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Nuclear Power: Black Sky Liability or Black Sky Asset?

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Abstract

Modern life relies on ready access to abundant electricity. During the past decade, it has become apparent that the Critical Infrastructure Sectors in the U.S. are vulnerable to a variety of natural hazards and man-made threats. The electrical infrastructure (the "Grid") is the foundation for all other critical civil infrastructures upon which our society depends. Therefore, protection of the Grid is an energy security, homeland security, and national security issue of highest importance. Geomagnetic disturbances (GMDs) induced by solar coronal mass ejections (CMEs), electromagnetic pulse (EMP) attacks, and cyber attacks are three events that have the potential to plunge the U.S. into partial or total Grid failure (de-energization) with subsequent blackouts so massive that they are referred to as "Black Sky Events" (BSEs). Embedded in the U.S. Grid are almost one hundred commercial nuclear power reactors in some sixty nuclear power plants (NPPs). This paper explores the nature of society's coupled "system of systems" (i.e. the Grid, other Critical Infrastructure, human operators of these infrastructures, the Government, and the Public) that would be stressed by a Black Sky Event, and presents an analytical framework for probing the behavior of this system during Black Sky Events. The question of how a prolonged Black Sky Event might impact NPPs, and what role, if any, NPPs can play in enabling a rapid recovery from a Black Sky Event is examined. The likely behavior of an NPP during a Black Sky Event is discussed, and it is concluded that current NPPs are Black Sky liabilities. However, a unique characteristic of NPPs (the large fuel inventory maintained in the reactor) could make the NPPs extraordinarily valuable assets should a Black Sky Event occur. Their value in this regard, depends on whether or not it might be possible to affect a number of changes in the NPPs, the Grid, and other Critical Infrastructure in the U.S. to enable the NPPs to become Black Start Units – generating stations that would be the foundation of recovering the Grid during a Black Sky Event. This paper poses the question, "*Can nuclear power plants be transformed from Black Sky Liabilities to Black Sky Assets, and if so, how?*" An integrated framework for addressing this question is proposed.

I. Introduction

Modern life is enabled by reliable access to electricity. This electricity is generated and delivered by a massive and complex system – the electrical grid, or simply "the Grid". The U. S. Grid, with rare exceptions, reliably delivers electricity to our nation's homes, businesses, and factories twenty-four hours a day, 365 days a year. The Grid is the umbilical cord of modern civilization – the lynchpin that enables

each of our society's sixteen Critical Infrastructure Sectors (Figure 1) to function **[*1*]**. Our petrochemical production, communications, information technology, transportation, healthcare, finance, and water/wastewater infrastructures are all designed with the assumption that interruptions of electricity supply will be extremely rare and short-lived when they do occur.

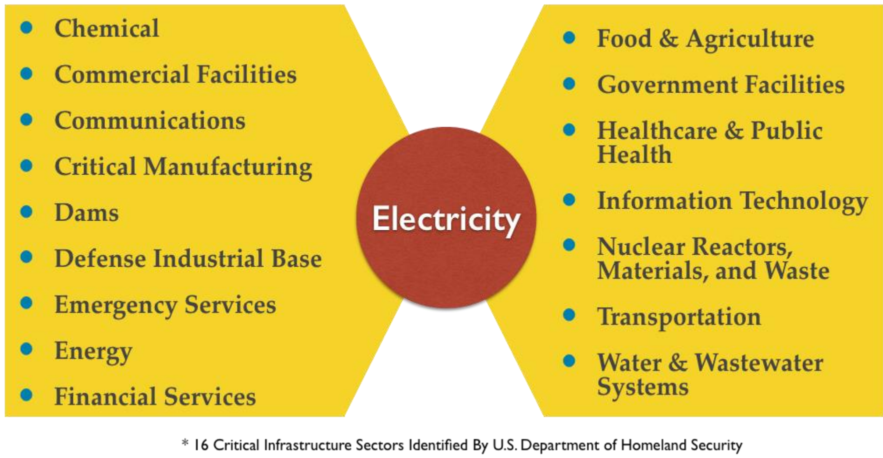

Figure 1. All Critical Infrastructure is dependent on the availability of electricity (Source: S. R. Greene, Advanced Technology Insights, LLC)

The Critical Infrastructure Sectors in the U.S. have become increasingly vulnerable to a variety of hazards and threats during the past decade.**[*2, 3*].** There are a number of natural and man-made events that have the potential to simultaneously compromise the functionality of multiple Critical Infrastructure Sectors on a subcontinental or even continental scale **[*4*]**. Such natural hazards include intense geomagnetic disturbances triggered by coronal mass ejections from our sun, massive seismic events, and extreme weather events such as superstorms and hurricanes. Man-made threats include electromagnetic pulse weapons and cyber-attacks.

With respect to the Grid, two hazards of particular interest are naturally triggered GMDs and man-made EMP attacks. The GMD-induced collapse of the Quebec Hydro grid in 1989 (which caused the entire Quebec power grid to collapse in ~ 90 seconds and affected some six million customers) is but one example of the potential impact of severe weather on the Grid **[*5*]**. Both the U.S. and the Soviet Union conducted high-altitude nuclear detonation tests in 1962 that demonstrated the potential for EMP weapons to have massive impacts on electrical infrastructures **[*6*]**. These natural and man-made phenomena have the potential to trigger partial, or even complete , failure (de-energization) of the Grid for periods of time ranging from hours to perhaps years in extreme cases **[*7*]**. Such outages are termed "Black Sky Events".

While many people in the U.S. have experienced weather-driven power outages lasting a few hours to perhaps a few days, most of the population of the U.S. has never experienced power outages lasting for weeks or months. Indeed, most citizens of the western world rarely even consider how our lives would be impacted by long-term failure of the Grid.

But we should.

Today, some sixty nuclear power plants consisting of roughly 100 nuclear power reactors are embedded in the U.S. Grid. This "NPP fleet" supplies approximately 20% of our nation's electrical production and some 63% of our low-carbon electricity generation **[*8*]**. It is prudent to ask, "*How would nuclear power plants be impacted by a prolonged Black Sky Event, and what role, if any, can NPPs play in enabling a*

rapid recovery from a Black Sky Event?" Or to pose the question another way, *"Are today's nuclear power plants Black Sky Liabilities or Black Sky Assets?"* And finally, if today's NPPs are Black Sky Liabilities, *"What can be done to transform nuclear power plants from Black Sky Liabilities to Black Sky Assets?"*

This paper provides a preliminary description of the "system of systems" which hosts and surrounds the U.S. electrical infrastructure, defines the challenges and opportunities presented by nuclear power plants in Black Sky environments, and proposes high-level analytical frameworks for further investigation of these issues.

II. The U.S. Grid In A System of Systems

Figure 2 is a highly simplified representation of the "system of systems" in which we live. This "system of systems" involves coupled physical infrastructure and human infrastructure. Each entity in Figure 2 can be depicted as an "intelligent agent" capable of sensing and interacting with its environment and other agents. The diagram depicts a causal event ("forcing function") such as a CME, EMP attack, seismic event, etc., impacting the Grid and the other Critical Infrastructures agents of our society. The Grid and the other Critical Infrastructures have an inherent or engineered response to these forcing functions. In addition, the Grid and every other Critical Infrastructure agent has a command, control, maintenance, and repair element staffed by human beings who interact with the physical infrastructure, and the other human agents in the system to modulate the infrastructure's behavior. In addition to laws, regulatory frameworks, etc., the Government agent also has a human element (not explicitly depicted in Figure 2) that plays a role in shaping the response of the Government to a BSE. Finally, there is the Public, who would be interacting in diverse ways with every other element of the system in the event of a BSE. During a BSE, all of the physical and human infrastructures (agents) would be compromised in some manner. Each would have varying and evolving degrees of situational awareness, be subject to competing and conflicting demands, and would interact with each other in real time to affect a plethora of evolving societal goals at the individual, family, community, regional, and national levels.

The granularity of the model depicted in Figure 2 could easily be expanded. For instance, the "Physical Critical Infrastructure" agent could be resolved into its sixteen Critical Infrastructure agents, and the "Government" agent could be expanded to depict various federal, state, and local governmental entities. Agents representing non-governmental organizations or "NGOs" (such as the Red Cross) could be added, and the "Public" agent could be expanded to depict diverse populations (such as infrastructure workers, first responders, etc.). Even without this extra level of granularity, the simple model depicted in Figure 2 could provide a useful framework for exploring a diverse set of technical, political, and behavioral questions relevant to Black Sky Events. Examples of such questions include:

- How do the separate Critical Infrastructure agents interact with and influence each other?
- How do various policies, regulations, laws, and operating procedures influence the course of events during a BSE?
- What are the best policies and regulations to deal with BSEs?
- What should the relative priorities be for restoring electrical power to various Critical Infrastructures and their functions?
- How do human actions or inactions influence the ability of society to endure a BSE and recover from it?

