The 3 R's of Critical Energy Networks: Reliability, Robustness and Resiliency

A White Paper Submitted to the MIT Energy Research Council[1]

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I. Framing the Problem

Energy comes in many forms: coal, oil, natural gas, nuclear, geothermal, wind, tidal, solar and more. Once collected at the source it is transported over networks that transform the raw power represented by the natural resource into useful energy products -- gasoline, electricity, natural gas, steam, etc. These products are then used to fuel our economy and support our lifestyles.

Many networks are involved in the collection, transport, transformation, and final delivery of energy to ultimate consumers. Additional, coupled networks are involved in the use of the delivered energy to fuel our vehicles, heat our homes, light our cities, etc. The delivery networks include gas and oil pipelines, the highway system, electricity transmission networks, etc. The usage networks include transportation networks (land, air, and sea), telecommunication networks, and the "end nodes" of certain transmission networks (e.g., private homes using electricity, natural gas, and/or oil). The two dominant US energy networks are 1) the system that produces, distributes, and delivers electrical energy and 2) the fuel system that brings fossil fuels from sources through pipelines to refine, store, and use for manufacturing, heating, and mobility.

The electrical system is under stress from growth of demand, the impacts of deregulation on new investment, and the lack of coordinated strategic planning to secure the present system and robustly expand it for the future. A recent rash of blackouts gives ample proof of its insecurity. The fuel network is largely privately owned and as indicated by the recent Hurricane Katrina event is vulnerable to disruption that can cripple the economy of the US. There is significant evidence that interconnectedness can lead to cascading failures both within *and* between the two systems. More electricity generation in the US is from fuels such as natural gas. In Hurricane Katrina, loss of electricity led to loss of pumps to move fuels for more than 30 percent of US demand. Loss of electricity also closed cell phone communications, hampering relief efforts.

The 3-R's critical energy networks project will study coupled energy networks with the goals of (a) increasing the reliability/resiliency/robustness of our networked infrastructure in the face of numerous uncertainties and (b) reducing capacity growth in these networks by reducing energy demands or deferring them from peak time periods. The 3 R's, while related, are somewhat different and cover the required spectrum of solidly performing networked infrastructure. ***Reliability*** means dependable and steadfast, not prone to random breakdowns perhaps due to component failures. For example, an electrical system is made more reliable by increasing the *mean time to failure* (MTTF) of components such as transformers. ***Robustness*** is strength and sturdiness, such as the encasement housing of a nuclear reactor. Or, a residential electrical distribution network that is underground is usually more robust than an above ground system using wooden poles. ***Resiliency*** implies a flexible and pliant system, able to bend under stress without breaking. An electrical distribution network that can shed loads gracefully on hot days, under contracts negotiated with large energy consumers, is resilient in the face of unusually large demands. The network is also resilient if it minimizes disruptions in service during unplanned equipment failures by reducing the risks of cascading failures characteristic of major blackouts.

We seek to undertake research that leads to improvements in each of the 3 R's for critical energy networks. We propose (1) to develop system models with sufficient fidelity to identify weaknesses in energy networks as well as potential for cascading failures; (2) to design and analyze new methods for improving infrastructure, taking into account the interactions with legacy systems; (3) to improve real-time monitoring and control of energy networks; (4) to develop new technologies for transmitting and storing energy; (5) to determine how economic and regulatory incentives can be used to direct investment for improving the network

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infrastructure; and (6) to reduce needed network capacity by decreasing peak energy demands via incentives and technologies for time-shifting the demand to off-peak hours.

As described below, the 10- to 20-year research program could involve all five schools of MIT, with major contributions from engineering, the natural and social sciences, and management. The program could involve collaboration with other key institutions.

II. Improving the 3 R's Performance of Coupled Critical Energy Networks

The networked energy infrastructure in the US is a complex, multifaceted patchwork of pipelines, roadways, railroads, waterways, power lines, generation plants, transformers, refineries, storage facilities, and much more. Most of it is privately owned, some is publicly owned, and much of the privately owned infrastructure is publicly regulated. Regulatory constraints derive from state and federal legislation, with the multitude of state requirements, e.g. vehicle emissions controls, in effect Balkanizing the country and virtually guaranteeing diminished economies of scale in order to meet state-specific requirements. In the case of gasoline, this means that the supply chain system that operates the oil-to-gasoline energy distribution network must create and distribute a whole host of different products to various parts of the US. The risks of shortages and disruptions are greater when one is dealing with many different products over the network.

