15th Annual Conference on Systems Engineering Research
Disciplinary Convergence: Implications for
Systems Engineering Research

Eds.: Azad M. Madni, Barry Boehm
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Redondo Beach, CA, March 23-25, 2017

Interdependency effects on the electricity grid following a “Black Sky” hazard.

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Abstract

The protection of the Bulk Electric System in the face of large-scale threats like Electromagnetic Pulse and Geomagnetic Disturbances poses several unique systems engineering obstacles. This class of hazards, known as “Black Sky” hazards, trigger unprecedented outages due to the scale of the triggering phenomena. Traditional risk assessment models and recovery plans have core assumptions that generation, transmission, and distribution are unlikely to be simultaneously impacted, and that physical damage will be relatively localized; based on these assumptions, industry can access power from neighboring grid networks, and restore some level of service fairly quickly, even if the localized problem takes far longer to correct. In contrast, outages at the scale caused by these “Black Sky” hazards cannot be addressed by these traditional techniques. Before we develop effective recovery strategies from such “Black-Sky” events, new insights about root-causes at such a large scale are required. Some of these insights are provided in this paper.

We start with an overview of the operations of one Black Sky triggering event, an Electromagnetic Pulse attack, showing how such an event could operate at a scale of impact that is far larger than anything experienced.

We then show that, due to the interdependencies between the electricity, natural gas, and communications infrastructures, the large scale of the EMP triggering event introduces failure modes not experienced in previous power outages. We analyse some of the key failure modes that will occur in outages of this scale, and show that systems and processes developed for recovering from more common hazards will not be able to correct these new types of failures. We will also show that attempting to recover by using these conventional procedures actually has the potential to damage additional equipment, placing recovery farther away than ever.

We provide a more nuanced understanding of the natural gas delivery system that we believe will be vital to curbing the potential effects of major pipeline disruptions resulting from a hazard that precipitates an outage combined with the second-order effects from the loss of electricity to refining and pumping operations.

Keywords: emergency response; electro-magnetic pulse; large-scale disaster; interdependency

1. Statement of the Problem

The protection of the Bulk Electric System in the face of large-scale threats that directly effects electronics like Electromagnetic Pulse (EMP) and Geomagnetic Disturbances (GMD) poses several unique systems engineering obstacles. This class of hazards, known as “Black Sky” hazards, create unprecedented outages due to the scale of the triggering phenomena. Traditional risk assessment models and recovery plans rely on core assumptions that generation, transmission, and distribution are unlikely to be simultaneously impacted, and that physical damage will be relatively localized. Based on these assumptions, industry could follow standard practice and access power from neighboring grid networks to restore some level of service fairly quickly, even if the localized problem takes far longer to correct. This methodology allows for a rapid (less than 72 hours) recovery of a large percentage (more than 75%) of outages and minimizes the number of major infrastructure systems affected. This was the case even in a large-scale event such as Superstorm Sandy, where 70% of the 8,511,251 peak customer outages were restored within 5 days of the storm[i] making landfall was met in large part due to access to electricity outside the affected area and a minimal impact to bulk generation assets. Common practice for grid restoration follows a market and economic-driven approach of providing electricity to the maximum number of customers in the minimum amount of time. Response activities typically include a concerted effort to restore connectivity to targeted critical infrastructure, however the criteria for what classifies as critical is generally subjective and changes based on local government priorities. This methodology requires access to adequate generation assets (and their fuel sources) and power transmission to meet all load requirements, in addition to having sufficient numbers of trained personnel and equipment. In short, the means of restoration is largely dependent on the breadth of impact and the availability of the equipment and assets classified as “long-lead” due to their relative rarity and complexity of installation; high-voltage transformers, large generation assets and the transmission lines providing the connective tissue. Under these more “routine” circumstances, the unprecedented challenges that accompany an outage with widely distributed damage lasting weeks or months are mostly avoided, making them poorly understood and inadequately planned for.

