energy system components, 2) energy and non-energy systems, 3) energy systems and human decision making, and 4) systems across extended time intervals between decisions and impacts
- Validate network and co-simulation models using real system data
- Apply complex network and complex system science to problems relevant to various energy sectors and their associated energy systems including the electric grid, transportation networks, and urban systems
- Develop operational strategies to manage complexity and optimize provision of energy services

2 Energy Sectors and Systems

2.1 Introduction to Energy Systems

Some of the most transformational opportunities exist at the systems level. They are enabled by the ability to understand, predict, and control very large scale and interconnected complex systems. Systems solutions can be broadly impactful across multiple technologies and sectors.

Within and between the electric grid, power, buildings, manufacturing, fuels, and transportation sectors, increasing interconnectedness and complexity are creating opportunities and challenges that can be approached from a systems perspective. This chapter presents a holistic view of the energy system and explores the opportunities in energy systems research. Systems approaches can help to identify critical technology needs and can also be used to develop solutions to complex energy challenges.

Energy systems are also becoming more tightly intertwined with systems that are focused primarily on other services, such as information and communications technology (ICT) networks, transportation networks, food production, and financial systems. The increasing use of digital technology is driving these interconnections. Finally, energy systems also interact with large and complex natural systems, such as water supplies, air basins, ecosystems, and, at the largest level, the global climate system.

With increasing system size, and connectivity within and between systems, there are a growing number of opportunities for improved system performance as well as risks to system operability. In many cases, the size and scope of these opportunities and risks are just beginning to be quantified. For example, as discussed in this chapter and explored in greater detail in Chapter 3, as the complexity of the electric grid grows, the risk of cascading failure could begin to outstrip built-in protections and redundancies.[1,2] Quantifying and mitigating systemic risks through robust system design and operation could prevent billions of dollars of lost productivity.[3]

Each of the technology chapters (3–8) in this report describes energy systems that provide a desired set of end-use services. Instances of technological competition (e.g., heat pumps versus furnaces), cooperation (e.g., passive solar coupled to heating, ventilating, and air conditioning [HVAC] system downsizing), and consequences (e.g., displacing fossil fuel emissions at distributed sites with grid-supplied electricity) are examples of system interactions that drive the form and function of energy technologies presented in subsequent chapters. These system interactions play out within each step of the energy value chain—from energy resources, their conversion to fuels and electricity, through distribution networks, and in the end-use services provided in the residential, commercial, manufacturing, and transportation sectors.

Technologies with the potential to radically alter the structure of the energy system, either physically by switching energy carriers or virtually through market transformations, can be identified through applied systems analysis. One example is improved energy storage, which could drastically alter the delivery of energy services if it were cheap and light enough to broadly untether energy users from suppliers for extended periods. Another example is decentralized electricity systems, where responsibility for reliability and resilience might shift toward the edge of the network much like it is on the Internet. The effectiveness of these technologies can only be evaluated through a systems perspective.

2.1.1 Enabling Modernization of the Electric Power System (Chapter 3)

Chapter 3 views the grid as a critical platform for innovation, future energy markets, and services, and considers how that system's architecture and capabilities must evolve to meet the changing generation mix, customer role, and risk profile. The broad deployment of variable generation resources (most notably, solar and wind), distributed energy resources, energy storage, electric vehicles, and actively managed loads could substantially alter how the system will need to be designed, operated, and protected. At both the transmission and distribution levels, advances in information and communications technologies are being leveraged to enhance system visibility, understanding, and control to improve reliability and resilience. However, significant challenges with component technologies, systems integration, and institutional change must be addressed, including cyber- and physical security concerns across the entire system. These technologies and issues suggest the need for new system architectures, but any transformation must take place in the context of existing infrastructure assets, market structures, and institutions, and their associated pace of change.

2.1.2 Advancing Clean Electric Power Technologies (Chapter 4)

Chapter 4 addresses the production of electric power as an "options space" (for more information, see Chapter 10 *Concepts in Integrated Analysis*) where renewable, fossil, and nuclear resources compete to produce electricity. In producing clean electric power, there are interdependencies among base load, intermediate and peaking; variable and flexible; and central and distributed generators. The chapter considers the systems-level drivers (i.e., reliability, reserves requirements, environmental criteria, siting characteristics, and proximity to supply and transmission infrastructures) that must be balanced in assembling the generation mix. Systems-level issues also include portfolio diversification with respect to fuel supply, generator size, and technology maturity. The economies of scale required to deploy clean power, including U.S. and international market dynamics, add a temporal dimension to the systems-level considerations associated with these technologies.

2.1.3 Increasing Efficiency of Building Systems and Technologies (Chapter 5)

Chapter 5 considers buildings as integrated systems designed to deliver end-use services such as thermal comfort, air quality, lighting, hot water, sanitation, food preparation and storage, labor-saving conveniences, productivity, communications, and entertainment. Interactions among and between end-use services and efficiency technologies are analyzed in a systems framework that evaluates the cumulative impacts of staged technology implementation. Efficient technologies tend to diminish potential savings from subsequent deployment (e.g., efficient light bulbs reduce the energy savings potential of automatic lighting controls); therefore, it is imperative to understand total system impacts under a wide range of scenarios. Additionally, miscellaneous and plug-loads, which include a very large number of different device types, represent a target of growing importance, but are difficult to address at the individual-technology level. Integration of building energy systems with electricity and fuel supply systems must be considered. Finally, the long timescales over which buildings are operated demand an evaluation of retrofit options.

2.1.4 Innovating Clean Energy Technologies in Advanced Manufacturing (Chapter 6)

Chapter 6 views manufacturing as three nested opportunity spaces: 1) process technologies and unit operations are at the core, where innovations can both improve energy efficiency and enable new clean energy products; 2) facility systems are an intermediate level, where crosscutting and plant-level technologies impact the efficiency, sustainability and competitiveness of U.S. industrial concerns; and 3) beyond the plant boundaries is the outermost layer, where innovations in manufacturing affect the sustainability of supply chains along with the energy and life-cycle impacts of products that are manufactured as a part of the clean energy economy. The intermediate level explicitly engages systems integration issues within the manufacturing plant by considering global optimization of material and heat flows, and integration with energy supply systems. Advanced process technologies, however, may also have system-wide impacts (e.g., supply chain impacts of additive manufacturing). A major systems-level challenge for advanced manufacturing technologies is measuring their full energy, security, cost, and environmental impacts (via life-cycle assessment or similar approaches).

2.1.5 Advancing Systems and Technologies to Produce Cleaner Fuels (Chapter 7)

Chapter 7 considers three primary fuel pathways: 1) fossil liquids and natural gas, 2) biomass, and 3) hydrogen. It examines the RDD&D opportunities for each pathway across the fuel value chain—resources for producing fuels, upgrade and transport, conversion and synthesis, distribution, and compatibility with end uses. Environmental concerns (e.g., greenhouse gas [GHG] emissions, land use, water use, etc.) are addressed at all stages of the value chain. This value chain depends on an extensive network of wells, farms, pipelines, refineries, terminals and distribution stations. At the systems-level, advanced technologies must be developed and deployed along a pathway that considers compatibility with infrastructure and vehicles. The potential co-production of fuels, electricity and/or heat from coal, gas and/or biomass (potentially with carbon capture and storage [CCS]) also presents a systems integration issue. Finally, responsible fuels production from biomass, as well as from hydraulically fractured oil and gas wells, requires mitigating energy-water systems issues.