Since our focus is on resiliency, reliability, and robustness, we are particularly concerned with how strategic, tactical, and operational decision-making affects these performance characteristics. An electric power distribution network that allows a massive blackout due to a sagging line on a hot day touching a tree limb is not resilient or robust. But identifying and ameliorating all aspects of the "system operation" that pertain to that risk is a large task because the nation's electric power distribution "system" is in fact a concatenation of many different local systems tied together by a variety of physical and procedural connections. Local control of a sub-network does not often work well for the entire system. Local instabilities can cascade and multiply into large system failures. Response to the tree limb problem is an operational one, but operations have been guided and constrained by tactical and strategic decisions previously made. Full analysis extends far beyond Maxwell's equations into organizational complexity (many private and public sector organizations), political realities, historical precedent, and more.

The "tree limb" problem can serve as a metaphor for many types of small system uncertainties that can glow into large malfunctions. More generally, we wish to consider the full range of probabilistic events that may occur, usually associated with four sources: "Mother Nature," human-caused accidents, computer software-caused problems and terrorist attacks. Mother Nature, as she has recently shown, can wreak havoc with hurricanes, tornadoes, earthquakes, floods, drought, large temperature deviations, and other phenomena. Human-caused accidents may be small or large, an example of the latter being the Chernobyl meltdown. A lack of sufficiently resilient software for managing intended or unintended events in these complex coupled networks is analogous to the human body functioning without its nervous system. Computer-software caused problems have been known to contribute significantly to cascading effects during several electric power blackouts. A terrorist attack not only destroys the immediate infrastructure, but also may cause reactive responses that negatively affect much of the remaining undamaged infrastructure. An example is the nation-wide, security-focused, massive disruption of our supply chains linking the US with Canada, Mexico, and other countries immediately following 9/11/01. This caused a substantial re-evaluation of an idea then held in good currency – JIT – *Just in Time* supply chains; while efficient they did not prove resilient. One of the challenges is methodological development of tools that allow for resiliency during unexpected events and, at the same time, efficiency during more normal conditions.

One promising course of immediate action would be to map in detail the entire set of energy infrastructure networks in the US and overlay that with a hazard map of risks due to the four sources of risk mentioned above. For human-caused accidents and terrorist attacks, there would likely be insufficient sample sizes to use relative frequencies as guides to probabilistic risk. In such cases, one would resort to Bayesian methods and/or scenario analyses. One could find much statistical evidence supporting computer-software problems related to major malfunctioning of the physical systems. Special attention would be placed on correlated risks, such as a hurricane disabling in its path a number of network-coupled assets, or a terrorist attack disabling one network (e.g., electrical) that is necessary for another network's assets (e.g., refineries) to function. This is what we mean by "coupled networks." Of particular interest are correlations between physical failures and computer-software malfunctioning. The research would attempt to identify large risks that are potentially massively disruptive to the American economy and lifestyle. And it would try to find ameliorating steps to reduce those risks to acceptable levels.

III. Themes for a Coupled Infrastructure Research Program

Theme 1: Improving the theory and practice of infrastructure networks analysis and design. Investigators will study how to detect weaknesses and potential cascading failures in existing and new systems through the development of better theory, models and methods, often assuming operation in an uncertain environment. The results will yield systems that integrate well with legacy systems as well as provide new approaches like decentralization, super grids, energy storage and hardening of energy intensive complexes. Network design or architecture will undoubtedly be influenced by our work, especially the aspect of our research that incorporates uncertainty in system behavior and operating environment. We see tradeoffs between efficiency and the 3 R's, the latter perhaps suggesting more local energy generation and/or storage facilities.

We intend to break down large scale, distributed, heterogeneous, interconnected systems into 3 "abstract" layers: The *physical (infrastructure) layer*, the *information layer*, and the *control/communication layer*. The first layer is concerned with the physical interconnections between the different energy systems that, at the most granular level, are very complex. The information layer sits on top of the physical layer and captures the real-time data available for processing either at a local level or a global level. This layer is often fed by sensors, and its history is stored in legacy databases that have evolved over the years and tend to be quite fragmented. But these databases contain enormous current and historical information through the extensive sensors and monitoring devices placed on various subsystems of the lower layer. The top layer describes the decision-making process, the information structure available to decision makers, and the communication network available to communicate such decisions. By exploiting the information layer, the top layer has the capacity to perform diagnosis, prediction, and distributed control and to communicate such decisions in an efficient and robust fashion.