Many important questions of this nature have not been probed in a rigorous scientific manner. A multi-agent model based on a simple architecture similar to that depicted in Figure 2 could provide a starting point for simulating the behavior of our society during Black Sky Events. This model could also inform regulatory and policy formulation, emergency preparedness and emergency response planning, and a myriad of other important Black Sky issues **[*9–14*].** As is true in many simulation efforts, the results

obtained from such analyses could prove to be more valuable for sharpening our questions than for answering them. The potential for such a model to yield useful insights into a diverse suite of Black Sky issues is discussed further in the following sections.

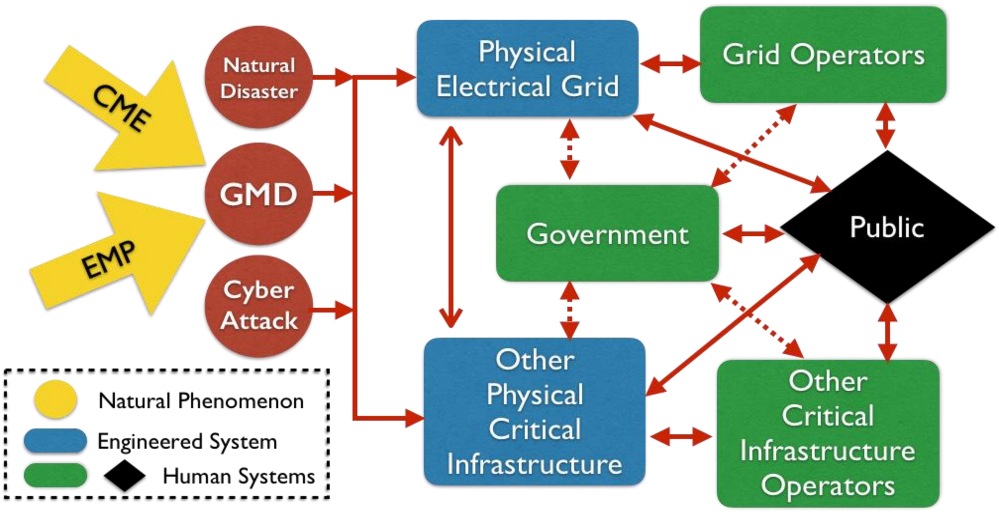

Figure 2. The Black Sky System (Source: S. R. Greene, Advanced Technology Insights, LLC)

III. Imagining A Black Sky Event

The probability of natural events that might trigger a BSE depends on the specific triggering event. For example, based on available satellite heliophysics data and Earth geophysical forensic analysis, Riley **[*15*]** estimated the probability of a CME-induced GMD of the same magnitude as the famous 1859 "Carrington Event" **[*16*]** to be on the order of 12% per decade. The Carrington Event occurred at a time when the only "wired" network in the U.S. and Europe was the telegraph system. Reliable reports from the event indicate widespread electrical arcing of telegraph lines, papers in telegraph offices (and even wooden telegraph poles) being set afire from arcing of nearby lines, shocking of telegraph operators, and telegraph systems continuing to run after being disconnected from their battery systems. Love **[*17*]** has predicted the probability of a similar event to be 6.3% per decade (roughly half of Riley's estimate). If Riley and Love's probability estimates are reasonably accurate, our world is overdue for a massive GMD. Indeed, the Earth has had very close encounters with a number of CMEs over the past few decades, narrowly missing an encounter with a Carrington-class CME as recently as July 2012 **[*18*].**

With regard to seismic hazards, the probability of massive earthquakes capable of triggering sub-continental Grid damage is location-dependent. Nevertheless, in the U.S. the potential exists for major seismic events in and around regions such as the San Andreas, the Pacific Northwest, and the New Madrid seismic zones **[*19*]**.

Finally, it is difficult to quantitatively assess the "probability" of human-based threats that might trigger Black Sky Events. However, it is prudent to assume there are entities in the world that are actively seeking to develop EMP and cyber weapons capable of triggering Black Sky Events.

As previously discussed, Black Sky environments, regardless of their cause, are characterized by the partial or complete de-energization of the Grid and would "…*share a common attribute: outages would span very large regions, and utilities could require weeks or potentially months to restore power to even the highest priority customers*" **[*20*]**. As has been demonstrated on numerous occasions, localized electricity outages can propagate through space and time to become much larger blackouts. The ultimate size of the blackout region would depend both on the original damage inflicted by the initiating event (e.g.

GMD, seismic event, EMP, etc.), and the subsequent *event cascade* within the Grid, between the Grid and other Critical Infrastructure sectors, and within other Critical Infrastructure Sectors.

Given the dependence of our Critical Infrastructure on the Grid, it is difficult to bound the ultimate Black Sky event cascade. The behavior of the complimentary physical and human system of systems (Figure 2) is exceedingly complex. For example, systems such as water supply, wastewater, fuel delivery (gasoline, natural gas, coal), ground and air transportation, communications, and finance would be severely degraded. The quest for information regarding the situation, and the competition for goods and services would quickly intensify at local, regional, and national levels, with requests for resources overwhelming their availability at virtually every geographical scale.

How would society endure, and then recover from such an event? Serious analysis of such situations must take into account the impact of the Black Sky environment on physical infrastructure, the people who must report to work to operate the physical infrastructure, and the Public who depend on the infrastructure and interact in complex ways with the people who operate it. Past experience with a limited number of major (but relatively short-term) blackouts in the U.S. gives reason for concern **[*21, 22*]**. In the 2013 report "Solar Storm Risk To The North American Electric Grid", Lloyd estimated that a Carrington-like event is likely to directly impact some 20-40 million people in the U.S., with power outages lasting from sixteen days to "1-2 years", inflicting $600 billion to $2.6 trillion in damage to the U.S. economy **[*23*].**

Our nation's legal, regulatory, political, and social institutions are ill-equipped to deal with the overwhelmingly disruptive scenarios described above. However, efforts are underway at the federal level and in NGOs to bring together the expertise and resources needed to accurately characterize the nature of the challenge and to formulate plans and actions to enhance our preparedness for such events **[*2, 4, 24*]**.

IV. The U.S. Grid and Nuclear Power's Place In It

The U.S. Grid (Figure 3) is comprised of some 7,300 generating units, a growing number of energy storage facilities, over 257,000 km (160,000 mi) of high voltage transmission lines, and millions of low voltage lines and distribution transformers **[*25*]**. Some five hundred companies and sixty-six "balancing authorities" whose responsibility it is to ensure, in real time, that electricity demand and supply are balanced, operate these assets.

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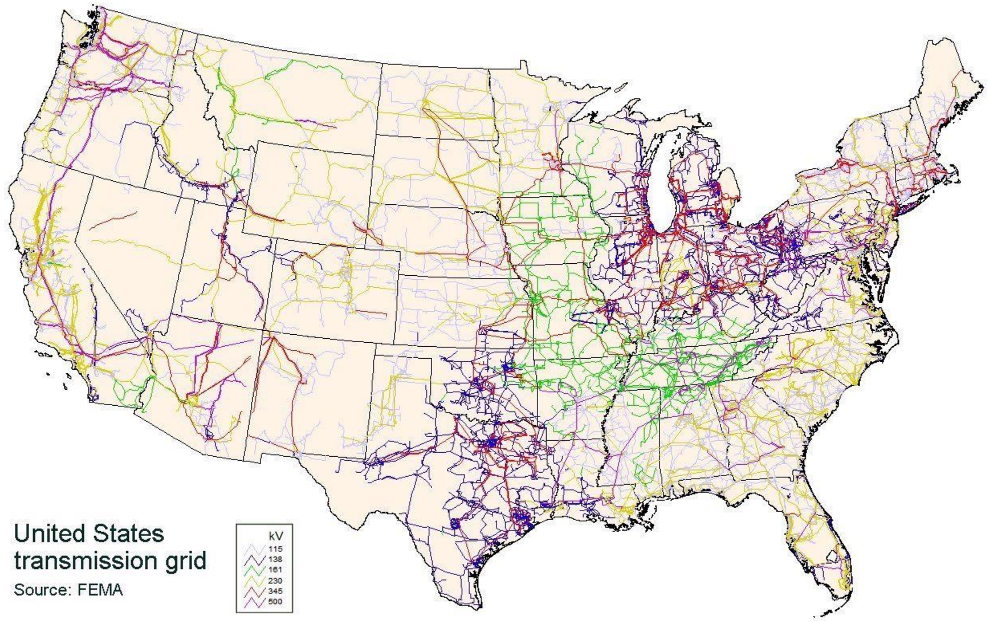

Figure 3. North American Electric Grid (Source: FEMA) (Source: https://en.wikipedia.org/wiki/North_American_Electric_Reliability_Corporation#/media/File:UnitedStatesPowerGrid.jpg, accessed 24 August 2016)

According to the U.S. National Academy of Engineering, the North American Grid is considered the largest "machine" created by mankind and the foundation of the greatest engineering achievement of the 20th century **[*26*]**. The U.S. Grid in the lower forty-eight states is configured into three "interconnections" (Figure 4): the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of Texas (ERCOT) Interconnection **[*27, 28*]**. The Eastern Interconnection covers the region from the Atlantic coast to the base of the Rocky Mountains. The Western Interconnection extends westward from its boundary with the Eastern Interconnection to the Pacific Coast. The ERCOT Interconnection covers most of Texas.