2.1.6 Advancing Clean Transportation and Vehicle Systems and Technologies (Chapter 8)

Chapter 8 takes an impact analysis approach to the transportation system, evaluating the potential for technologies at various maturity levels to reduce GHG emissions. Considered are the following: improvements to combustion-powered vehicles; development of plug-in electric vehicles; pathways to enable hydrogen fuel cell vehicles; information-enabled transformation of personal and freight transportation systems; and improvements to other modes of transit such as aviation, ship, rail, and pipeline. At the single-vehicle level, efficiency, safety, and lightweighting improvements can be mutually reinforcing, and the compound benefits can only be evaluated in a systems framework. Integration of vehicle technologies with energy delivery infrastructures (biofuels, electricity, hydrogen) is a systems issue that could limit or accelerate the impacts of advanced technologies. Finally, systems developments that change the paradigm of personal vehicle control and/or ownership (connected and automated vehicles, shared vehicles) may drastically alter patterns of transportation energy use with unforeseen consequences.

2.1.7 Sector Cross-Connections

In addition to the systems view of the technology space covered by each chapter, there are systems interactions between and among the technologies covered in separate chapters. For example, technologies that enable better hydrogen storage onboard vehicles are explored in Chapter 8 (*Transportation*), while the benefits of those technologies can only be realized through the production of hydrogen, which is described in Chapter 7 (*Fuels*). When dividing the energy space into sectors, such overlaps are inevitable. However, there are other cases where the overlaps between chapters are intrinsic to the technology and not the report structure. In the case of GHG emissions management, a suite of technologies will need to be tailored to specific applications within the power sector (including coal and gas-fired generators), the industrial sector (including cement, steel, ethanol, and other large point sources of carbon dioxide [CO_2]), as well as to offset use of fossil fuels in distributed applications too small for CCS (e.g., by using instead electricity or zero-carbon fuels).

Ways to address these crosscutting themes are explored in the *Conclusion* (Chapter 11). A table of crosscutting technologies and description of related themes, as well as the affected sectors, is included in Table 2.1 at the end of this chapter.

Cybersecurity

Information and communications technologies (ICT) are enabling significant improvements in the performance and efficiency of many energy systems. However, transferring data in and out of energy systems relies on wireless and/or Internet-connected communications channels, which form an attack surface for cyber intrusion. Many of the facets of security for the electric grid are explicitly addressed in Chapter 3. The magnitude of the cyber threat extends well beyond the grid, as described below.

- The entire fuels production and distribution value chain—from subsurface instrumentation or automated farming equipment; to the supervisory control and data acquisition (SCADA) systems at oil- and bio-refineries; to pipeline, rail, and truck distribution networks—are increasingly computer controlled and subject to cyber attack.
- Power plants are at the nexus of electricity, water, and fuels networks. Their control systems form a virtual link between these critical infrastructures, each of which is subject to cyber attack.
- Communications networks in buildings, which are increasingly accessible to wireless and remote monitoring and control, are a growing cybersecurity and privacy concern. Security concerns are particularly important in hospitals and other sites where life and safety are at risk.
- As control of manufacturing systems evolves from (relatively) localized SCADA to more broadly networked smart manufacturing platforms that integrate with supply network coordination frameworks, the potential for cyber intrusion is growing.[4]
- Automated and connected vehicles have multiple network intrusion points and represent a safety-critical cyber risk. Hacking of single-vehicle networks through wireless sensors has been publicly demonstrated.

Challenges for addressing the energy systems' cyber vulnerabilities include the following:

- Rigorous application of cybersecurity best practices (e.g., encryption, firewalls, and unidirectional gateways) on energy ICT systems
- Tools to measure the maturity, security, and resilience of ICT-enabled energy systems and networks
- Situational awareness of small- and large-scale cyber attacks on connected and embedded systems with integrated forensics and coordinated rapid incident response
- Design of self-configuring systems adaptable to a variety of network architectures, including transition to, and operation in, an island mode in order to mitigate the spread and impact of a cyber attack
- Maintenance and update of software in embedded low-cost devices to address evolving security vulnerabilities
- Legacy ICT systems in energy system components that may have multidecade service lives
- Supply chain integrity of the components that, once assembled, form the systems used for data acquisition, command, and control of energy infrastructure
- Qualified and trained workforce that focuses on the unique cybersecurity requirements of energy devices and networks that are fundamentally different from traditional information technology services

2.2 Energy Systems Integration

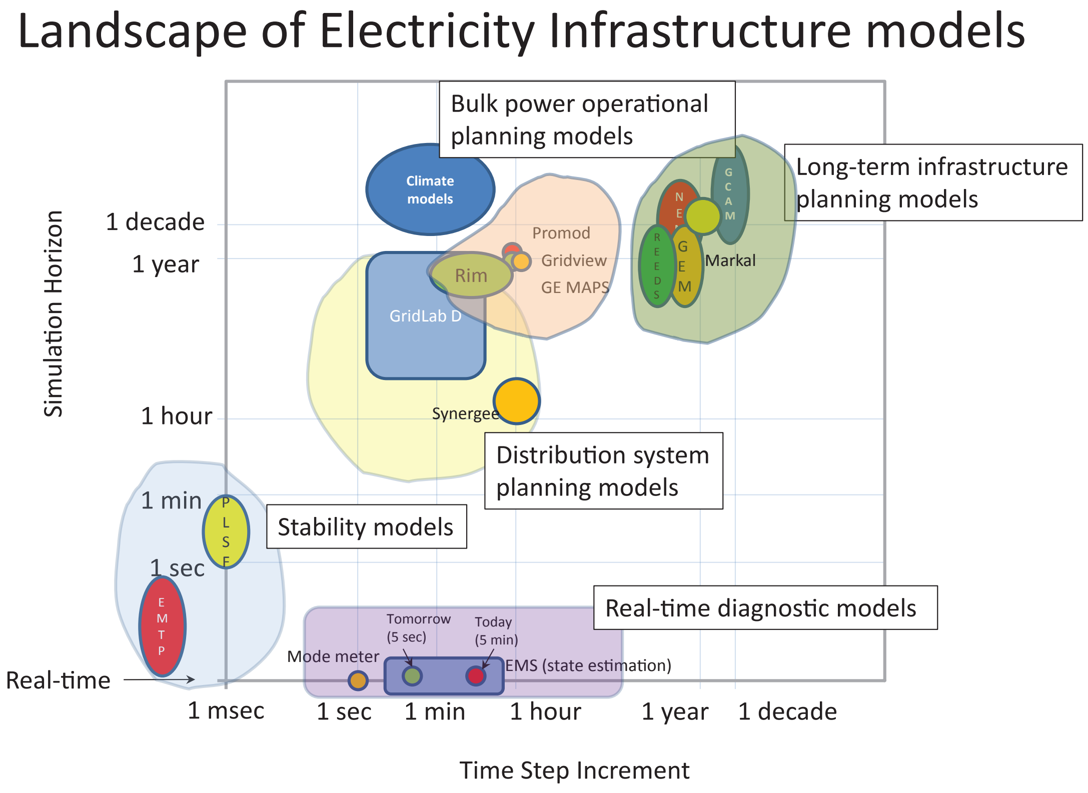
Energy systems are becoming increasingly interconnected to each other as well as to other systems that have, until recently, been analyzed largely in isolation. Feedbacks between energy and ICT systems are an obvious example, but it is also recognized that energy systems are becoming more tightly coupled to water resources, raw and finished material supply chains, agricultural systems, patterns of land use, and energy-related financial systems. This section explores the research, development, demonstration, and deployment (RDD&D) opportunities associated with integrating systems at multiple scales, the failure modes associated with integrated systems, and the potential benefits and risks that this integration entails.