Our work will focus on developing appropriate tools to derive decision-oriented multi-resolution dynamic models that can allow for prediction and distributed feedback control at an appropriate level of abstraction. The challenge is to develop "simplified" parsimonious models of such a complex dynamic system that capture its most critical behavior. Such models need to depict the "influence" that each subsystem has on the entire network, allowing for prediction of the overall performance of the network when degradations or failures occur in any of the subsystems. Such models should allow us to identify the critical components of the interconnected system to which the overall system is very sensitive. The models should encompass notions of cooperation as well as adversarial behavior in a realistic and meaningful way. New innovative tools for multi-resolution model reduction will be developed to address such a challenge.

Cascading Failures. Existing electric power networks are highly interconnected. Under normal circumstances this works well: the interconnections provide a highly reliable backup to power plants, providing power in the event of equipment failure. In highly stressed situations, however, the interconnection can (and does) cause cascading failures as the connecting transmission lines impose loads that draw power from otherwise healthy system areas to failing areas. The resulting large area failure is a 'blackout', and restoration takes an inordinately long time. In situations like this, deliberate 'islanding' of the network would allow small areas to 'go down' while preserving the rest of the interconnected network. Moreover, distributed small-scale energy sources could be strategically placed to ensure minimal service to the majority even during the extremely abnormal system conditions. The resulting small area failure could be restored more quickly. We seek to understand quantitatively the conditions that lead to blackout and methods for separating systems when cascading failures would occur, preserving the larger network.

The purpose of "dynamic" feedback is to decrease sensitivity to random failures in the subsystems (*reliability*), to enforce a graceful degradation of performance of the network as various subsystems degrade slowly (*resilience*), and finally enable drastic actions in the face of "large" perturbations (*robustness*). Examples of dynamic decisions to assure reliability, robustness, or resilience are abundant. For instance, timely resource re-allocation after a subsystem failure is detected can prevent cascaded failures of energy systems. Changing the operating conditions of power plants if data predict certain deteriorations can result in minimal degradation of performance. Finally, performing a subsystem “graceful shutdown” in order to preserve the overall network is another example of dynamic decision making enhancing robustness. New innovative real-time distributed decision making methodologies need to be developed to address this challenge.

A robust communication network that connects various decisions and makes available necessary data from the information layer is critical to the success of such a design. Sharing data from different subsystems presents a challenge given the existing legacy databases and their incompatible interfaces. Such exchange has to be done without a human in the loop and as a result, the adoption of Open Source Platforms becomes quite necessary. The organization of the decision making process may end up being a combination of a hierarchical and distributed architecture, which necessitates automated open communication channels.

We anticipate that deriving the large scale multi-resolution models, automated decision making systems, and protocols for real time communication will entail developing new tools that can deal with the convergence of learning, control, communication, and computation. The group from LIDS has done pioneering work in this area.

Theme 2: Improving real-time monitoring and management using ITs, sensors, and controls.
This theme will focus on the ways in which new technology and organizational studies may be applied to each of the two critical coupled systems. These are now poorly organized in each mode, fuel and electricity, and there is no coherent coupling between systems. The research will pursue an enhancement of existing Supervisory Control and Data Acquisition (SCADA) systems for monitoring, managing and controlling the two critical systems and their interdependencies in a multi-modal manner. The legacy SCADA system will continue to serve as a basis during normal conditions. A future multi-layered SCADA system would be capable of 1) supporting much autonomous monitoring and control at the individual layers; 2) spatial and temporal multi-resolution of information exchange among the industry layers; and 3) minimal multi-resolution coordination among the layers. Introducing such a system and integrating it into the existing SCADA can be successfully done developing fundamental understanding of relevant sub-processes, and creating a family of models that capture such interacting sub-processes.

Theme 3: New technologies and strategies for producing, moving, and storing energy.
There are numerous ways to improve the technologies of the networks themselves that go beyond decentralization. These include superconductivity, better pumps, dual systems for moving and cooling energy flows, etc. These include technologies for better transmission that reduce losses and are more robust, the approach to better storage systems especially for electrical systems. Storage will be vital to bring intermittent renewable energy into the despatchable power needed by the grid for its stability. Work in chemical engineering on the ‘refinery of the future’ will focus on the handling of uncertainty in inflows, processes and outflows as the need for more refining capacity is addressed.

Theme 4: New approaches economic and regulatory incentives
The US energy system is a set of complex networks that is formed by the interconnections of private and public subsystems and serves a wide variety of consumers with different energy needs. A complete understanding of the operation of these networks requires analyzing the interactions between various entities that have multitude of economic interests and service requirements. Economic incentives of service providers have a first-order effect on their investment decisions that may lead to improved network infrastructure. The choice of pricing policies affects consumer demand for energy usage, thus impacting congestion management and network control schemes. A combined study linking economic incentives of service providers and users to alternative control algorithms is essential for the design and future evolution of energy networks.