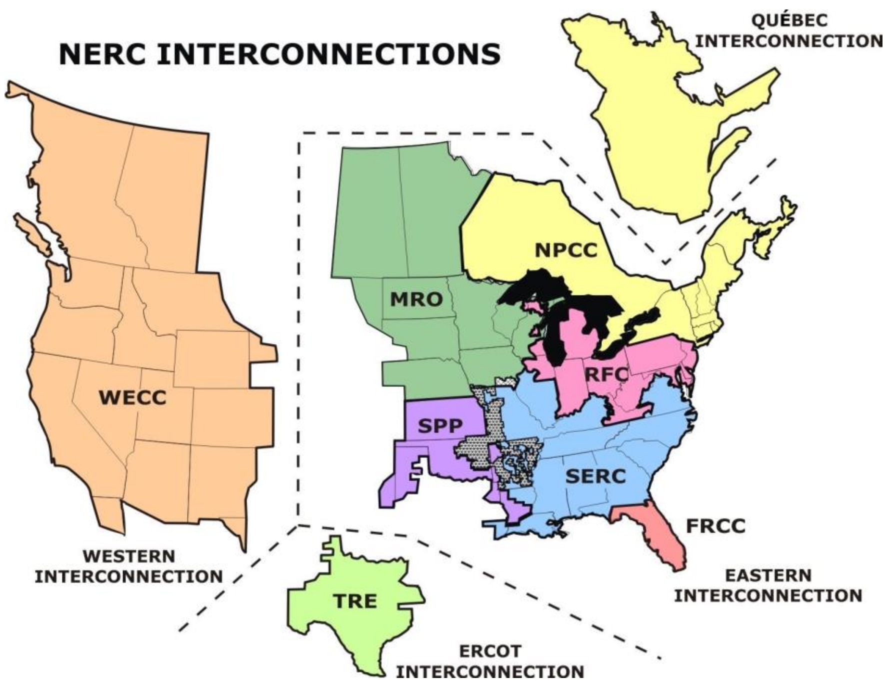

Figure 4. North American Electric Reliability Council (NERC) Interconnections (Source: http://www.nerc.com/AboutNERC/keyplayers/Documents/NERC_Interconnections_Color_072512.jpg accessed 24 August 2016)

All of the electric utilities within an Interconnection are connected with each other (under normal operating conditions) and operate at a synchronized frequency of 60 Hz. Interconnections can be joined to each other via high voltage direct current power transmission lines (DC ties) or via variable frequency transformers (VFTs). Variable frequency transformers permit a controlled flow of alternating current (AC) across the connection, while preventing the transmission of AC frequency perturbations between interconnections. The Eastern Interconnection is connected to the Western Interconnection via six DC ties, to the ERCOT Interconnection with two DC ties, and to the Quebec Interconnection with four DC ties and a single VFT **[*29*]**. In addition to being tied to the Eastern Interconnection, the Texas Interconnection has one DC tie and one VFT tie to systems in Mexico **[*30*]**.

Approximately 100 of the 7,300 generating units mentioned above are nuclear power reactors (Figure 5). At the risk of over-simplification (and with recognition that details such as voltage levels and even the names of components can be plant-specific), it is helpful to view the interface between a nuclear power plant and the Grid in terms of four primary connections (Figure 6):

- The NPP unit's Main Power Transformer, which steps up the ~ 25KV output of the main generators to 345 KV, which is then fed to the Grid through the station switchyard
- The NPP unit's Startup Transformer or "SUT" (also called the Station Auxiliary Transformer), which steps down the 345 KV from the station switchyard to the ~ 6.6 KV required to energize the NPP equipment for plant start-up
- The NPP unit's dedicated Engineering Safety Feature (ESF) Transformer, which provides electricity from the Grid to power the NPP's Engineered Safety Features
- A variety of Supervisory Control and Data Acquisition (SCADA) systems

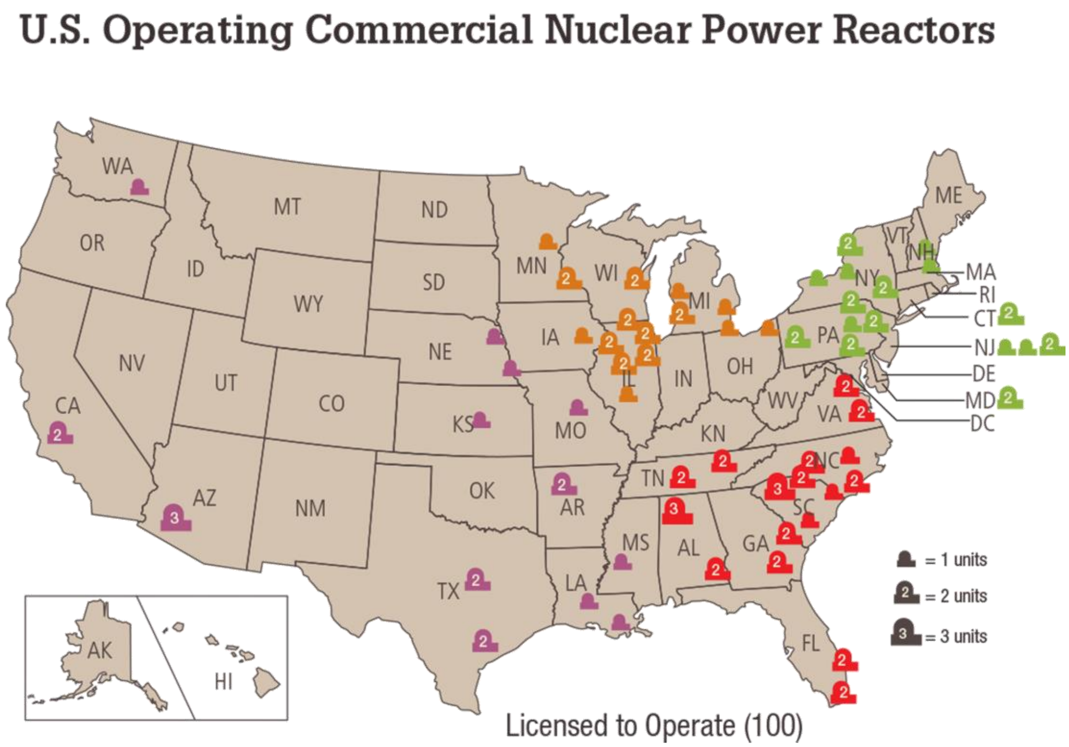

Figure 5. Operating Commercial Power Plants In U.S. – November 2015 (Source: U.S. Nuclear Regulatory Commission, http://www.nrc.gov/reactors/operating/map-power-reactors.html, accessed 24 August 2016)

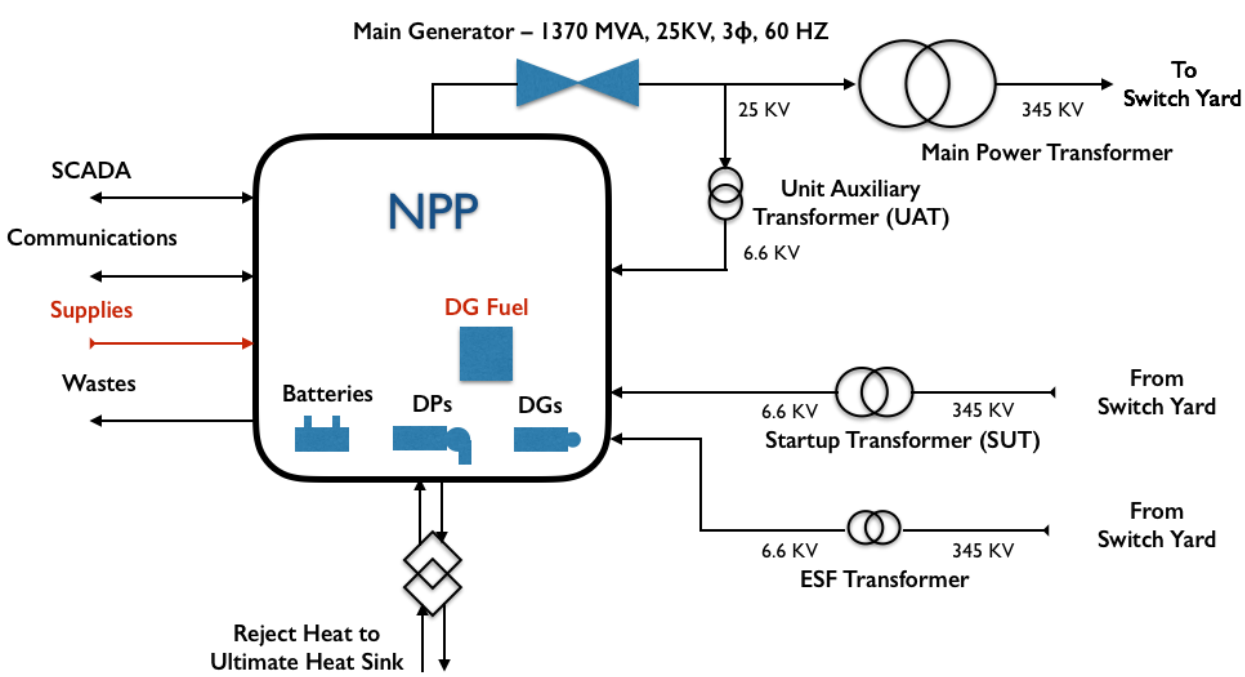

Figure 6. Simplified representation of NPP interfaces with the Grid and the world outside the plant boundary (Source: S. R. Greene, Advanced Technology Insights, LLC)