Potential benefits of integrated systems include efficiency, resource savings (money, time, energy), reduced GHG emissions, and increased resiliency. For example, the water savings from energy-saving programs in Arizona could reduce non-agricultural water use from 2% to 15%, while water conservation policies could also reduce statewide electricity use from 1% to 3%.[5] It has also been argued that integration of different energy systems (e.g., electricity, natural gas, petroleum, biofuels, and transportation) can minimize disruption from natural or human-caused events by increasing connectivity throughout the energy system.[6]

However, there are also challenges and risks associated with systems integration. Integrated systems can create bottlenecks and single points of failure for multiple systems. Moreover, the economic efficiency of integrated energy systems may conflict with flexibility requirements. Mitigating these risks becomes especially challenging when market drivers push systems integration faster than regulations, institutions, and planning processes

Figure 2.1 Multiple Scales of the Integrated Electrical System. Note: "simulation horizon" indicates the length of time that the model simulates, whereas "time step" indicates the increment or resolution of the model. Colored patches indicate the ranges across which different models, indicated by their acronyms, operate. Certain areas are not addressed by these models, and furthermore, these models are often unable to easily communicate with each other.

Credit: Michael Kintner-Meyer, Pacific Northwest National Laboratory



evolve. For example, gas use for electricity generation is increasing rapidly despite ongoing coordination challenges between electricity and gas markets. Timely research on integrated energy system architectures and planning will smooth these technology and institutional transitions.

Appropriate application of systems integration requires understanding, control, and optimization across multiple sectors (e.g., fuels, power, buildings, and water), time frames (from fractions of a second for operations to years for planning), spatial scales (devices, buildings, campuses, city, region/state, nation), and functions (e.g., data, analysis, controls, and markets). Integration also requires an understanding of costs, particularly the capital costs of deploying new and/or integrative technologies, but also the financial implications of deployment and operations. An example (see Figure 2.1) is the electric grid, where timescales span from milliseconds to decades, and where existing modeling frameworks span only subsets of this space. Changes at one scale may impact other scales that cannot be predicted in the current simulation paradigm. Research is needed on basic and applied systems science, data, architectures, computational analysis, communications, and control. The results of such research could help system designers and operators to optimize the operations of interconnected systems with appropriate risk mitigation, including such strategies as appropriate system sizing and graceful disconnection.

2.2.1 Systems of Systems

There is potential to enhance performance of large, integrated systems by improving communications between sub-systems and by improving the overall structure of the system so as to reduce the likelihood of operations that are locally optimal but globally sub-optimal.

Examples of cross-system interactions are highly varied and include the following:

- Electric vehicles (EV) and distributed solar generation are penetrating deeply in some neighborhoods and scarcely at all in others. Neighborhood social networks (e.g., local observation, word-of-mouth, and peer pressure) combine with geo-localization of socioeconomic conditions to drive this uneven adoption of energy technology. That adoption pattern, in turn, drives uneven requirements for equipment on the electrical distribution grid. Social and decision science research can help inform photovoltaic (PV) and EV grid integration requirements.
- The fuel supply is a system of systems at the largest scale. For instance, the expansion of domestic oil extraction from the Bakken and Eagle Ford shales and the increased use of ethanol-blended gasoline at the 10% level are increasing the amount of fuel being shipped by rail across the United States. Petroleum fuels and ethanol, which have two entirely separate production systems, first compete for space in the rail transportation system and then are blended at refineries and terminals and sold as a single product.
- Energy systems are becoming increasingly reliant on the ICT systems that now span the entire globe in the form of the Internet. ICT systems, in turn, have always been dependent on electrical power (critical ICT infrastructure, for example, usually incorporates backup power). Advanced ICT capabilities enable more sophisticated algorithms for managing energy systems and more diverse energy systems (e.g., building, campus, regional, national) to communicate with one another. On the other hand, ICT also opens a wide range of new risks from the inherent issues of complex system dynamics to cyber vulnerabilities.

2.2.2 Interdependency

Tight coupling of otherwise independent systems can simultaneously increase redundancies and the risk of catastrophic, multisystem failure.[7,8]

Coupled energy-ICT systems are becoming more commonplace. In the electricity sector, smart meter and synchrophasor data are just beginning to affect near-term markets that are already deeply digitized, simulation-based, and forecast-dependent. The energy-water nexus has become a well-documented case of dependent coupled systems—electricity generation requires water for cooling, while moving and treating water requires electricity.[9] It is critical to understand how each "half" of the coupled system is affected when performance of the other half is degraded. The propagation speed of disturbances and "tipping points" into catastrophic failure depend on the nature of connectivity within and between systems.

Energy systems are also coupled to weather. In hot weather, thermal cooling is less effective, resulting in the de-rating of power plants. Also during hot weather, demand for electricity-based air conditioning increases. However, high-voltage transmission lines experience temperature-induced sagging, so the capacity of such lines must be reduced to avoid contact with trees or structures. These events occur at the same time, all of which result in a strain on electricity generation systems. Droughts also affect energy systems. Shortages of water and water intake and outlet temperature limitations can constrain cooling of thermal power plants or reduce hydrological resources. Droughts also affect biomass production.[10] Cold weather increases demand for building heating, placing a strain on energy delivery systems, while ice and snow can cause problems for wind turbines, solar cells, power lines, and fuel delivery by truck or rail. It is also well known that electricity grids often fail during storms due to downed power lines, lightning strikes, and flooding.

In a feedback loop with many unknown parameters, emissions of GHGs from the use of fossil energy are driving changes in the climate. These changes have implications of higher variability and uncertainty in weather patterns and extreme weather events. The long-term coupling of energy systems, and climate, and therefore with weather is clear, and research is ongoing to better quantify the timing, localization and severity of impacts. A fundamental understanding of the energy system's impacts on climate and improved understanding of the climate's impacts on energy systems, together with evaluation of mitigation and adaptation strategies, will reduce the risks associated with this interdependency.