In the proposed work, we will develop a systematic framework that studies the complex interactions between different stakeholders in the energy network. Our research will involve development of new mathematical tools to analyze these models and new efficient computational methods to characterize equilibrium and non-equilibrium strategies. We will study pricing and investment decisions of for-profit service providers that compete for user demand in energy markets. This requires us to analyze price competition models in the presence of congestion externalities, which take into account the congestion control schemes used in the communications layer of the energy network. Models that incorporate economic incentives and network control functions have been studied in the context of transportation and communication networks. Considerable progress has been made recently in understanding the behavior with competing service providers and decentralization of system-wide performance using feedback control signals. Our goal is to use similar models in the study and regulation of energy markets. In particular, we will compare the performance of models with a system-wide optimum and provide bounds on the losses in performance that result from lack of centralized coordination. For the cases when the performance loss is high, we will design appropriate incentives and centralized intervention schemes to regulate service provider behavior.

Theme 5: Reducing Network Capacity Requirements by Reducing or Deferring Consumption
Here we focus on reducing total and/or peak-hour energy consumption as a way to reduce required network capacity. The objective is to use technology-enabled innovations to encourage network owners and customers (individuals, companies, communities) to use less energy or to defer its use to off-peak times. While it may appear that this effort is distinctly different from the Themes 1-4, it is not; all are intimately connected. For example, a 5 percent reduction in energy demand implies that a network's capacity can be reduced by 5 percent, often saving billions of dollars. Or, a shift of time of usage from peak to off-peak, resulting in a 20 percent reduction in peak usage, would imply a 20 percent reduction in peak usage network capacity – a huge reduction. So, network capacity and perhaps even network architecture are influenced, often even determined, by usage statistics – total usage and time-of-day, day-of-week, season-of-year usage.

Deferral of energy usage to off peak times can be accomplished by dynamic pricing policies, using what the airlines call "revenue management." These ideas are already used in Singapore and London to discourage drivers from entering the central city at peak hours. Applying these concepts to electricity production and consumption can build on work done at MIT 15 years ago, under leadership of the late Professor Fred Schweppe. Currently, there is no real-time coupling between the consumer behavior and the networks' conditions. Degradation of performance, or even failures, can be eliminated by a timely feedback mechanism that influences consumer behavior. New innovative technologies need to be derived to enhance the consumer choices and provide usage restraints at critical times. Many uses for electricity and natural gas can be deferred, sometimes for many hours, without noticeably affecting lifestyle (e.g., running the dishwasher at 3:00 AM). Social policies that make these moves feasible and desirable could have a first-order impact on energy usage and thus required capacities of energy networks.

IV. MIT Resources and Needs to Perform this Research

Collectively, in this multidisciplinary research, we need to learn from historians, political scientists, management scientists, and regional planners as well as from engineers and scientists. Areas in which MIT does not have sufficient depth might be filled by faculty hires either through the new energy initiative or by departments in their regular processes. CEE, ESD, and AA searches recently have not been able to find the right 'critical infrastructure' candidate; we hope they will keep trying. Meanwhile, departments such as CEE, ESD, EECS, AA, DUSP, Economics, Political Science, and Sloan encompass a considerable body of ongoing research ready to come together. For example, EECS should be considering a return to its roots in electrical network systems, a promising research venture cut short by the untimely death of Fred Schweppe 1.5 decades ago. The collaboration among faculty members on this White Paper indicates that several people might step forward and lead such an effort. Existing organizations like LFEE or the ESD Center for Engineering Systems Fundamentals could be a natural home for this interdisciplinary effort.

Of the several sources for financial support, the major oil producers and their fuel transport components should be interested in how their systems may be expanded and protected from cascading failures. Similarly the electrical industry needs a thorough reworking of its present system both technically and organizationally. The investment community is interested in the incentives and regulations to be put in place to provide the needed investments from private funds. From a governmental point of view this problem is at the core of the mission of the Departments of Homeland Security, Defense and Energy. NSF may provide seed money.

Competition for funding and personnel is emerging; Illinois and Purdue and their partners have secured through their congressional delegations a grant of 7.5 million dollars per year for a new center. Other centers are Carnegie Mellon University in electrical systems and UC Berkeley. We would need to reach out to these communities to bring this activity to its proper level of about 20 to 30 faculty members and 100 graduate students in four schools.