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Though not an interface to the Grid, the reactor's Unit Auxiliary Transformer (UAT) plays an important role in plant operations. This transformer taps a portion of the plant's 25 KV Main Generator output to energize ~ 6.6 KV buses that provide for a variety of housekeeping or "auxiliary" plant loads during operation. Thus, once an NPP is started, it could run without being connected to the Grid. It would, however, need to be able to reduce its power level ("runback") to a very low-power generation level just sufficient to meet the plant's housekeeping loads while rejecting any unneeded power through the plant's condenser and normal waste heat removal systems. *Finally, it is important to emphasize that once shut down; the NPP cannot restart without AC power supplied from external sources through the NPP's Startup Transformer.*

V. U.S. Grid Recovery During Black Sky Events

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) have put in place a series of System Restoration Reliability Standards designed to enhance the ability of the Grid operators to re-energize and recover the Grid following widespread Grid outages **[*31, 32*]**. These "Gray Sky" restoration procedures envision a Grid fractured into a large number of "islanded" entities. These recovery procedures are basically "bootstrapping" exercises in which each of these isolated entities initially restarts specially configured "Black Start Generating Units", or simply "Black Start Units", that are coupled through secure transmission lines to tightly controlled load centers. Once these initial islands are operational, and damage assessments and situational awareness permit, breakers are closed in a carefully choreographed manner to re-energize other parts of the system. This sequential approach allows other generating plants to restart, and larger portions of the Grid to be re-energized as the electrified islands expand, sync, and reconnect to each other. This process is easily envisioned as many random points of light on a dark map of the U.S. expanding until their boundaries merge and the entire map is illuminated.

These emergency operating procedures (EOPs) require transmission operators, balancing authorities, and reliability coordinators to have Grid restoration plans, test protocols, and Black Start Resources (Black Start Units) in place to enable rapid recovery from large Grid failure events. Black Start Resources are defined as "*generating unit(s) and its associated set of equipment which has the ability to be started without support from the System or is designed to remain energized without connection to the remainder of the System, with the ability to energize a bus, meeting the Transmission Operator's restoration plan needs for real and reactive power capability, frequency and voltage control, and that has been included in the Transmission Operator's restoration plan,*" **[*31*].** Where available, hydro plants (dams) are favored Black Start Resources. However, many regions of the country do not have direct access to hydro assets and must rely on other assets, such as gas turbines and oil-fired units, for meeting the Black Start Resource requirements. A practical consideration in the selection of Black Start Resources is that these generating units must have sufficient fuel available to attempt multiple system restarts and to be capable of performing their required Black Start functions for some duration of time following their initial start-up attempt. (History suggests extraordinary steps can be taken to secure Black Start and cranking power sources in extraordinary circumstances. For example, the United States Army's nuclear barge Sturgis was a refitted cargo ship containing a 10 MWe nuclear power plant that supplied electrical power for the locks of the Panama Canal between 1968 and 1976. Some years later (in November 1982) the United States nuclear-powered attack submarine USS Indianapolis was ordered into Nawiliwili Harbor on the hurricane-ravaged Hawaiian island of Kauai for the purpose of interconnecting with and repowering the island's electrical system. However, the planned interconnection between the submarine's nuclear power plant and the island's electrical grid was never completed because diesel generators supplied by the U.S. Navy succeeded in cranking the island's main power plant. Thus a precedent exists for employing nuclear powered naval vessels as Black Start and cranking power supplies in coastal areas.)

It is difficult, if not practically impossible, to thoroughly test Independent System Operator and Regional Transmission Organization Black Sky / Black Start Grid emergency operating procedures and system restoration plans in *truly prototypic* Black Sky environments. This is true because realistic Black Sky test environments cannot be created without impacting the public in an unacceptable manner. For this reason, testing of system restoration procedures typically employs some combination of computational simulation and synthesis of results from testing conducted at subsystem and component levels.

The tendency to assume near-perfect execution of emergency response plans and operating procedures is a potential Achilles heel of validation approaches that rely on simulation and limited testing at subsystem levels. It is easy to overlook the inter- and intra-dependencies of organizational functionalities and human frailties – realities that would present significant emergency procedure execution challenges during Black Sky Events. Given the difficulty of testing Black Sky recovery procedures at full scale and in prototypic environments, intelligent agent-based system models similar to that depicted in Figure 2 might provide additional useful insights into relevant infrastructure and human interactions and interdependencies. Such models could be developed and applied at the individual power station, electric utility, regional transmission organization, NERC Region, Interconnection, or entire continental Grid levels. Depending on their focus and specific questions to be addressed, such models might incorporate elements such as the FERC/NERC emergency operating procedures into the "Grid Operators" agent shown in Figure 2, individual power plant emergency operating procedures (if individual power plant agents were incorporated into the simulation), the emergency recovery plans of other Critical Infrastructure sectors, and planned emergency actions of governmental entities (e.g., the U.S. Department of Homeland Security / Federal Emergency Management Agency, etc.). Such simulations might offer insights useful for informing and optimizing Grid and Critical Infrastructure Black Sky emergency operating and recovery procedures, power restoration priorities, regulatory structures, national Black Sky strategies, and a host of other related issues.

VI. The NPP's Initial Response To A Black Sky Event

This section examines the likely response of an NPP to Black Sky Events – both those for which advance warning is available and those that present themselves as unanticipated propagating Grid failures. It should be noted that the most likely response of a particular NPP would no doubt depend on plant-specific issues, including the manner in which the NPP is interfaced (**Figure 6**) to the Grid and the Grid architecture beyond this interface. There are circumstances in which an NPP operator might receive advance notice (either through federally-issued alerts from the space weather network, the plant's SCADA system, or by other means) of an imminent threat of massive Grid disruptions. In such cases, the NPP operator would almost certainly take preemptive action to both protect the power plant and enhance the likelihood the Grid could be recovered rapidly in the wake of a Black Sky Event. Theoretically, plant operators might respond to such notices in two ways:

- **Manual Shutdown** – in which the NPP operators manually shut down the plant and transition it to normal shutdown decay heat removal, probably with early managed transition to onsite diesel-driven power systems to avoid the possibility of unnecessarily harsh transitions if the anticipated **loss of offsite power (LOOP)** event actually occurs.

- **Manual Runback** or "cutback" – in which the NPP isolates from the Grid and reduces its power level to only that required to supply internal housekeeping loads (typically several percent of full power).

Assuming a plant is capable of shifting to the runback mode, the relative desirability of these two actions could depend on a variety of factors – such as the potential for direct damage to NPP plant and equipment from the Black Sky initiating event, the period of time offsite power might be unavailable to the NPP, etc.

An unanticipated Black Sky Event would initially be "sensed" by a NPP as an anomaly in one or more Grid interface characteristics (frequency perturbations, power factor anomalies, load perturbations, etc.). The plant's initial response to the event would depend on how it was first sensed **[*33, 34*].** (Note: the first three scenarios described below would be transitory phases, all ultimately evolving into LOOP events.)

- **Partial Load Rejection** – a load rejection is a sudden reduction in electric power demand at some point in the Grid. Such events could result in the opening of interconnections between the parts of the Grid experiencing the load rejection, eventually propagating to the region of the Grid to which the NPP is tied. While some power reactors designed by Combustion Engineering were designed for 85% or greater load rejection capability, NPP's typically can manage load rejections of up to ~ 50% by reducing power (runback) and dumping excess steam as necessary to the unit's main condenser (assuming AC power is still available at that point to drive the pumps that supply water to the secondary side of the condenser).

- **Complete Loss of Load** – for the case of an unmitigated BSE, the NPP might experience a momentary or short-term partial load rejection that quickly evolves to a complete (100%) load rejection – a "loss of load" event. This loss of load event could descend on the NPP with little advance warning. The NPP's normal response to the loss of load would be to open breakers at the generator output, "islanding" the NPP from the Grid, and (today) "tripping" the reactor. In such cases, it might be possible for the NPP to runback its power level to that required to supply its own housekeeping electrical loads – provided (once again) that AC power is available to drive the pumps that supply water to the secondary side of the condenser. If this delicate operation cannot be achieved and maintained, the reactor will be tripped. It would then transition to the shutdown decay heat removal mode powered by AC provided from the Grid. This offsite power would not be available in a Black Sky Event; so diesel-driven systems would supply the needed backup power to maintain safe shutdown cooling.