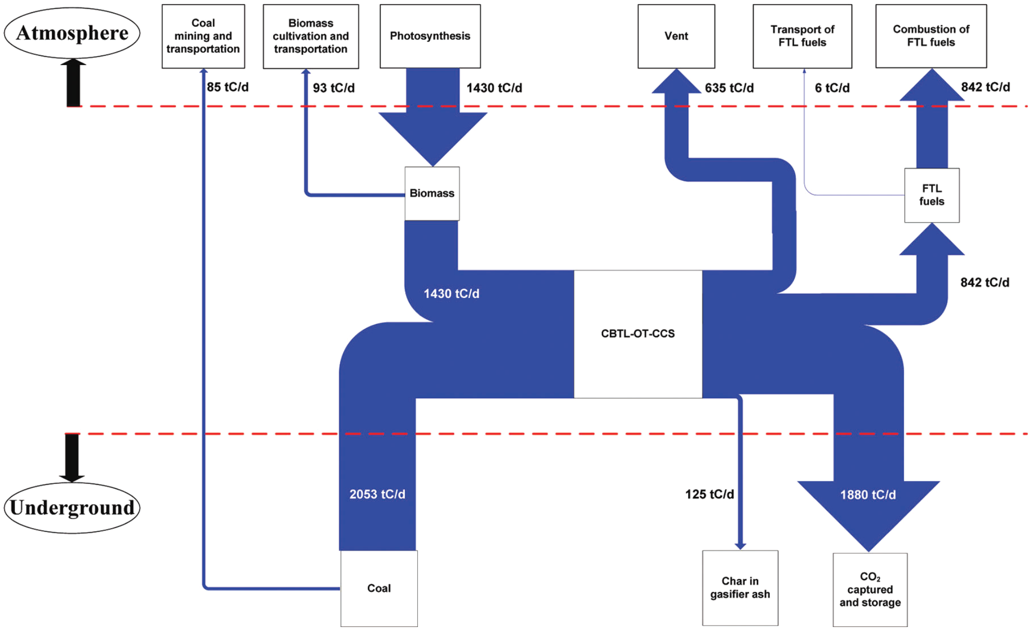
2.2.3 Hybrid Systems

Hybrid energy systems can improve overall energy efficiency by combining multiple inputs and/or outputs, or using waste from one system as input to another. Examples include combined heat and power in buildings and manufacturing; polygeneration of electricity and fuels, chemicals or fresh water; and hybrid systems that combine nuclear with renewables, or co-fire coal and biomass (potentially with CCS). With respect to the consumer, examples include hybrid space[11] and/or water[12] heating, solar PV and/or thermal heating,[13] daylight/task lighting systems,[14] and combination appliances[15] or electronics.[16]

One example of a dual-fuel, polygeneration hybrid system that has received significant attention for its potential to mitigate GHG emissions is combining coal and biomass to produce liquid fuels and electricity with CCS (CBTLE-CCS), as illustrated in Figure 2.2. There are several ways in which such a system could be configured, but the underlying principle is to integrate the heat and mass flows of 1) a gasification and Fischer-Tropsch fuel synthesis plant with 2) a combined-cycle cogenerating electricity plant. Depending on the ratios of biomass-to-coal in the plant inputs and fuels-to-electricity in the plant outputs, the net carbon emissions of the polygeneration system (including the CO_2 from the fuel it produces) could be positive, negative or zero. Assuming the system displaces electricity that would otherwise have been generated by a carbon-emitting power plant, the net environmental benefits could be significant. Detailed cost and energy analysis down to the equipment level shows the cost and performance benefits of an integrated system over separate fuels- and power-production systems competing in the same markets.[17] Scenario analysis has shown that such carbon-negative systems are important options for achieving global emissions goals.[18] Chapter 7 Section 7.5.3 provides further details, describes challenges, and notes overarching RDD&D needs.

Figure 2.2 Potentially Net-Negative Carbon Flows in a Hybrid Polygeneration CBTLE-CCS System

Credit: Reprinted (adapted) with permission from Guangjian Liu, Eric D. Larson, Robert H. Williams, Thomas G. Kreutz, and Xiangbo Guo. "Making Fischer-Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis." Energy & Fuels 25 (1), 415-437. Copyright (2011) American Chemical Society.



2.2.4 Research Needs

Integrated systems present a variety of challenges that cannot be met by studying component systems in isolation. Potential research pathways include the following:[19]

- Expanding knowledge of global interdependencies among networks of different types[20]
- Identifying trade-offs among multiple objectives
- Quantifying uncertainties, developing robust solutions that hold up under uncertainty, and developing methods of identifying and quantifying networked risk and uncertainty
- Identifying and addressing market barriers to adopting integrated systems, including high capital costs as well as the complexity hurdles that prevent adoption even when there is clear financial payback
- Advancing the science of integrated system design to manage risks associated with the introduction of new components and interactions
- Co-simulation modeling of the interdependencies between and among 1) energy system components; 2) energy and non-energy systems; 3) energy systems and human decision making, including operator and consumer behavior; and 4) systems across extended time intervals between decisions and impacts
- Close integration of theory and computation with empirical and experimental efforts, including game theory, laboratory and Web-based experiments, agent modeling, and data mining
- Model validation using real system data (energy system data must be curated, cleaned, and sanitized for privacy and made available to researchers)
- Performing scenario analysis on potential future energy systems that are radically different from today's systems due to significant uptake of architecture-altering technologies (e.g., local energy storage and decentralized electricity systems)

2.3 Complex Systems and Networks

As complexity and interconnectedness within the energy system grow, the difficulty of characterizing the system increases. Examples of systems exhibiting growth in complexity include transportation networks, urban infrastructures, and the electric grid. Advances in the operation, planning, modeling, and simulation of complex systems[21] are being actively pursued.[22] In some cases, the science of complex systems may enable the prediction and subsequent control of some macroscopic properties and behaviors, including disruptions, that emerge from system interconnectedness.

Complex systems are multicomponent, multidomain, multiscale, and/or multidimensional, and can be difficult to fully characterize.[23] Literature from the discipline of formal "complex systems science"[24] defines a subset of systems that are impossible to fully characterize because of a large number of nonlinear interactions between sub-components. In these inherently multiscale systems, emergent properties or behaviors can only be predicted and managed from a systems perspective.

There are a number of warnings from complex systems scientists who argue that increased interdependence, and the complexity it brings, may increase vulnerability rather than reducing it.[25] It has been demonstrated[26] that interconnected networks can fail more easily precisely because they can propagate failures more rapidly and thoroughly than isolated systems. Such systems can result in "uncontrollable situations even when decision makers are well-skilled, have all data and technology at their disposal, and do their best."[27] Researchers find that interconnected networks can sometimes lead to outcomes that are opposite those found in isolated networks, indicating that predictions or experience based on simple systems may be fundamentally flawed when it comes to complex interconnected systems. Redundancy—a fundamental tool to guard against catastrophic failure—is often reduced in interconnected systems in an attempt to be more efficient.[28]

Potential remedies to the vulnerabilities of complex systems include limiting connections between systems, slowing the speed of propagation by introducing virtual "friction" when needed, allowing coordination to exist locally but perhaps not globally and by the design of the network hubs and their interconnections.[29] More research is also needed—in many cases simply to explore and prepare for, contingencies normally considered outside the realm of possibility. This is because state distributions in interconnected systems are often highly correlated, related in nonlinear ways, and extreme risks are often poorly characterized. Models that capture the important components of a complex system are vital. Approaches include: 1) more comprehensive models that capture all known detail and sample the full range of the distribution space, and 2) holistic models that reveal and characterize emergent system behavior at the expense of detail.