By contrast, outages at the scale caused by “Black Sky” hazards cannot be addressed by traditional techniques due to the inherent complexity of their rarely experienced impacts. The defining characteristics of Black Sky hazards are a large geographic footprint and duration measured in weeks and months instead of hours and days. While the breadth of impact is largely attributable to the nature of the precipitating event, the duration is a combination of the scale of the hazard and a cascading impact on interdependent infrastructure systems essential for power generation and grid operation. This manifests in the form of 1) Load shortage – typically the result of extensive damage to the distribution system thus reducing demand to balance generation, 2) An inability to balance load – likely due to insufficient connectivity within the transmission system, or 3) Inadequate capacity of electricity to deliver because of damage to generation assets or a lack of fuel to operate. Any one of these factors experienced over a large enough area or for a long enough period of time necessitates a fundamental shift in how grid restoration is conducted. Instead of the standard customer and market-driven methodology described earlier, the electricity industry is forced to focus on protecting the backbone of the Bulk Electric System (BES) itself in order to re-start the system from within, a process known as “black start.” Designated black start generators are intended to serve as the “islands” of electricity upon which the rest of the grid will be restored beginning with the transmission corridors that connect them, known as “cranking paths.” Determining the amount of generation included in the black start plan is usually the responsibility of the Independent System Operator (ISO), or the Regional Transmission Operator (RTO) (figure 1), who operates as a balancing authority within the three larger interconnects in the United States (figure 2).

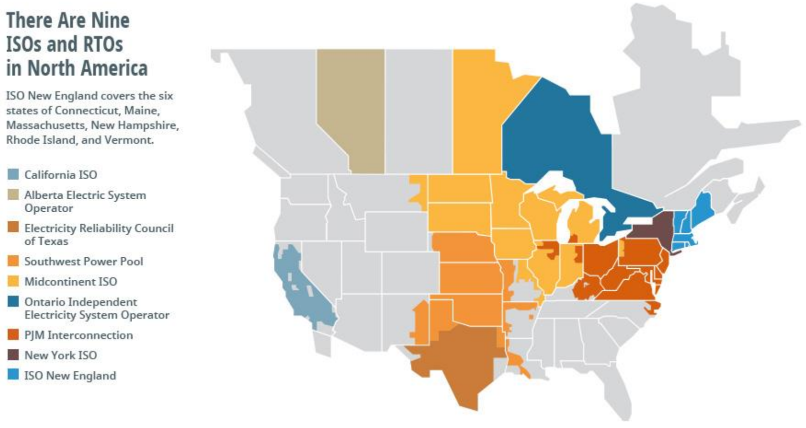

Figure. 1. Map of the nine Independent System Operators (ISO) of North America

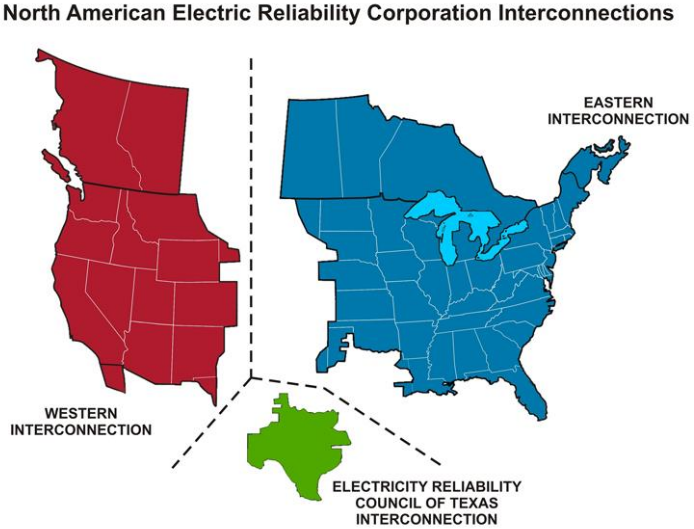

Figure. 2. Map of NERC Interconnections

The electricity demand served by the black start plan, known as “critical load,” consists of three primary categories of load customers: 1) Nuclear power stations in order to ensure their ability to go into safe shut down during an emergency, 2) “Hot start” generation plants that would be damaged without near-term restoration, and 3) Natural gas infrastructure, a term which is broadly defined and varies regionally. This process does not allow for much emphasis on power needs outside of the electricity sector and creates a circumstance where other life-support infrastructure systems are highly unlikely to be restored in a timeframe that aligns with any of their contingencies for alternate, back-up power. The result is a prisoner’s dilemma, where the decisions made by the electricity industry intended to preserve their internal requirements are done potentially at the cost of system they depend on. In the case of electricity delivery, the two most vital dependencies for effective operation are the communications systems needed to operate power flows over the grid and access to the primary fuel sources of generation. Any significant disruption of developing effective recovery strategies from such “Black-Sky” events, new insights about root-causes at such a large scale are required.