- **Voltage and Frequency Perturbation-Induced Reactor Trips** – North American Grid AC frequency is typically controlled to within (an amazing) ± 0.05 Hz. The initial stage of a BSE would no doubt involve large variations in system voltage and frequency as load shedding and real or reactive power supply-demand mismatches cascade throughout the Grid. A NPP senses Grid AC voltage and frequency via several mechanisms. Changes in Grid AC voltage and frequency produce forcing functions within the NPP's turbo generator as it seeks to remain in synchronization with the Grid. These Grid voltage and frequency perturbations also directly impact the speed of AC pumps used to circulate cooling water through the reactor, steam generators (if a pressurized water reactor), secondary and containment cooling systems, feedwater to the reactor's condenser, etc. Thus, the thermodynamic balance of the plant can be significantly impacted by Grid AC voltage and frequency perturbations. In addition, most AC pumping systems are protected by breakers designed to open under unacceptable voltage and frequency perturbations to protect the systems from overheating due to excessive currents. The control band for these protection systems is relatively narrow. Given these design features, excessive Grid voltage and frequency perturbations would trigger the NPP's protection systems to rapidly trip the reactor and transition it to onsite or offsite AC-powered shutdown cooling.

Even if the NPP initially senses the BSE as a load rejection, loss-of-load, or voltage/frequency perturbation event, it will ultimately (perhaps quickly) sense it as a LOOP event. In response to the loss of power to NPP systems, the plant protection system shuts down (trips) the reactor (if it was not already tripped by one of the transients discussed above) and transitions the plant to shutdown cooling. These cooling systems are controlled and powered by station batteries, diesel generator-powered AC-driven cooling systems, and/or direct diesel-driven pumping systems **[*35*]**. The period of time an NPP can remain safely in this

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shutdown cooling mode depends on plant design features (such as the capacity of the station batteries and control air systems and the design and performance of its diesel generator and diesel-driven pumping systems, etc.), *and the ability of the world outside the plant to provide meaningful assistance such as resupplying diesel fuel, additional diesel generators and diesel-driven pumps, etc., if/as required.*

Thus, the likely response of today's NPPs to a BSE would be to shut down (either manually in response to event warnings or automatically in response to sensed Grid anomalies) and transition in a normal fashion to dependency on shutdown decay heat removal systems controlled and powered by station batteries and diesel generator-driven or diesel-driven pumps. The NPP (reactor, primary containment, spent fuel pool) would be in a "safe shutdown mode" *as long as the required cooling is available*. The NPP operators would have no way of knowing the extent of damage to the Grid, nor how long offsite AC power would be unavailable at the outset of the event. They would be relying strictly on onsite diesel generators and/or diesel-driven pumping systems to supply the necessary power. *Thus they would be dependent on the inventory of diesel fuel stored on, or very near their site to maintain cooling to the reactor, the reactor's primary containment, and the spent fuel pool.*

It is likely that the transfer of materials, equipment, and personnel between the NPP and the outside world, along with communications with the outside world, would be greatly compromised during the Black Sky Event, with the situation worsening as the event persists. The situational awareness of all entities involved would be compromised, complicating damage assessment and response planning both within and outside the NPP.

VII. The NPP's Long-term Black Sky Response

For all their benefits, the NPP fleet poses a unique Black Sky challenge. Nuclear power plants can't simply be "turned off" like other forms of electrical power generation. The nuclear fuel in commercial power reactors continues to produce significant "decay heat" long after their electrical power production has ceased. (For example, nuclear fuel still produces ~ 1% of it's original operating power two hours after shutdown. The decay power level drops to ~ 0.4% three days after shutdown, ~ 0.3% seven days after shutdown, and ~ 0.04-0.05% six months after shutdown. The exact power level produced depends on several factors such as the original operating power level, time at power, reactor fuel composition, fuel burn-up, etc.) By way of example, the core of a 1000 MWe / 3000 MWt) commercial nuclear reactor might still be producing ~2-3 MWt of power three months after the reactor has shut down. Thus, in the absence of forced cooling, a reactor of this size, depressurized to 1 atm pressure, would boil off 3200-5000 kg/h or ~830-1320 gallons/h of water to remove this much energy. This decay heat is produced whether the fuel is in the reactor or in the plant's spent fuel pool, and must be removed (in current reactors) by pumping cooling water through the core of the reactor (and/or spent fuel pool) with electrically driven pumps. Under normal circumstances the power for these cooling systems is supplied from the Grid. In the event offsite electrical feed isn't available, the NPPs rely on onsite diesel-driven pumping systems to supply the necessary power.

The potential impacts of long-term loss of offsite power events in NPPs have been extensively studied **[*35*]**. The accident that occurred at Fukushima Dai-ichi in 2011 in the wake of the Great East Japan Earthquake evolved to a multi-reactor LOOP event – albeit one that was greatly complicated by the physical damage inflicted on the plant by the earthquake and the tsunami. From the safety standpoint, the events at Fukushima Dai-ichi had a galvanizing impact on the commercial nuclear power industry, not unlike that which occurred in the wake of the accident at Three Mile Island in the U.S. in 1979. Among other things, the U.S. Nuclear Regulatory Commission (NRC) conducted a detailed "lessons learned" analysis of the implications of the Fukushima accident **[*36*]**. The NRC subsequently implemented a structured activity (still ongoing) to address the insights identified therein. The U.S. National Academy of

Science also conducted a detailed evaluation of Fukushima with an eye toward identifying key lessons learned **[*37*]**.

One of the key focus areas of the NRC and U.S. nuclear power industry in the wake of the accident at Fukushima Dai-ichi has been to enhance U.S. NPPs' ability to cope with extreme external events, including sustained loss of offsite power. The nuclear industry's FLEX Program was one result of this effort **[*38*]**. Under the FLEX program, NPP owners have invested heavily in additional onsite diesel generators and diesel-driven pumping systems. Efforts have been made to expand onsite diesel fuel storage capabilities. (For example, the Tennessee Valley Authority's 3-unit Browns Ferry Nuclear Plant has the capacity to store at least 282,240 gallons of diesel fuel onsite for its FLEX diesel generators **[*39*]**.) Beyond this, the FLEX program has pre-staged additional emergency response equipment at two regional response centers – one in Memphis, Tennessee and the other in Phoenix, Arizona. Their goal is to enable delivery of critical equipment by ground and air transport to NPPs anywhere in their region within 24 hours **[*40*].**

The FLEX program illustrates an aggressive and innovative response of the nuclear power industry to the Fukushima Dai-ichi accident – one that should significantly reduce the risk imposed by a spectrum of traditional external events. This said, <u>the FLEX program is not designed to mitigate Black Sky Events</u>:

"*Solar-Geomagnetic disturbances could also lead to extended loss of off-site power due to geomagnetically-induced currents in electrical power transmission systems. However, this hazard was not included in Reference B-1 so it is not explicitly listed here. Nevertheless, while such disturbances could cause an extended loss of off-site power, they are not expected to impact the on-site safety-related equipment (e.g., diesel generators and internal distribution equipment) due to their being housed in reinforced concrete structures and would not change the approach to devising FLEX strategies*" **[*38*].**

Three observations about the FLEX Program are relevant to the present discussion:

First, existing FLEX strategies are clearly based on the assumption civil infrastructure outside the plant boundary is not so degraded by triggering events as to prevent delivery of equipment and diesel fuel to the plant for as long as necessary to keep the plant in a safe shutdown state. The same assumption (that regardless of the initiating event, the outside world can render meaningful assistance to the plant) has been incorporated in virtually every NPP risk assessment performed prior to the Fukushima Dai-ichi accident ***[35]***. *This assumption is at least questionable, if not clearly invalid for prolonged Black Sky Events. Indeed, Black Sky Events are among the ultimate "common cause" events with the potential to both damage the NPP and prevent the world outside the NPP from rendering meaningful assistance to it in a timely manner.*

Second, the question of whether NPP equipment could withstand a major GMD such as the 1859 Carrington Event, or a major EMP attack, is somewhat uncertain. An analysis conducted by Sandia National Laboratories in 1983 **[*41*]** concluded, "*… the likelihood that individual components examined will fail is small; therefore, it is unlikely that an EMP event would fail sufficient equipment so as to prevent safe shutdown.*" This analysis focused on EMP events rather than GMDs triggered by CMEs, and technologies and systems in place in the early 1980s before the digital era. It is not entirely clear how differences between the CME-induced GMD and EMP events, and the transition to digital instrumentation and control technologies within the NPP impact the conclusions of the 1983 analysis.

Lastly, a Black Sky Event in the Eastern U.S. would likely place several NPPs in jeopardy *simultaneously*. The FLEX regional response centers are not designed for situations in which several NPPs are simultaneously in need of FLEX equipment and resources – *even if transport of equipment from the regional response centers to the affected NPP sites in not an issue.*

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One must also consider the human side of the NPP's Black Sky endurance challenge. The likelihood that transportation fuels will rapidly become scarce or unavailable in an extended BSE, and that ground transportation pathways will become clogged and dysfunctional, is a serious issue with respect to maintaining adequate NPP staffing during the event. The longer the BSE persists, the more difficult it would become for the NPP's workforce to commute from offsite to the plant, and the more likely it is that NPP staff will feel compelled to place the immediate safety and security of their families above the needs of the NPP. This same issue applies to the workforce of electrical utilities and all Critical Infrastructure Sectors (Figures 1 and 2).