2.3.1 Electric Power System

The electric power system is unambiguously complex, and the research community is working to propose and validate formal complex network models of the electric grid to inform and support its evolution.

The electric grid is evolving from a twentieth century model of largely centralized, controllable generators and distributed, independently controlled loads to one with a potentially much larger number of distributed, variable generators and participatory, coordinated loads. The current system is a stable one, even though it is quite complicated with respect to the number of devices connected to it. The number of agents that could affect the state of the system was limited; the variability of energy input to the system was small; and many of the largest loads intrinsically reduced consumption in response to a drop in system frequency. For any given area, a handful of generators and control devices could reliably maintain frequency and voltage. Architectures and control systems were designed with sufficient margin such that disruptive events (i.e., loss of a generator, loss of load) could be swiftly isolated and remedied, thereby avoiding cascading failure.

New and increasingly affordable technologies are changing this landscape. Both the number of agents on the supply side and the connectivity between agents of all types are rapidly increasing. Distributed generation, capable of offsetting local power needs and occasionally selling excess power into the broader market, is becoming an attractive investment option. Feedbacks, with widely varying time delays, are being established between pricing authorities (i.e., utilities) and consumers through the implementation of demand-side management and dynamic pricing. Rapid deployment of utility-scale wind generation and utility-, commercial-, and residential-scale solar generators is increasing the fluctuations of energy inputs to the grid. An additional layer of connectivity arises from the deployment of new monitoring, communication, and controls.

Each of these developments is beneficial in support of a specific goal. Distributed generation can both leverage a near-term market opportunity and increase local resilience to distribution-level (and possibly transmission-level) outages. Dynamic pricing can drive more consistent economic efficiency of the entire electric system. Demand response programs can avoid costly capital expansion with minimal economic risk. And variable renewable electricity sources can offset GHG emissions. However, each of these technologies adds complexity to the system. When viewed from a holistic systems perspective, these developments may have detrimental impacts by adding fluctuations, feedbacks, and connectivity along which failure can propagate. Conversely, they may also strengthen the system through increased diversity, agility, and flexibility.

Approaches to managing the complexity that these clean energy technologies bring include the following:

- Develop, verify, and validate complex system and network models and simulations
- Identify operating modes and interactions among technologies that increase the risk of failures and outages, as well as those which reduce these risks
- Develop strategies to mitigate risks with currently available tools and architectures
- Conduct R&D on complex systems to identify novel architectures that fundamentally increase reliability and resilience
- Conduct demonstrations and facilitate the deployment of technologies that further validate successful integration into the electric power system

There is a continuing need for basic understanding of the complicated physics and engineering of the current and future electric grid. Combining basic and applied science with power systems engineering will enable improved understanding and control of the complex phenomena occurring on the electric grid.

There are already significant research collaborations underway between and among energy systems domain scientists, complicated systems simulation experts, and complex systems researchers. The Multifaceted Mathematics for Complex Energy Systems (M2ACS) project[30] is one example of such collaboration. Under this collaboration, electrical engineers and computer scientists from universities and DOE's national laboratories are developing algorithms to more effectively simulate the operation of very large electricity networks on high-performance computers, to leverage patterns of complexity in the electrical system to generate better predictive models, and to better predict cascading failures in short intervals.

Simulation of systems as large as the U.S. electric power system with high spatial and temporal resolution can quickly surpass current modeling capabilities and computing speeds. However, as simulation skill and capability develops, there will be increasing opportunities to identify improved architectures, strategies, and control systems that meet emerging needs while maintaining stability.

2.3.2 Transportation Networks

Networks of roads, rails, waterways, and airports on which hundreds of millions of vehicles travel, facilitate movement of people and cargo on billions of trips across trillions of miles each year in the United States. Complex systems analysis techniques are already in use, analyzing traffic patterns and helping to optimize shipments of freight. For example, information about traffic (via the sight-lines of drivers) has historically propagated locally over very short distances. The interactions between vehicles (via control inputs of steering, acceleration, and braking) have occurred on human-actionable timescales. These highly localized and relatively slow interactions give rise to macroscopic patterns of traffic congestion that cannot be predicted with models of traffic as a simple continuum flow. Rather, more intricate models of vehicle interaction are required, and their application results in far more accurate simulations.[31]

Today, a new layer of complexity is emerging in the transportation system—autonomous and connected vehicles. Much like the new layers of complexity that are affecting the performance of the electric grid, these vehicles stand to benefit the entire transportation system. Well-designed smart vehicle systems may reduce traffic fatalities, reduce traffic congestion and optimize drive cycles for greater efficiency. They may also reduce capital costs if transportation is delivered as a service that replaces traditional vehicle ownership.

Connected and autonomous vehicles likely will receive traffic and routing information from the Internet based on local and wide-area congestion conditions. The vehicles may engage in local vehicle-to-vehicle communications of position, velocity, acceleration, and “intent”[32] that would increase both safety (collision avoidance)[33] and efficiency (“platooning”).[34] Autonomous vehicles likely will function in much the same way that traditional vehicles do—applying control inputs in response to visible (e.g., camera, radar) cues in the local environment, but at a much increased response rate compared to their human counterparts.[35] These local and global interactions are likely to give rise to new macroscopic traffic phenomena. Designers and operators of such systems will need to leave room for the networks to evolve with behaviors that improve the safety and efficiency transportation beyond what is initially envisioned. The impacts of these new transportation technologies on energy use, however, are unknown and range from improved efficiency reducing energy use to increased trips resulting in increased energy use.

2.3.3 Urban Systems

Cities are complex, multiscale, adaptive systems whose most important feature is their population density.[36] Cities also are manifestations of densely packed interdependent infrastructure networks. These networks include not only energy (electricity, gas, and liquid fuel) supply and distribution, but also water supply and sanitation, communications, public and private transportation, food distribution and service, health care delivery, and emergency services.

While humans, with limited and error-prone decision-making abilities, are the most unreliable component of the network, they also are the best able to adapt and recover from off-normal conditions.[37] Technologies that assist urban citizens to optimize energy use, minimize environmental damage, and avoid and/or recover quickly from emergency conditions are of increasing interest.

In urban systems, multiple infrastructures interact on multiple timescales, from minutes (in the case of emergency response) to decades (in the case of infrastructure planning). Incorporating energy, end-use services, and the environmental consequences of energy consumption into the complex system models that support urban operations and planning is a relatively new endeavor. Institutes such as the Center for Urban Science and Progress at New York University[38] are finding ways to improve urban systems simulation with the massive amounts of data that are newly available from the information technologies rapidly penetrating the consumer, commercial, and municipal markets.