2. Constraints on potential solutions, and the resulting systems-engineering trade-space for candidate solutions

In order to solve the problems associated with energy restoration in a Black Sky event, it is important to understand the extent of interdependencies with communications and natural gas infrastructure in both a technical and an operational context. Additionally, the context of a particular hazard, in this case an Electromagnetic Pulse (EMP) attack and its unique effect on electronics, will demonstrate the complexity of the these constraints. Without this working knowledge, a myopic focus on the grid would not produce results that can be implemented successfully.

2.1 Communications Interdependency

Reliable and efficient delivery of electricity requires the careful balancing of load over vast distances between thousands of substations utilizing sophisticated Industrial Control Systems (ICS) and Supervisory Control and Data Acquisition (SCADA) systems housed in control centres (figure 3).

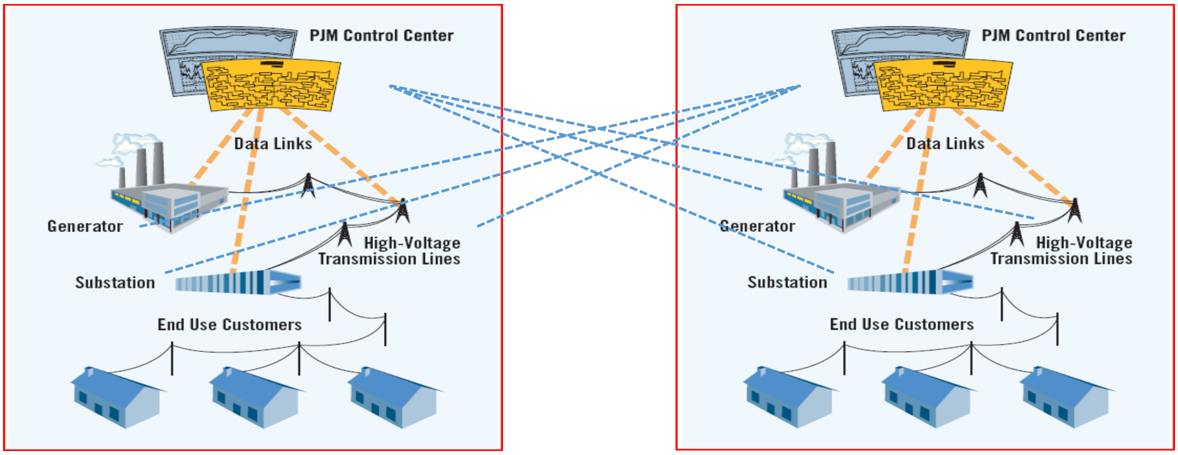

Figure. 3. PJM Interconnection Redundant Control Centre Model for grid optimization

The substantial majority of all substations are operated remotely, making them completely reliant on internet, voice, or fibre connectivity in order to inform a control centre of voltage levels, the status of breakers and relays, and the overall health of components[ii]. This connectivity also includes the “dispatch” of generation assets, which consists of remote commands brining more or less electricity on-line to match demand. Without access to these automated systems, manual operation is required to provide timely readings of demand and response signals at substations, and to locally operate breakers and equipment needed to alter power flows. This form of operation is not only logistically challenging due to personnel constraints, but the lack of real-time data in such a dynamic environment coupled with the comparative delay in operator activities means it is impossible to achieve the same level of grid efficiency in such circumstances and is likely to result in additional outages. While some redundancies exist within the industry to provide a means of back-up communication, there is a significant reliance on commercial communications systems that require access to sustainable grid electricity in order to function at a level needed to connect the thousands of endpoints in the grid network (figure 4).

