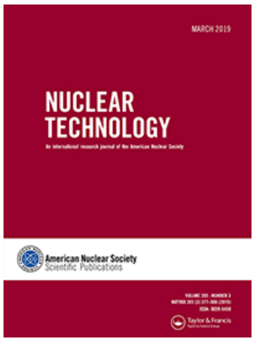

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Enhancing Electric Grid, Critical Infrastructure, and Societal Resilience with Resilient Nuclear Power Plants (rNPPs)

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Abstract — *This paper, the fourth in a series, presents the results of a study conducted to explore the role current U.S. commercial nuclear power plants (NPPs) play and the role a new type of NPP—a resilient nuclear power plant (rNPP)—could play in enhancing U.S. electric Grid, Critical Infrastructure, and societal resilience. A rNPP is a NPP intentionally designed, sited, interfaced, and operated in a manner to enhance Grid resilience. Four specific rNPP applications are discussed: (1) rNPPs as "flexible operations" electricity generation assets, (2) rNPPs as anchors of nuclear hybrid energy systems, (3) rNPPs as Grid Black Start Resources, and (4) rNPPs as anchors of Resilient Critical Infrastructure Islands. These four applications, individually and collectively, could enhance U.S. Grid, Critical Infrastructure, and societal resilience during normal conditions and in the wake of major national calamities stemming from natural hazards and/or malevolent human actions. rNPPs would be both tactical and strategic resilience assets, thereby extending the value proposition of nuclear energy well beyond that associated with nuclear power's traditional baseload electricity generation. These are important topics as society grows increasingly dependent on electricity, and the natural hazard and malevolent human threat portfolio to the Grid continues to evolve.*

Keywords — *Grid resilience, Critical Infrastructure resilience, resilient nuclear power plant, Resilient Critical Infrastructure Island.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Electric Grid resilience is a subject of growing importance in the United States and abroad as modern societies continue to expand their dependence on electric power and the infrastructure that generates and delivers it.[1] (The term "Grid," with or without the "electric" modifier, is employed in this paper to refer to the integrated system of electricity generation, storage, transmission, and distribution assets required to supply electricity to the end user.) Issues such as the basic definition of Grid resilience, how Grid resilience can be measured and estimated, the value of Grid resilience to society, how Grid resilience can be monetized, and how Grid resilience can be achieved and secured have recently attracted significant attention in the United States.[2–4]

Previous papers by the author[5–8] have examined the nature of Grid resilience and the role today's commercial nuclear power plants (NPPs) play in enabling U.S. Grid resilience as well as defined the key attributes and functional requirements for a new type of NPP: a resilient nuclear power plant (rNPP) that would be "intentionally designed, sited, interfaced, and operated to enhance Grid resilience."[7] This paper introduces and discusses four specific rNPP applications that would leverage the operational and performance capabilities of future rNPPs to provide transformation Grid resilience benefits.

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Sections II, III, and IV provide essential context for considering potential rNPP applications. Section II provides a working definition of Grid resilience. Section III summarizes prior research findings regarding the Grid resilience value of current U.S. NPPs (Refs. 5 and 6) and discusses nuclear power's unique fuel security, which is an attribute that, if harnessed, could transform nuclear power's value proposition with respect to U.S. Grid and Critical Infrastructure resilience. Section IV presents the two rNPP key attributes, the Six rNPP Functional Requirements, and ten illustrative enabling rNPP design features previously identified by the author.[7]

Sections V through VIII discuss four potential rNPP applications that would significantly enhance Grid and other Critical Infrastructure resilience while transforming the value proposition of nuclear energy in the 21st century. These applications are

1. rNPP flexible operations (Sec. V)
2. rNPP-based hybrid nuclear energy systems (HNESs) (Sec. VI)
3. rNPPs serving as Grid Black Start Resources (Sec. VII)
4. rNPP-based Resilient Critical Infrastructure Islands (RCIIs) (Sec. VIII).

Though not the focus of the study, Sec. IX discusses a few important economic challenges related to monetization of Grid resilience and realization of rNPPs. Section X summarizes the main points of the paper.