2.4 Conclusion

The energy economy is a deeply nested and interconnected system of systems. The six chapters that follow—**Grid**, **Power**, **Buildings**, **Manufacturing**, **Fuels**, and **Transportation**—are the first layer of a set of organizing principles for assessing energy technology RDD&D opportunities.

The opportunities for systems research within each chapter can be broken down into two overlapping classes: 1) energy systems integration, and 2) complex systems and networks. This chapter has briefly surveyed these opportunities. The subsequent chapters will examine the opportunities in the context of specific technology advances that can affect the overall energy system.

Table 2.1 Crosscutting Technology Table

Crosscutting theme description	Crosscutting technology	Sectors affected
Grid Modernization describes the transition from a centrally-controlled, system with one-way power flows in distribution to a much more distributed, stochastic, and dynamic system with bi-directional flows in distribution. Growth in the deployment of variable generation, electronic converters, and digital communications and control technologies is impacting core characteristics of the electricity system. Grid-related technologies need to evolve with the changing supply and end-use technologies landscape. Simultaneously, the RDD&D associated with technologies that connect to the grid (e.g., renewable power supplies, efficient motor controllers, electric vehicles, and smart loads) should consider the evolving interface with the grid.	Microgrids	**Grid**, Buildings, Manufacturing
	Demand response and dynamic pricing	**Grid**, Buildings, Manufacturing, Transportation
	Distributed generation	**Grid**, Buildings, Manufacturing, Power
	Physical and synthetic inertia	**Grid**, Power
	Generation flexibility	
	Electric vehicles	**Transportation**, Grid
	Power electronics	**Manufacturing**, Grid, Buildings, Power, Transportation
Systems integration recognizes that energy systems are becoming increasingly interconnected to each other as well as to other systems such as water systems and material supply chains. Potential benefits of integrated systems include efficiency, resource savings, reduced GHG emissions and increased resiliency. There are also challenges and risks associated with systems integration such as potential bottlenecks and points of failure. Appropriate application of systems integration requires understanding, control, and optimization across multiple sectors (e.g., fuels, power, thermal, and water), time frames (fractions of a second for operations to years for planning), spatial scales (devices, buildings, campuses, city, region/state, nation), and functions (e.g., data, analysis, controls, and markets). Integration also requires an understanding of costs, particularly the capital costs of deploying new and/or integrative technologies, but also the financial implications of deployment and operations. Integration of technologies such as fuel cells, energy storage, rooftop solar, and microgrids will all be affected by systems integration strategies. The results of such research could help system designers and operators to optimize the operations of interconnected systems with appropriate risk mitigation, including such strategies as appropriate system sizing and graceful disconnection.	Polygeneration	**Fuels,** Power
	Hybrid generation	**Power**
	CO_2 as a working fluid	
	Combined heat and power	**Manufacturing**, Power, Buildings
	Waste heat recovery	**Manufacturing**, Buildings, Transportation, Power
	Carbon management	**Power**, Manufacturing

Table 2.1 Crosscutting Technology Table (continued)

Crosscutting theme description	Crosscutting technology	Sectors affected
Cybersecurity is essential to the increased use of ICT in modernizing energy systems. The proliferation of computer controlled, wireless and/or Internet-connected energy devices creates a growing attack surface for cyber intrusion. Cybersecurity is being actively investigated for the electricity system, but is also a concern for SCADA hardware and evolving smart and connected systems that control fuels production, power generation, building energy use, and manufacturing facilities. It will also be increasingly important to automated and connected vehicles in the transportation sector.	Cybersecurity	**Grid**, Power, Buildings, Manufacturing, Transportation, Fuels
The energy-water nexus describes the water demands of energy extraction and conversions, and the energy demand of supplying fresh water and managing wastewater. In the fuels sector, the water injected into, and returned from, hydraulically fractured oil and gas wells and the irrigation water required to produce biofuel crops are the primary energy-water concerns. In the power sector, water used for cooling thermal power plants (coal, gas combined cycle, nuclear, etc.) is the largest category of water withdrawal in many regions. Process and cooling water is also a critical resource in energy-intensive industries, and the energy used to supply water to agricultural, residential, and manufacturing consumers is a significant percentage of total energy demand in some locations.	Produced water management	**Fuels**
	Agricultural best practices	
	Low-water and dry cooling	**Power**, Manufacturing
	Process intensification	**Manufacturing**, Fuels, Power, Buildings
	Energy harvesting from wastewater	**Manufacturing** (also Municipal Systems)
Subsurface science and technology enables understanding and control of fracture, fluid flow, and chemistry in underground rock formations. Because most phenomena in the subsurface cannot be observed directly, significant advances in remote sensing and simulation are required to advance the state of the art. Similarly, because subsurface environments are often hot, highly pressurized and remote, advancements in well drilling, completion, and fluids management can make subsurface energy operations more safe, environmentally responsible, and cost effective. In addition to oil and gas, enhanced subsurface science and technology addresses: 1) geothermal energy, which requires maintenance (and sometimes creation) of networks of underground fractures in hot rocks; 2) carbon dioxide sequestration, which requires flow and caprock seal assurance, as well as characterization of potential storage reservoirs; and 3) nuclear waste disposal in a geologic repository, which requires multi-thousand-year simulations to ensure that future generations will be protected.	Drilling and completion	**Fuels**, Power
	Fracture mechanics	
	Advanced proppants	
	Multi-physics porous media flow simulation	
	New subsurface signals	

Table 2.1 Crosscutting Technology Table (continued)

Crosscutting theme description	Crosscutting technology	Sectors affected
Materials influence the performance and cost of nearly all energy technologies. Development of materials is application specific. Identification, development, and production of advanced materials is a substantial enabling science, engineering, and manufacturing challenge. R&D activities on critical materials crosscut the power and transportation sectors (permanent magnet motor/generators) and the buildings sector (phosphors for lighting). Wide bandgap semiconductors are applicable to the grid, power, manufacturing, buildings, and transportation sectors. Functional materials such as membranes, catalysts and photovoltaics have a similarly broad reach, including advanced fuels production. Strong and lightweight materials are critical to transportation system efficiency. Materials for harsh service conditions are engineered to variously withstand high pressure, high temperature, corrosive environments, and radiation in boilers for applications in the power sector and downhole environments in the fuels sector.	Critical materials	**Manufacturing**, Power, Buildings, Transportation
	Wide bandgap semiconductors	**Manufacturing**, Grid, Power, Buildings, Transportation
	Functional materials	**Manufacturing**, Fuels, Power, Buildings
	Lightweight materials	**Transportation**, Manufacturing, Power
	Materials for harsh service conditions	**Manufacturing**, Fuels, Power, Transportation
	Working fluids	**Buildings**, Power, Manufacturing
	Additive manufacturing	**Manufacturing**, Power, Transportation
	Roll to roll manufacturing	**Manufacturing**, Power, Buildings, Transportation
Fuel-engine co-optimization. Engine performance, which drives efficiency across the entire transportation fleet, can be limited by the properties of the fuels available. With bio-derived, and/or other synthetic fuels, there is an opportunity to optimize the end-to-end fuel-vehicle system for improved efficiency and reduced environmental impacts. Engines that take advantage of the special properties of appropriately engineered fuels may be able to operate at higher compression ratios and under alternate combustion regimes (homogeneous or partly stratified charge). Similarly, fuels derived from non-petroleum feedstocks can be formulated for use in advanced technology engines. A co-optimized fuel and engine system therefore has the potential to improve fleet-scale efficiency and reduce vehicle GHG emissions. Fuels derived from low, zero or negative-carbon feedstocks and processes will result in further emission reductions. Foundational science and technology research that crosscuts the fuels and transport sectors is required to achieve these goals.	Combustion	**Transportation**, Fuels, Manufacturing
	Fuel design	**Fuels**, Transportation