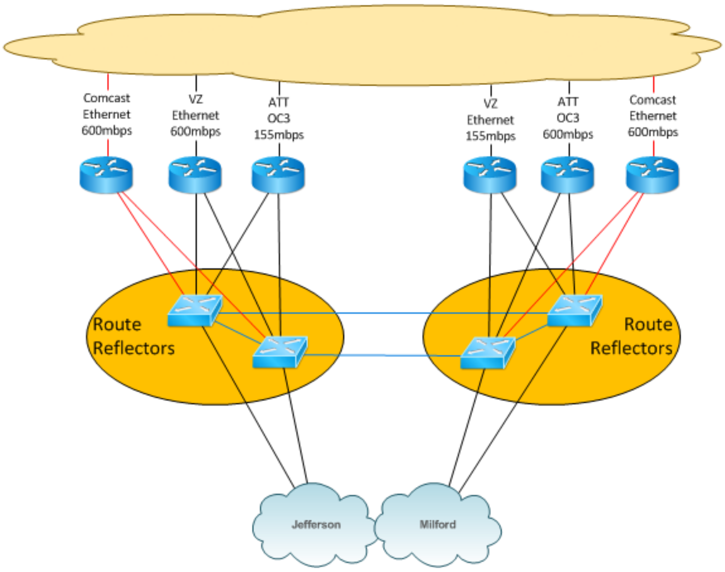

Figure. 4. PJM control centre internet connectivity for grid operations

The information carried by the communications networks is not limited to commands for grid operations, it also includes large quantities of data[iii] utilized for the creation of load forecasts used to anticipate future power requirements, and to operate the energy markets that sustain the financial models of the companies connected to it. While the operation of the grid is prioritized over the operation of the markets and data flows can be reduced to a quantity that is limited to critical functions, the loss of complete data will lead to inefficiencies that could threaten the entire system if the outage persists. Additionally, the grid is broken into transmission operator zones, marking a segment of operational data known as State Estimators (SE), which essentially aggregates the data and provides the means to balance the input and output of each zone. The loss of a single state estimator will immediately affect the system, but the extent of impact is dependent on both the relative size of the transmission operator zone and the duration of the outage. In the event that multiple SEs are down or one is down for an extended period of time, the overall balance of the system will continue to drift towards inefficiency and the unavoidable result would be outages if SEs are not restored.

The backbone of these systems is a highly interconnected network of cellular sites, switching stations, and data centres used to operate and control traffic over the various lines of communications. These sites are widely distributed and completely dependent on electricity, and while control centres are well-equipped to function on back-up generation for a period of 3-5 days, the communications infrastructure they rely is not as well equipped to handle long-duration outages.

2.1.1 Key Issues, Risk Areas, and Required Information.

There are several topics of research needed in order to conduct a systems-level analysis of the communications sector's interdependency with the electricity industry. Ongoing studies at organizations like the North American Transmission Forum's (NATF) Spare Tire project and the Electric Infrastructure Security (EIS) Council's BSX project[iv] identify some of the broad-level issues in this space. Both projects indicate that currently there are insufficient redundant communications systems to operate in this type of environment to operate with adequate sufficiency to operate in a Black Sky environment. However, more work within the electricity sector is needed to determine:

- How many communication end points within the electricity sector need to be connected in order to execute black start and operate the grid with enough efficiency in order to service critical load already identified?
- What is the type and quantity (bandwidth) of voice and data needed in order to accomplish the aforementioned critical tasks?

This information is vital to determining the base-level functionality of a dedicated communication system to operate in this environment.

2.2 Natural Gas Interdependency

Second only to a loss of communications, the greatest threat to the successful operation of the electricity is the loss of its primary fuel source for generation. While there is a relatively diverse base of fuel sources currently available, there are limitations of each fuel to function in a Black Sky environment and the trend line for fuel mix is rapidly changing (figure 3).