Decades of disaster recovery experience and current disaster planning practices suggest that the first 72 hours of a disaster event are especially critical. During this period, disaster management is almost completely a local and individual responsibility **[*42, 43*]** and the reality and uncertainties of one's situation begin to crystalize. The more complex and labor-intensive the required BSE coping actions, and the longer the need for activity persists, the greater the risk that pre-established emergency coping procedures will not be executed as planned. *Therefore, rapid recovery of the Grid and the NPP's normal shutdown configuration is imperative.*

Nuclear power plant operators in the U.S. employ a framework of carefully-crafted Emergency Operating Procedures (EOPs), Severe Accident Management Guidelines (SAMGs), FLEX procedures, and Extensive Damage Mitigation Guidelines (EDMGs) to guide their actions during unlikely extreme events involving progressive deterioration of plant functionalities. These procedural frameworks have evolved over several decades, and incorporate lessons-learned from major federal and industry safety analysis programs and thousands of accumulated years of plant operating experience. The nuclear power industry has indeed done a laudable job in preparing for "the unthinkable". Nevertheless, Black Sky Events would pose unprecedented challenges to the effective real-time integration and execution of these procedures. *Tabletop exercises in which these procedures are "tested" in Black Sky environments can offer initial insight with respect to areas in which existing procedures and guidelines can be improved for Black Sky applications. Additionally, the intelligent agent-based simulation approach discussed in Section II above, coupled with appropriate NPP simulation tools, might provide useful insights into the integration and optimization of these EOP/SAMG/FLEX/EDMG frameworks in Black Sky environments.*

Two key questions emerge from this discussion of current NPP's ability to endure a Black Sky Event:

- Under current industry operating procedures, and with sufficient forewarning, NPPs would almost certainly shut down in advance of a BSE and isolate themselves from the Grid. Shutting down the reactor is presumed to be the safest response to an event in which the anticipated damage to the Grid and potential risk to the NPP is difficult to predict. <u>However, shutting down the NPP places its continued safety at the mercy of its diesel generators and its diesel fuel supply at a time when neither the duration of the offsite power outage nor the continuing availability of diesel fuel from offsite sources can be known.</u> One can reasonably ask, "*Would a safer response be to runback and run through the BSE with the reactor still operating but safely isolated from the Grid for as long as necessary to ride through the Black Sky Event*?"

- If it is neither feasible nor advisable to attempt to *runback and run through* the Black Sky Event, the question then becomes: *What can be done to extend and enhance the NPP's shutdown heat removal capability for Black Sky Events*? This line of inquiry would involve investigating: (a) "beyond-FLEX" improvements to the NPP's onsite diesel generator, diesel pump, and diesel fuel supplies; (b) "beyond-FLEX" improvements in the civil infrastructure outside the plant to provide assistance (at least diesel fuel) to the NPP despite widespread infrastructure damage and competition for available resources; (c) establishment of a secure offsite electrical power feed to

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the NPP that is not vulnerable to the Black Sky Event; and (d) addition of alternative onsite emergency electrical power supplies (such as solar photovoltaic systems or even small nuclear reactors) capable of powering all essential shutdown cooling functions during the Black Sky Event.

VIII. Today's NPPs *Are* Black Sky Liabilities

In the years since the first U.S. NPP became operational in 1957, the U.S. commercial nuclear power fleet has proven to be a safe, reliable, around-the-clock source of electricity. Through time, and in response to lessons learned from a handful of accidents in NPPs around the world, the nuclear power industry and its regulators have continued to improve the ability of NPPs to safely respond to and cope with a variety of external events and natural hazards. The industry's response to the accident at Fukushima Dai-ichi is a notable example. Nevertheless, today's generation of NPPs has a combination of design and performance attributes that present operational and safety challenges during, and after, Black Sky Events. Chief attributes include:

1) While they can easily be "shut down", NPPs cannot simply be "turned off" in the normal manner of speaking. NPPs continued to produce "decay power" at non-trivial levels for many months after they are shut down. This decay power must be removed on a continuous basis if damage to the reactor's core is to be avoided. Today's NPPs are not designed to remove this decay power (without outside assistance) in Black Sky (i.e. total loss of offsite power) conditions that persist for a several weeks or longer;

2) Once shut down, today's NPPs require electrical power from the Grid to restart;

3) If today's NPPs could be rapidly restarted (or powered-up from a runback status), it is unclear if they can perform the frequency matching and (possibly extreme) load following maneuvers likely required to service the Grid during the early stages of the Black Sky recovery effort.

Given the three characteristics discussed above, it is difficult to avoid the conclusion that today's NPPs are indeed Black Sky Liabilities – generating assets that require ongoing attention and "tending" during a BSE, and are of little help in recovering from the Black Sky Event.

IX. The Potential Value of NPPs Under Black Skies

Despite the concerns raised in the previous section, it is noteworthy that NPPs have one unique advantage with respect to other steam cycle generating assets – an advantage that could make them an extremely attractive Black Start Resource. Nuclear power plants are typically refueled every eighteen to twenty-four months. Thus on average, an NPP can be assumed to have one year of fuel "in the tank". The NPP's fuel storage advantage dramatically surpasses that of coal-fired, gas-fired, and oil-fired plants (Table 1). Fuel supply pipelines would be inoperable or at least unreliable in Black Skies environments. Therefore, if a NPP can somehow endure the initial stages of the BSE without being damaged, restart (if necessary), synchronize with and connect to the Grid, and load-follow as required, the plant would become a Black Start Resource of extraordinary value. This could be a game-changing asset during a time when transportation systems and other essential Critical Infrastructures are degraded or inoperable.

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X. Current Nuclear Industry and NRC Posture With Respect to Black Sky Events

Neither the U.S. Nuclear Industry nor the U.S. NRC have taken a formal position on Black Sky issues *per se*. Rather, the Nuclear Industry and the NRC have been focused on implementing the lessons evolving out of the Fukushima Dai-ichi accident with respect to mitigation of hazards posed by external events.

Table 1. NPP's fuel supply is unique asset in Black Sky environment

Steam Plant Type	Typical Onsite Fuel Supply (days)	Fuel Replenishment Mechanism
Gas Fired	< 1	Pipeline
Oil-Fired	< 7 (?)	Pipeline & Truck
Coal-Fired	30 – 90	Truck, Rail, Barge
Nuclear	~ 365*	Truck

* assumes mid-point of 2-yr refueling cycle

(The aforementioned FLEX Program is one such example.) The relevant dialog to date within the Nuclear Industry, between the Nuclear Industry and the NRC, between the NRC and the U.S. Congress, and between the NRC and the Public has primarily focused on the ability of the NPPs to achieve and sustain safe shutdown and long-term spent fuel pool cooling following GMDs or EMP attacks. The NRC announced in November 2015 a proposed rule requiring NPPs to establish an integrated response capability for mitigation of Beyond-Design-Basis events with a special focus on mitigation of external hazards **[*44*]**. The NRC does not consider GMDs an "immediate safety concern"**[*45*]**. It is continuing to evaluate whether specific regulatory actions are required via the aforementioned rule-making process and is participating in an interagency task force developing a National Space Weather Strategy and an associated action plan **[*45*]**.

XI. Formulating "The Question"

Given the conclusion that today's NPPs are Black Sky Liabilities, and in consideration of the potential value of having NPPs capable of serving as Black Start Units, there is a compelling reason to investigate what might be required to achieve such operability. Thus "The Question" with regard to commercial nuclear power plants and Black Sky Events is:

"Can today's nuclear power plants be transformed from Black Sky Liabilities to Black Sky Assets, and if so, how?"

The Question can be deconstructed into sub-questions, namely:

1. What can be done to extend a NPP's ability to cope with Black Sky Events (complete loss-of-offsite power events in which the surrounding civil and social infrastructures are so degraded that deliveries of diesel fuel, equipment and commodities to the plant are not possible)?
2. Assuming the NPPs shut down prior to or during the Black Sky Event, and is not damaged during the event, what might be done to enable the NPPs to restart under Black Sky conditions?
3. Assuming the NPPs have run through or can restart during Black Sky conditions, what might be done to enable the plants to synchronize with, reconnect to, and feed the Grid as necessary to energize it and bootstrap the Grid out of the Black Sky condition?

These sub-questions will be explored further in the next section.

XII. A Framework For Addressing NPP – Black Sky Issues

Figure 7 presents a highly simplified event/capability tree that provides further insight into the nature of the questions that must be answered and capabilities that must be enabled if today's NPPs are to become Black Sky Assets. The responses and capabilities combine to produce eight basic NPP Black Sky Response pathways.

The event tree begins on the extreme left of Figure 7 at the moment NPP operators become aware of an impending BSE or the plant senses the effects of the BSE. Immediately upon becoming aware of an impending loss-of-offsite-power event, the NPP can preemptively respond by running back power or completely shutting down. If advance warning is not received, the plant will sense the Black Sky Event via one or more of the mechanisms discussed in Section VI, and automatically trip (shut down). Response 1 in Figure 7 is the approach in which the NPP shuts down, is successfully cooled for as long as necessary, and then successfully restarts, synchronizes with and reconnects to the Grid, and load-follows as necessary to bootstrap the Grid. Response 6 achieves the same outcome as Response 1, but it does so by allowing the NPP to runback and run through the BSE, reconnect, synchronize, and load-follow. (As indicated in Figure 7, it is also possible the plant might initially attempt to runback and run through the event, only to find it necessary to shut down later. This sequence is not presented in Figure 7 as a distinct response path. Rather, it can be envisioned as an early transition from Response 6 to Response 1.)