Table 2.1 Crosscutting Technology Table (continued)

Crosscutting theme description	Crosscutting technology	Sectors affected
Energy storage is important to a modernized electric grid, and also for electric vehicles, albeit with vastly different requirements. Flexible, low-cost, high round-trip-efficiency storage technologies can provide short term (frequency support) and long-term (firming, arbitrage) services to the electricity system. Alternatives to hydrocarbon fuels such as hydrogen and batteries are under investigation for electric vehicles. Fundamental research on development and manufacturing of efficient, durable, low-cost, high energy-density storage could enable transformational change across multiple sectors.	Batteries	**Transportation**, Grid, Manufacturing
	Hydrogen	**Fuels**, Transportation, Manufacturing, Power, Grid
	Thermal storage	**Power**, Grid, Buildings
	Flywheels	**Grid**, Transportation
	Pumped hydro, compressed air energy storage	**Grid**, Power
Computational modeling and simulation represents a set of tools that enable better understanding and design of complex natural and energy systems. Large increases in computational capability, driven both by advances in chip technology and integration of more processors into massively parallel supercomputers, can impact all stages of the RDD&D process. Research in areas such as materials for extreme environments, biofuel production, and photovoltaics can be accelerated thanks to larger and more complex simulations. In all of these areas, increases in computing power, the development of new mathematical algorithms, and increased integration of simulation with experimental validation will increase the importance of advanced simulation in energy technology.	Processor technology	**Grid, Power, Buildings, Manufactring, Fuels, Transportation**
	Parallelization	
	Algorithms	
	Integration of simulation with experimental validation	
Data and analysis. Opportunities to apply advanced analytics and management of extremely large data sets transect the entire clean energy economy. In particular, the ability to obtain actionable information from an ever-increasing quantity of data ("big data") is both an opportunity and a research need. Increasingly inexpensive and effective ways to monitor and control data-dense energy systems is enabling novel and potentially more resource-efficient transaction-based control. Enhanced abilities to establish complex correlations in massive and disparate data sets and by automatically synthesizing the results of large numbers of research studies, can materially advance the scientific process.	"Big data" tools	**Grid, Power, Buildings, Manufactring, Fuels, Transportation**
	Semantic processing	
	Data dense monitoring and control	

Table 2.1 Crosscutting Technology Table (continued)

Crosscutting theme description	Crosscutting technology	Sectors affected
Analysis of complex systems. Given the convergence of the energy system and its technical systems, advancements in the discipline of analysis of complex systems need to be coupled with the benefits of the confluence of theory, modeling, synthesis, and characterization and advancements in computational modeling and simulation, data and analysis, and decision science (including risk analysis) to effectively facilitate the transition to a clean energy economy.	Complex networks	**Grid, Power, Buildings, Manufacturing, Fuels, Transportation**
	Complex systems	
	Model validation	
	Risk and uncertainty quantification	
Characterization and control of matter at multi-scales. Extraordinary advances in characterization and modeling of materials and chemistry have paved the way for design and control of materials at the atomic, nano-, and mesoscale to create new tailored functionalities.	X-ray light sources	**Grid, Power, Buildings, Manufactring, Fuels, Transportation**
	Neutron sources	
	Nanoscale materials theory, synthesis, fabrication, and characterization	

Endnotes

[1] Carreras, B. A.; Newman, D. E.; Dobson, I. "Does Size Matter?" *Chaos: An Interdisciplinary Journal of Nonlinear Science* (24:2), 2014; 023104. Available at: http://dx.doi.org/10.1063/1.4868393.

[2] Buldyrev, S. V.; Parshani, R.; Paul, G.; Stanley, H. E.; Havlin, S. "Catastrophic Cascade of Failures in Interdependent Networks." *Nature* (464:7291), 2010; pp. 1025-1028. Available at: http://dx.doi.org/10.1038/nature08932.

[3] "Final Report on the August 14, 2003, Blackout in the United States and Canada." Federal Energy Regulatory Committee, U.S.-Canada Power System Outage Task Force, April 2004. Accessed April 21, 2015: http://www.ferc.gov/industries/electric/indus-act/reliability/blackout/ch1-3.pdf.

[4] "Cybersecurity for Smart Manufacturing Systems." National Institute of Standards and Technology, March 2014. Accessed March 30, 2015: http://www.nist.gov/el/isd/cs/csms.cfm.

[5] Bartos, M. D.; Chester, M. V. "The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona." *Environmental Science and Technology* (48), 2014; pp. 2139-2149. Available at: http://dx.doi.org/10.1021/es4033343.

[6] McCalley, J.; Krishnan, V.; Gkritza, K.; Brown, R.; Mejia-Giraldo, D. "Planning for the Long Haul." IEEE *Power & Energy Magazine* (11:5), 2013; pp. 24-35. Available at: http://dx.doi.org/10.1109/mpe.2013.2268712.

[7] Buldyrev, S. V.; Parshani, R.; Paul, G.; Stanley, H. E.; Havlin, S. "Catastrophic Cascade of Failures in Interdependent Networks." *Nature* (464:7291), 2010; pp. 1025-1028. Available at: http://dx.doi.org/10.1038/nature08932.

[8] Newman, D. E.; Nkei, B.; Carreras, B. A.; Dobson, I.; Lynch, V. E.; Gradney, P. "Risk Assessment in Complex Interacting Infrastructure Systems." System Sciences, 2005. HICSS '05. Proceedings of the 38th Annual Hawaii International Conference, January 3–6, 2005; p. 63c. Available at: http://dx.doi.org/10.1109/HICSS.2005.524.

[9] U.S. Department of Energy, "The Water-Energy Nexus: Challenges and Opportunities", June 2014. http://www.energy.gov/downloads/water-energy-nexus-challenges-and-opportunities.

[10] Morrow, W. R., III; Gopal, A.; Fitts, G.; Lewis, S.; Dale, L.; Masanet, E. "Feedstock Loss from Drought Is a Major Economic Risk for Biofuel Producers." *Biomass & Bioenergy* (69), 2014; pp. 135-143. Available at: http://dx.doi.org/10.1016/j.biombioe.2014.05.006.

[11] "Air to Water Heat Pump Systems." Daikin Industries Ltd., 2015. Accessed March 28, 2015: http://www.daikin.com/products/ac/lineup/heat_pump/index.html.