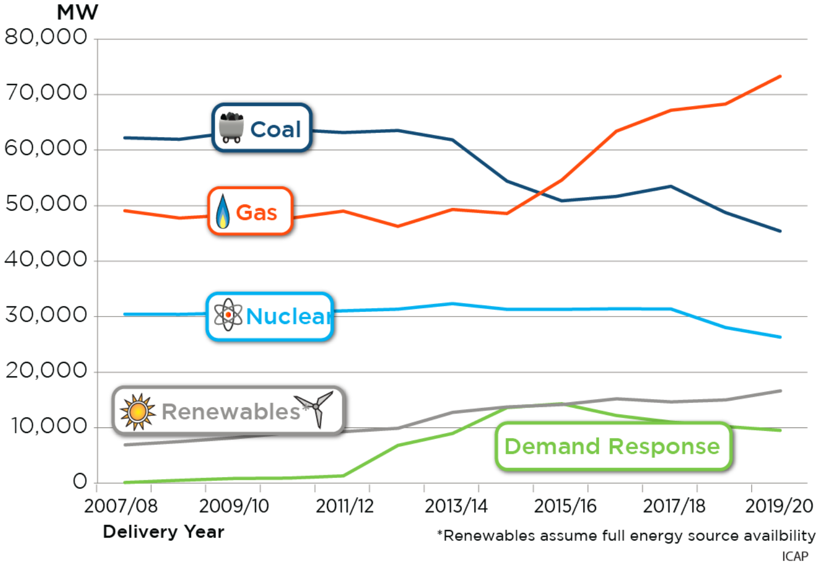

Figure 3. Trend line for fuel sources in PJM Market

As noted in the figure, natural gas surpassed coal as the largest source of generation in the PJM market in 2015 and is currently on pace to produce a substantially greater portion of the total within the next 3-5 years. The trend is largely the result of the dramatic increase in the availability of natural gas due to hydraulic fracturing resulting in significantly lower prices in the United States, and new emission standards for carbon output in electricity generation. This is especially relevant given the particular weakness of natural gas generation as a black start plant as compared to other fuel types when evaluated based on the criteria of fuel security, variable load functionality, and overall reliability on a scale of 1 (low) to 5 (high):

Black Start Capability	**Fuel Security (*t*)**	**Variable Load (*t*)**	**Reliability *(t)***
Nuclear	5	1	**4**
Coal	4	5	**5**
Renewable	3	2	**3**
Natural Gas	**3**	**5**	**5**

Table 1. Black start capability assessment.

Table 1 Definitions:

- Fuel security – On-site storage and the susceptibility of supply to be interrupted
- Variable Load – Ability of generation station to raise and lower output to meet demand
- Reliability – Track record of meeting generation dispatch when called upon

Nuclear generation sites typically have up to 18 months of fuel stored on-site and operate at a high level of reliability, but they do not have any variable load capability and are not authorized to operate without access to external grid electricity. Renewable sources such as wind and solar have some variable load capability under certain configurations and when combined with storage, but their fuel source is dependent on weather conditions and they are not as consistently reliable as other sources. Coal routinely maintains up to 6 months of fuel stored on-site and has an excellent record for reliability and variable load functionality, but the number of sites is dropping rapidly in response to the low cost of natural gas and the higher rate of carbon emissions. By comparison, natural gas matches the reliability and variable load capability of coal, but does not have a comparable ability to maintain a reserve of fuel on-site due to the cost and environmental constraints, instead relying on just-in-time delivery of natural gas through pipelines.

Compounding the challenge is the structure of the natural gas transmission industry, the accepted norms of restoration prioritization and the sector's growing dependence on electricity to extract, refine, and transport gas through each stage of delivery. The industry is far more fragmented than electricity, with no comparable physical network of interconnections or regional-level transmission operators to ensure reliable delivery. However, the greatest similarity for operations is a reliance of ICS and SCADA in order to manage flow in the network. Much like the electric grid, the vast majority of nodes throughout the delivery system are unmanned, instead relying on a network of remotely monitored sensors and controls to provide services. The system is broken in Local Distribution Companies (LDCs), with 23 LDCs in PJM's territory alone to coordinate with (Figure 4).