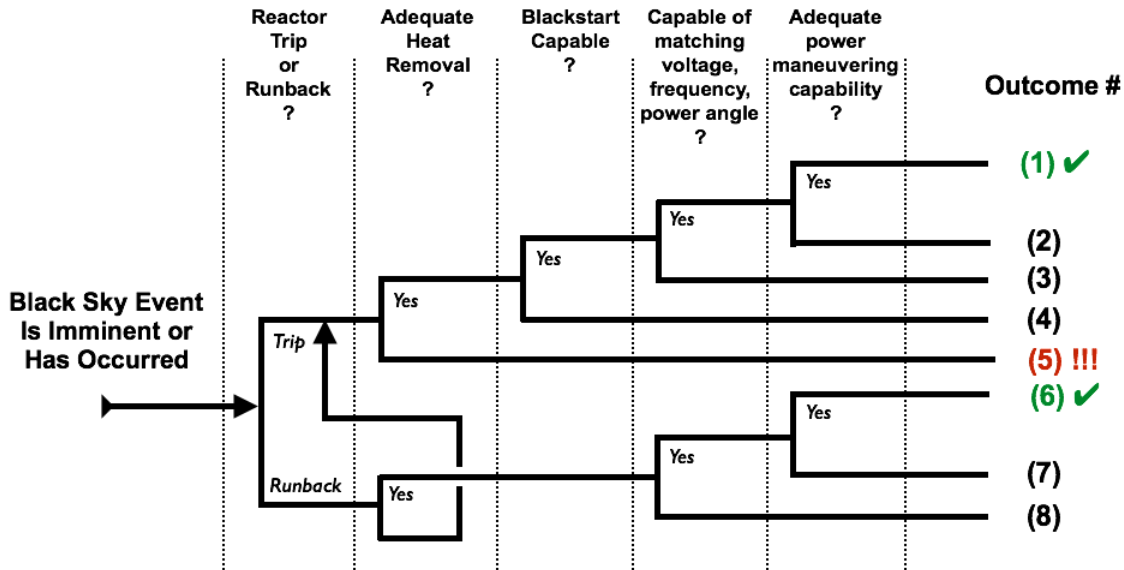

Figure 7. NPP Black Sky Evaluation Framework (Source: S. R. Greene, Advanced Technology Insights, LLC.)

Response 5 is the response to be avoided because it would almost certainly result in severe damage to the NPP due to loss of heat removal function after the reactor has runback and/or shutdown. The timing and rate of progression of the damage in Response 5 will depend on a number of factors, including whether the reactor tripped from full power or from reduced (runback) power, how long cooling was maintained after the reactor was shutdown, etc. Assuming all equipment functions as designed (including emergency diesel-driven backup systems), the timing of core damage in Response 5 is tied directly to when the NPP's diesel fuel supply is exhausted **[*35*].**

All other Responses (Responses 2 – 4 and 7 – 8) in Figure 7 place the NPP in various intermediate states of readiness for repowering the Grid. Response 4 is one in which the previously shut down NPP cannot restart. Responses 3 and 8 are cases in which a plant that has either restarted or runback/run through an event cannot synchronize with the Grid and reattach to it. Responses 2 and 7 are cases in which the NPP has successfully reconnected to the Grid, but cannot load follow as necessary to handle the real and reactive power swings present on the (compromised) Grid.

The event/capability tree presented in Figure 7 mirrors a decision tree based on four key questions:

1. Should the NPP attempt to "runback and run through" the Black Sky Event (and if so, what changes in the NPP and the NPP-Grid interface are necessary to enable this), or should the NPP shutdown and transition to shutdown decay heat removal operations?
2. What changes to the NPP, the NPP-Grid interface, the Grid, and other Critical Infrastructures might enable the NPP to restart under Black Sky conditions?
3. What changes to the NPP, the NPP-Grid interface, and the Grid are necessary to enable the running NPP to synchronize with a (possibly unstable) Grid, and reattach to the Grid under Black Sky conditions?
4. What changes to the NPP, the NPP-Grid interface, and the Grid are necessary to enable the NPP, once reattached to the Grid, to remain attached and to maneuver as necessary to match the load placed upon it by a Grid whose health is unknown, and whose functionality is impaired?

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The answers to these questions will yield the information needed to construct a set of candidate options for translating NPPs from Black Sky Liabilities to Black Sky Assets. Once these options are defined, a second tier of questions must be addressed:

A. Which options provide the highest benefit with regard to enabling rapid recovery of the Grid and minimizing societal impacts of the BSE?
B. What are the probable impacts of each option on the NPP's availability, reliability, safety, and cost of normal operations?
C. What are the costs (relative and absolute) of implementing each option?
D. How testable and maintainable are the hardware and procedures required to implement each option?

The answers to these questions will be somewhat plant-specific due both to the features of the NPP, the NPP-Grid interface, and the features of the NPP's "hosting" Grid entity. However, useful insights could be gained by a methodical evaluation of these questions for one, or a few, actual "reference plant/Grid" examples chosen from today's U.S. Grid.

Finally, while the focus of this discussion has been on issues related to ***existing*** NPPs and Black Sky Events, the opportunity exists to optimize *future* reactors to avoid the Black Sky challenges presented by current NPPs, and present real Black Sky / Black Start benefits to their owner/operators. Two potential types of future reactors are of particular interest. First, small modular reactors (SMRs) could be designed for assured Black Start capability, and optimized to enable their placement in and interface to the Grid at locations that maximize their value in terms of Grid resiliency and Black Start recovery. Second, the possibility exists that "micro reactors or "megawatt class reactors" could be co-located onsite with existing large power reactors to serve as assured onsite auxiliary power sources and assured cranking power sources for their larger companion. Such small reactors might be configured to operated continuously at very low power and configured in a manner in which they are completely isolated from the offsite Grid and Grid disturbances. Designers of these future reactors and their potential customers are encouraged to factor these considerations into their decisions.

XIII. A Word About Risk

During the past three decades, the NRC and the U.S. Nuclear Industry have evolved a "risk-informed" regulatory regime that illuminates virtually every aspect of the nuclear power enterprise. Current reactor designs, NPP licensing, NPP operations and maintenance, emergency response planning, and the implementation of NPP backfits and modifications are all informed by risk management considerations. This process has unquestionably improved safety and reduced the risk to the public of nuclear power operations. It is useful to reflect on how the consideration of Black Sky Events might fit into such a risk-informed regulatory regime.

From the practical standpoint, the "risk" associated with a undesirable event is defined to be the product of the probability of the event and the consequences of that event, summed over all relevant events **[*37*].** There are two generic categories of events: "Internal events" include phenomena such as valve failures, relay failures, etc. "External events" are considered to be events resulting from natural phenomena such as fires, floods, seismic events, GMDs triggered by coronal mass ejections, etc**. [*46*]** Overt or intentional actions taken by humans – such as EMP and cyber attacks – are external events of a special type. The assignment of a "probability" for premeditated human actions can rapidly become tangled in philosophical argument.

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The application of risk-informed paradigms and traditional "cost/benefit" analyses such as application of the NRC Backfit Rule **[*47*]** to evaluate the efficacy of potential Black Sky-motivated modifications to NPPs and the Grid is particularly challenging. This is due to the fact that external events of the type that might trigger a Black Sky Event are considered, "high-impact, low-frequency" events **[*48*].** The challenge presented by such events is that there is (or there is believed to be) an "*insufficient statistical basis to directly estimate the probabilities and consequences of their occurrence*" **[*48*]**. While it may be possible to estimate the cost of implementing a Black Sky-motivated backfit to an NPP or the Grid, estimation of the risk benefit (reduction) of doing so can be extraordinarily difficult. What is the true probability of a Carrington Event-class CME/GMD? What is the "probability" of an EMP attack? Quantification of the consequences of such events is perhaps even more difficult.

There are those who would argue that if a true Black Sky Event actually occurred, the devastation to and impact on our society would be so overwhelming it is not reasonable to be concerned with questions such as those posed in this paper. It is tempting to consider Black Sky issues as the same class as, say, those related to the impact of a massive meteorite impact on Earth – extraordinarily low frequency incidents of such devastating scale and effect, there is no value in attempting to mitigate the risk they pose to society.

It is worth noting that *if* Riley's and Love's estimates of the probability / frequency of Carrington-class GMDs are correct **[*15, 17*]**, these events represent a class of hazards far more probable than the proverbial "dinosaur-killing" meteorite. In fact, if Riley and Love are remotely correct in their estimation of the probability of such events (say an event frequency of 1 in 100 to 1 in 1000 years), the probability of such events is significantly higher than that of many events included *within* the design basis of current generation NPPs. Indeed, the International Atomic Energy Agency (IAEA) safety standards require NPP designers and licensing authorities to ensure "Postulated Initiating Events" (PIEs) with probabilities exceeding 1 in 10,000 years result in "*no radiological impact at all, or no radiological impact outside the exclusion area*" of the plant **[*49*]**. *The key question, and perhaps the largest uncertainty is how the probability of a CME or other natural or man-made* ***initiating*** *event translates to the probability of the "ultimate loss of off-site power" event to which the NPP might be exposed*. And then, of course, there's the additional initiating event "probability" contribution from EMP and cyber threats.