[12] "Defender Safety System and Non-defender TTW2 Power Vent Water Heaters." Bradford White Water Heaters, 2015. Accessed March 28, 2015: http://www.bradfordwhite.com/defender-safety-system-and-non-defender-ttw2-power-vent-models.

[13] "SolarWall PV/Thermal Hybrid Solar Heating." Conserval Engineering Inc. 2014. Accessed March 28, 2015: http://solarwall.com/en/products/pvthermal.php.

[14] Cates, M. R., "Hybrid Lighting: Illuminating Our Future." *Oak Ridge National Laboratory Review* (29:3), March 1996. Oak Ridge, TN. Accessed April 27, 2015: http://web.ornl.gov/info/ornlreview/rev29_3/text/contents.htm.

[15] "All In One 24-inch Compact Washer/Dryer." LG Electronics, 2015. Accessed March 28, 2015: http://www.lg.com/us/washer-dryer-combos/lg-WM3455HW-washer-dryer-combo.

[16] "Multifunction Printers." Xerox Corporation, 2015. Accessed March 28, 2015: http://www.shop.xerox.com/shop/office-equipment/multifunctions.

[17] Liu, G.; Larson, E. D.; Williams, R. H.; Kreutz, T. G.; Guo, X. "Making Fischer-Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis." *Energy & Fuels* (25), 2011; pp. 415-437. Available at: http://dx.doi.org/10.1021/ef101184e.

[18] "Climate Change 2014: Synthesis Report, Summary for Policymakers." Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, November 2014. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf.

[19] Helbing, D. "Globally Networked Risks and How to Respond." *Nature* (497:7447), 2013; pp. 51-59. Available at: http://dx.doi.org/10.1038/nature12047.

[20] Ibid.

[21] Carreras, B. A.; Lynch, V. E.; Dobson, I.; Newman, D. E. "Complex Dynamics of Blackouts in Power Transmission Systems." Chaos (14:3), September 2004; pp. 643-652. Available at: http://dx.doi.org/10.1063/1.1781391.

[22] Carreras, B. A.; Newman, D. E.; Dobson, I.; Poole, A. B. "Evidence for Self Organized Criticality in a Time Series of Electric Power System Blackouts." *IEEE Transactions on Circuits and Systems I* (51:9), September 2004; pp. 1733-1740. Available at: http://dx.doi.org/10.1109/TCSI.2004.834513.

[23] Bar-Yam, Y. "General Features of Complex Systems." Chapter 1. Kiel, L. D., ed. Knowledge Management, Organizational Intelligence and Learning, and Complexity. *In Encyclopedia of Life Support Systems (EOLSS)*. Paris, France: Developed under the Auspices of the UNESCO, Eolss Publishers, 2002. Available at: http://www.eolss.net.

[24] Braha, D.; Minai, A.; Bar-Yam, Y. "Complex Engineered Systems: A New Paradigm." Chapter 1. Braha, D.; Minai, A.; Bar-Yam, Y., eds. *Complex Engineered Systems*. New York, NY: Springer, 2006; pp. 1-21.

[25] Helbing, D. "Globally Networked Risks and How to Respond." *Nature* (497:7447), 2013; pp. 51-59. Available at: http://dx.doi.org/10.1038/nature12047.

[26] Buldyrev, S. V.; Parshani, R.; Paul, G.; Stanley, H. E.; Havlin, S. "Catastrophic Cascade of Failures in Interdependent Networks." *Nature* (464:7291), 2010; pp. 1025-1028. Available at: http://dx.doi.org/10.1038/nature08932.

[27] Newman, D. E.; Nkei, B.; Carreras, B. A.; Dobson, I.; Lynch, V. E.; Gradney, P. "Risk Assessment in Complex Interacting Infrastructure Systems." System Sciences, 2005. HICSS '05. Proceedings of the 38th Annual Hawaii International Conference, January 3-6, 2005; p. 63c. Available at: http://dx.doi.org/10.1109/HICSS.2005.524.

[28] Ibid.

[29] Reis, S. D. S.; Hu, Y.; Babino, A.; Andrade, J. S.; Canals, S.; Sigman, M.; Makse, H. A. "Avoiding Catastrophic Failure in Correlated Networks of Networks." *Nature Physics* (10), September 2014, pp. 762-767. Available at: http://dx.doi.org/10.1038/nphys3081.

[30] "Multifaceted Mathematics for Complex Energy Systems (M2ACS)." Annual Report FY 2014. September 2014 (internal only).

[31] Helbing, D. "Traffic and Related Self-driven Many-particle Systems." *Reviews of Modern Physics* (73:4), 2001; pp. 1067-1141. Available at: http://dx.doi.org/10.1103/RevModPhys.73.1067.

[32] Kumar, S.; Shi, L.; Ahmed, N.; Gil, S.; Katabi, D.; Rus, D. "CarSpeak: A Content-Centric Network for Autonomous Driving." *ACM Sigcomm Computer Communication Review* (42:4), 2012; pp. 259-270. Available at: http://dx.doi.org/10.1145/2377677.2377724.

[33] Reichardt, D.; Miglietta, M.; Moretti, L.; Morsink, P.; Schulz, W.; Inria, I. "CarTALK 2000 Safe and Comfortable Driving Based upon Inter-vehicle-communication." *IV 2002: IEEE Intelligent Vehicle Symposium, Proceedings*, 2002; pp. 545-550. Available at: http://dx.doi.org/10.1109/IVS.2002.1188007.

[34] Li, F.; Wang, Y. "Routing in Vehicular Ad Hoc Networks: A Survey." *IEEE Vehicular Technology Magazine* (2:2), 2007; pp. 12-22. Available at: http://dx.doi.org/10.1109/mvt.2007.912927.

[35] Levinson, J.; Askeland, J.; Becker, J.; Dolson, J.; Held, D.; Kammel, S.; Kolter, J. Z.; Langer, D.; Pink, O.; Pratt, V.; Sokolsky, M.; Stanek, G.; Stavens, D.; Teichman, A.; Werling, M.; Thrun, S. "Towards Fully Autonomous Driving: Systems and Algorithms." 2011 IEEE Intelligent Vehicles Symposium (IV), 2011; pp. 163-168. Available at: http://dx.doi.org/10.1109/IVS.2011.5940562.

[36] Lugaric, L.; Krajcar, S.; Simic, Z. "Smart City—Platform for Emergent Phenomena Power System Testbed Simulator." Innovative Smart Grid Technologies Conference Europe (ISGT Europe), October 11–13, 2010, Gothenburg, Sweden. *IEEE PES* (1:7), 2010; pp. 11-13. Available at: http://dx.doi.org/10.1109/ISGTEUROPE.2010.5638890.

[37] Amin, M. "National Infrastructures as Complex Interactive Networks." Chapter 14. Samad, T.; Weyrauch, J., eds. *Automation, Control and Complexity: An Integrated Approach*. ISBN: 0-471-81654-X. West Sussex, England: John Wiley and Sons, 2000; pp 263-286.

[38] "Urban Informatics." Center for Urban Science and Progress (CUSP) at New York University (NYU), 2015. Accessed February 15, 2015: http://cusp.nyu.edu/urban-informatics/.