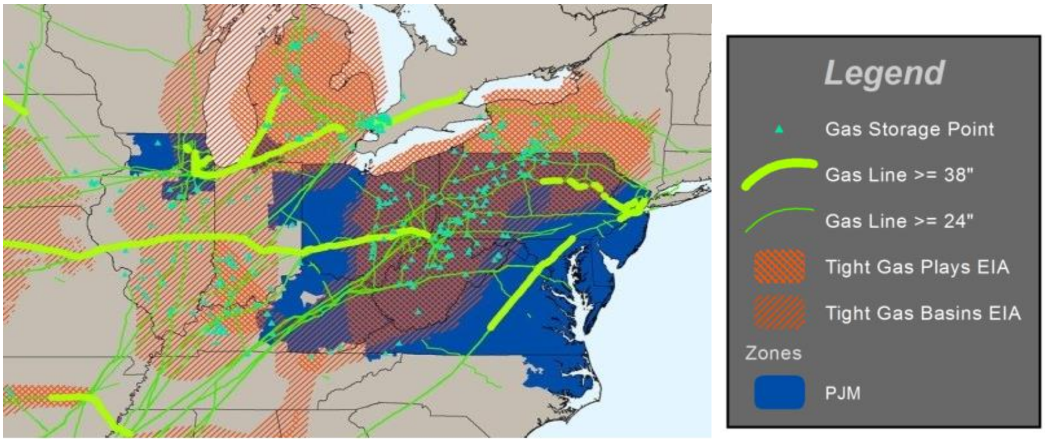

Figure 4. Natural Gas Local Distribution Companies in PJM Territory

Throughout these LDCs, there is network of storage and pumping stations, along with compression stations along the pipelines that keep the flow of fuel moving. All of these systems are becoming increasingly reliant on electricity in order to function. While most of the compression stations rely on in-line fuel in order to run, an increasing percentage of them are converting to electric compressors in order to decrease their carbon emissions and improve their overall efficiency. Without continuous access to grid electricity, their back-up diesel generators cannot run for extended periods of time. Compounding the challenge is the method by which gas companies prioritize their supply of natural gas in circumstances where the volume of natural gas is reduced, known as "tight" conditions. First priority goes to homeowners, given the common use of natural gas for heating and cooking. Unless generation companies incur additional costs for secure "firm" service contracts to be placed at the front of the line for delivery of natural gas, they fall towards the bottom of the list when production is limited. Without the just-in-time delivery of fuel, pipeline-fed natural gas generation stations cease to function within hours.

2.2.1 Key Issues, Risk Areas, and Required Information.

Given this set of constraints, there are several key areas of discovery needed to advise a data-driven systems engineering analysis of the natural gas sector as it pertains to its share of the larger challenge of Black Sky restoration. The following information is needed:

- How many communication end points within the natural gas sector need to be connected in order to execute black start and operate the pipelines with enough efficiency in order to service black start generators already identified?
- What are the minimum service levels of gas delivery needed in order to adequately supply the

black start generators?
- Identify and aggregate the critical loads of natural gas infrastructure (refinement, storage pumping, compression stations for distribution) for service in an outage environment.

2.3 The Electromagnetic Pulse Threat

The greatest collective threat to these systems is a hazard that sits at the intersection of their shared vulnerabilities. The case study for this analysis will utilize an electromagnetic (EMP) event, which is caused by the E1 pulse generated by the high-altitude detonation of a nuclear weapon. The effects of such an attack would be profound, and the infrastructures discussed in this paper would be significantly affected. The primary vulnerability to EMP is dense clusters of low-voltage electronics, something found in abundance in the control centres, data centres, and substations of the three systems discussed. Additionally, the geographic footprint affected by an EMP attack is consistent with the hallmark of a Black Sky event in that it is large enough to impact a substantial portion of the continental United States simultaneously. The failure of electronics as a result of the E1 pulse varies based on a variety of factors including their protection against such an effect and their relative proximity and line-of-sight to the pulse, but the compound effect of so many components in so many systems being affected simultaneously is likely to be catastrophic. Even the process of conducting the engineering assessment of what specific components are damaged following an attack is an activity that would take far more time to complete than what is acceptable for standard restoration operations. In the case of the electricity industry, the most important task to complete in the early stage of a response is to rapidly assess the overall health of the system. This activity is not only vital to determining the extent of damage, but to avoid causing undue harm to the system by improperly balancing load and further damaging critical components that were unharmed from the initial event. To compound the issue, the communications systems (and their back-ups) needed to conduct this rapid assessment are certain to be affected and will have significant operational limitations in this environment largely due to their constraints on back-up power (Siegel, 2017)[v]. Even if the electrical grid achieved an acceptable level of restoration, the control systems employed by the natural gas transmission industry are certain to be impacted as well and cannot ensure uninterrupted fuel delivery to the generation sites needed to execute black start.