Given current uncertainties regarding the probability of Black Sky initiating events and how they translate to NPP accident initiator events, and the response of Critical Infrastructure (including the Grid and NPPs) to them, "*How can and when will society make decisions regarding issues surrounding NPPs and Black Sky Events?*" Analyses of the type discussed in this paper can inform that process.

XIV. Summary Observations and Recommendations

Reliable access to electricity is a key enabler of modern life and the foundation of all other Critical Infrastructures. The Grid is the "machine" which generates, stores, and delivers this electricity. The U.S. Grid is vulnerable to a number of natural hazards and man-made threats that have the potential to cause Black Sky Events – blackouts of extraordinary geographical scale lasting for weeks, months, or even longer. Embedded within the U.S. Grid are almost 100 commercial nuclear power reactors.

This paper has addressed two levels of relevant NPP Black Sky issues:

1) The behavior of the interconnected "system of systems" that is the coupled physical infrastructure-human infrastructure world in which Black Sky Events would evolve; and

2) The role of nuclear power plants in Black Sky Events.

The role of NPPs in Black Sky scenarios is largely unexplored territory.

A Black Sky Event will ultimately present itself to an NPP as a sustained loss of offsite power (LOOP) event. Both from the regulatory and technical standpoint, the response of NPPs to a Black Sky event in today's environment would be to isolate from the Grid and "cocoon" until offsite power is restored or available diesel fuel supplies are exhausted. Thus the safety of the NPPs during a continuing Black Sky Event will ultimately depend on the ability of world outside the plant to resupply diesel fuel, other consumables, and perhaps additional equipment to the plant at a time when all Critical Infrastructures are compromised, transportation systems are dysfunctional, and there is keen competition for available resources. Once shutdown, today's NPPs cannot restart without an external source of AC power. It is difficult to avoid the conclusion that for all their many benefits to society, today's NPPs are Black Sky Liabilities.

Today's NPPs employ an operational framework of EOPs, SAMGs, FLEX, and EDMG procedures designed to cope with a wide variety of beyond design basis events. However, these procedures were not designed for sustained Black Sky environments.

Internal to the NPP lies an asset that would be of extraordinary value during Black Sky Events if the NPP and the Grid could be modified to access it. A NPP might have as much as 24 (full power) months of fuel in the reactor at the start of a Black Sky Event. When compared to the onsite fuel inventory at a coal-fired electrical generating plant (typically 30-60 days), or gas-turbine plants (hours to perhaps a few days), *the NPP's nuclear fuel inventory could enable the NPP to become the foundation of a robust U.S. Grid restoration strategy*. This benefit can only be realized if the plant could endure the Black Sky Event without damage, run through the event or restart in the midst of Black Sky conditions, synchronize with the Grid, reconnect to the Grid, and run as required to match voltage, frequency, and (real and reactive) power demands. This could be an enormous societal benefit during a time when all Critical Infrastructures are compromised and virtually all resources are over-subscribed. *NPPs could become nearly ideal Black Start Resources ("Units") and an enabler of Grid resiliency - if these functionalities could be achieved.*

In light of these observations, the following recommendations are offered as a catalyst for generating further dialog with respect to NPP-Black Sky issues:

Recommendation 1 – *the utility of agent-based simulation (ABS) approaches for probing several issues relevant to the role of nuclear power in Black Sky Events should be explored.* Agent-based simulation approaches employing model topologies similar to that depicted in Figure 2, could provide useful insights to inform a host of Black Sky questions and issues. The range of issues worthy of consideration include understanding; (a) interdependences between the electric power infrastructure and other Critical Infrastructure Sectors; (b) optimal extension of existing NPP EOP/SAMG/FLEX/EDMG procedures in Black Sky environments; (c) NPP operational decision making in situations involving degraded situation awareness and quality of information; (d) the development of federal, state, and local emergency response plans; and (e) the development of relevant policy and regulatory frameworks. The model "level" (e.g. individual generating plant, Regional Transmission Organization, NERC Region, Interconnection, etc.), type of intelligent agents employed, and phenomenological models and rules implemented in ABS approaches would necessarily be tailored to the specific questions targeted for exploration. One intriguing pathway for exploration would focus on evaluating the efficacy of existing FERC / NERC emergency operating procedures within a single nuclear generation and transmission entity in the U.S. Grid. At the other end of the spectrum, a very high-level multi-agent model might be useful for probing questions such as who/what should receive priority for power restoration in the event of a major Black Sky Event.

Recommendation 2 – This paper has defined a preliminary framework for addressing the question, "Can today's nuclear power plants be transformed from Black Sky Liabilities to Black Sky Assets, and if so, how?" This framework is built upon a simplified NPP Black Sky event / functionality tree (Figure 7) that

identifies the key actions required (and therefore the key capabilities needed) if an NPP is to become a Black Start Resource. *The simple event/functionality tree defined in Figure 7 should be expanded to provide a useful analytical framework, and applied to individual NPPs to provide a better understanding of the challenges, implications, and intricacies of achieving Black Start functionality.*

Recommendation 3 – Todays NPPs are operated and regulated in a manner that assumes diesel-dependent safe shutdown mode is the safest response to all loss of offsite power events. *The risk implications of this assumption in an "all hazards / all threats" environment including Black Skies should be revisited*. Given recent developments regarding our understanding of the probability of naturally induced GMDs, it is quite possible (perhaps even likely) the safest mode for NPPs would be to runback/run through a loss of offsite power event rather than to shutdown and simply hope offsite power is restored before the diesel fuel is exhausted.

Recommendation 4 – *The feasibility of enabling existing NPPs to runback / run through a BSE in a low power, "islanded" mode should be explored.* Most NPPs were designed for significant runback capability, but it is rarely employed. Why? It is likely to be difficult to discriminate in real-time between events in which a reactor trip is appropriate, and those in which runback is advised. Achieving this capability would be one challenging aspect of this approach to BSE response – especially because restart of the reactor once it has tripped is not possible absent offsite AC power feed.

Recommendation 5 – *The possibility of providing sustained NPP safe shutdown cooling during prolonged Black Sky Events by harnessing the capabilities of collocated micro-reactors as auxiliary power sources should be examined*. Such a capability would free the NPP from dependence on diesel fuel supplies for sustained shutdown decay heat removal during Black Sky Events.

Recommendation 6 – *The efficacy of configuring NPPs, dedicated offsite cranking transmission lines, and Black Start resources into "Secure Enclaves" should be examined; and the extent to which this approach has been / is being deployed in the electric power industry should be understood.*

Recommendation 7 – *The possibility of enhancing a NPP's ability to remain connected to an unstable Grid (both in terms of the NPPs power transmission interties and is offsite power feed) should be investigated.* Two aspects of the challenge are evident. The first involves enhancing the NPPs load-following capabilities. The second involves buffering (to the extent possible) the NPP from Grid anomalies via use of DC-DC and VFT connections, rather than standard AC-AC connections for both power transmission <u>from</u> the NPP and offsite power feed <u>to</u> the NPP. Such connections might buffer the plant from Grid voltage, frequency, and power angle anomalies that currently trigger plant trips and inhibit reattachment of the NPP to the Grid during Black Sky recovery operations. Opportunities may also exist to enhance relay and switching technologies, and fault detection and management technologies in the NPP's switchyard and on the Grid. Such actions could result in an NPP-Grid interface that is more robust, more reliability, and more resilient for both normal operations and Black Sky Events – and NPPs that are more capable of aiding in Grid recovery during Black Sky Events.

Recommendation 8 – *The possibility of enabling existing NPPs to become Black Start Units by providing assured onsite cranking power supplies and enhancing their ability to match a dynamic load of the type expected in the initial states of a Black Sky recovery should be explored.* Innovative approaches such as providing small onsite megawatt class reactors for cranking power (see Recommendation 5) and changes such as those described In Recommendation 7 could enable existing NPPs to become true Black Start Units capable of cranking other power plants and "boot-strapping" the Grid during an ongoing Black Sky Event.

Recommendation 9 – The opportunity exists to optimize future reactors (megawatt class reactors and Small Modular Reactors) to both avoid the Black Sky challenges presented by current NPPs and offer Black Start capabilities not afforded by today's nuclear power fleet. *Studies should be conducted to understand (a) the functional requirements of a megawatt class reactor and its interface to an NPP that would enable it to perform as an assured onsite auxiliary power supply or cranking power supply for the NPP in the case of loss of offsite power; (b) the SMR design features that would enable it to function as a Black Start Resource; and (c) the SMR siting considerations and SMR-Grid integration considerations that would maximize the SMR's contribution to Grid resiliency during routine and Black Sky conditions.*

Every day, as we go about our lives, the nation's nuclear power fleet quietly provides enormous benefits to society. A Black Sky Event has the potential to disrupt life as we know it. *Can nuclear power be the key to protecting society from the ravages of Black Sky Events?*

We can and should move promptly to address this question.

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