3. Candidate solution, arising from the systems engineering studies

Given the scope and scale of the challenge, the key issues and required information from each sector should be compiled in order to advise a systems engineering process to determine the minimum service levels required to function in a Black Sky environment. Each sector must use common planning frameworks with overlapping objectives designed specifically to support black start activities and their resulting communications requirement. The current status of compatible planning varies widely between industries relative to their degree of fragmentation, regulation, and anti-trust-based collaboration. However, the comparatively limited scope of information requirements defined in this paper allows for a prioritized approach to collection and gives operational benefit to all participating entities. Enabled with this information, the existing work on a systems architecture[vi] can be refined to meet these sector-specific internal and external requirements (Figure 5).

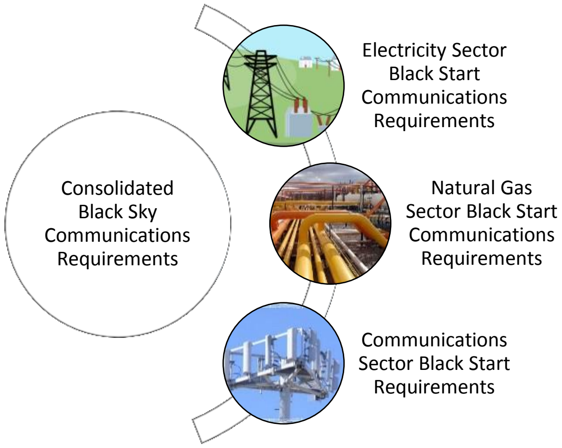

Figure 5. Convergence of Black Sky Requirements from Key Sectors

4. Summary, portions of the problem remaining unsolved, candidate next steps.

The interdependencies described are not simply trends that can be quickly reversed, and the services provided by each sector cannot be replicated by another to eliminate or reduce the dependency (for example, power companies cannot be expected to replace the full capability of the commercial communications sector). The cost constraints and the practicality of such an effort make it infeasible. The intersection of these issues rests with the ability of the electricity industry to continue performing their essential functions without access to the fully-functioning versions of the system they rely on.

Several questions must be answered in order to progress towards a viable solution:

- A system-wide assessment of the communications end points needed in order to allow the electrical grid to function at a high enough level to facilitate black start operations. This effort is underway with the initial social architecture developed by Dr. Siegel[vii], but will need to include further study on the internal systems of grid operators. In addition, a similar assessment is needed for the natural gas industry.
- Determine the minimum amount of voice connectivity and data bandwidth needed by the electricity and natural gas industries to accomplish the black start objectives described.
- Additional research is needed to identify the most effective hardening measures to protect back-up communication systems and its components from EMP for inclusion as part of the solution.

Enabled with the answers to these questions, technical solutions can be developed and field-tested for viability and industry will need to incorporate them into their communications protocols to ensure interoperability and develop the requisite operational and emergency procedures to employ these solutions.

Appendix A. About the Author.

Jonathon Monken is the Senior Director, System Resiliency and Strategic Coordination for PJM Interconnection, working in the areas of business continuity, physical and cyber security, risk management and resilience planning for the world’s largest wholesale energy market. Most recently, Mr. Monken served as VP, U.S. Operations for the EIS Council, developing best practices to improve the resilience of life support infrastructure systems to “Black Sky” events. Mr. Monken served as Director of the Illinois Emergency Management Agency (IEMA) where he oversaw Illinois’ disaster preparedness and response, nuclear safety and homeland security programs. Monken also served for two years as Acting Director of the Illinois State Police and possesses a distinguished military career as an armor officer for one tour of duty in Kosovo and two combat tours in Iraq, during which he was awarded the Bronze Star Medal and the Army Commendation Medal with “V” Device for valor in combat. Monken graduated from the United States Military Academy at West Point, and holds an MBA from Northwestern University's Kellogg School of Management.

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