II. GRID RESILIENCE: A WORKING DEFINITION

Any discussion concerning the Grid resilience value of nuclear power must of course be predicated on an explicit definition of Grid resilience. There is currently no consensus definition of Grid resilience among the various industry, regulatory, customer, and policymaker stakeholders.[1] The foundation for synthesis of a practical working definition of Grid resilience is a more general definition of system resilience such as the following: *System resilience is the ability of a system to withstand a change or a disruptive event by reducing the initial negative impacts (absorptive capability), by adapting itself to them (adaptive capability), and by recovering from them (restorative capability).*[9] With this in mind, the author has proposed the following working definition of Grid resilience[6]: *Electric Grid resilience is the system's ability to minimize interruptions of electricity flow to customers given a specific load prioritization hierarchy.* Thus, Grid resilience is defined in consideration of the reality that all electric loads served by the Grid are not of equal priority/value. The impacts of failure to serve various loads are dependent on the nature of the loads (customer class, specific societal function associated with the load, etc.).[6,10] Reference 6 provides a detailed discussion of the concepts of generic system and Grid resilience.

III. U.S. NUCLEAR POWER AND GRID RESILIENCE: CURRENT REALITIES

III.A. Nuclear Power's Demonstrated Performance

Today's commercial NPPs exhibit a suite of operational and performance characteristics that are the basis for nuclear power's current role in Grid operations. From a tactical day-to-day perspective, NPPs are low-carbon-energy sources capable of continuous 24-7 operation day and night. U.S. NPPs exhibit high capacity factors (~92% in 2017, compared to 37% for Grid-scale wind generation systems and 27% for Grid-scale solar photovoltaic systems).[11]

Transitioning from the tactical to the strategic perspective, NPPs have on multiple occasions demonstrated their ability to operate during extreme weather events that either degraded or completely shut down operations at fossil-fired generating plants in the same geographical region.[12,13] The severe cold weather event that gripped much of the Southwestern United States in late January and early February 2011 is one example. During that event, more than 50 nonnuclear power plants, representing 7 GWe of capacity, were rendered inoperable in the Electric Reliability Operating Council of Texas (ERCOT) alone. To make matters worse, the demand for electricity in ERCOT on February 2 was over 9 GWe higher than the published forecast peak load and ~1.4 GWe higher than the previous all-time winter peak load.[12] All categories of power plants (including most wind energy resources) *other than nuclear* experienced outages or were unable to operate in Texas during the event.[12] The Midwest, South Central (including Texas), and East Coast regions of North America experienced an extreme cold weather condition known as a polar vortex in early January 2014. According to the North American Electric Reliability Corporation[13] (NERC), cold weather and issues related to fuel combined to produce over 35 GWe of outages during the height of the event as many of the affected regions experienced record high electricity demands. Natural gas–fired electricity generation facilities were particularly hard-hit during the event due to curtailment of their fuel supplies as natural gas was diverted to residential and commercial customers.

Nuclear power plants do not rely on fuel that can be diverted to other uses (as is the case with natural gas) and do not have coal piles and coal feed systems that can freeze or become frozen during prolonged periods of frigid weather. Also, NPPs do not have exhaust stacks that can become clogged or otherwise compromised when moisture in combustion exhaust gases condenses and freezes due to extreme cold. Thus, today's NPPs have demonstrated their ability to provide Grid resilience benefits for certain national and regional Grid emergencies, *provided* the bulk Grid transmission and distribution infrastructure is not physically damaged or compromised in any significant manner.

III.B. Current U.S. NPPs in a Disrupted Grid

The conclusions presented in Sec. III.A relate to situations in which the nongeneration Grid infrastructure (transmission lines, high-voltage transformers, distribution load centers, etc.) is largely intact and undisturbed. But, what about situations in which this infrastructure is damaged or otherwise functioning in a manner that alters normal NPP-Grid interface conditions (transmission and off-site power voltage, frequency, real/reactive power balance, etc.)? Reactive power is power that flows out of phase with real power in alternating-current (AC) systems, as required to establish and maintain various electromagnetic fields in generators, motors, and transformers and along transmission lines. Previous analyses of such situations[5,6] support the conclusion that while current U.S. NPPs are safe and reliable energy and capacity resources, the design, operational, and regulatory approaches adopted to achieve these safety and reliability objectives have resulted in plants that are intolerant of transmission load and off-site power anomalies. Indeed, today's NPPs are frequently among the first generating plants to shut down and the last plants to return to service in the wake of major Grid disruptions. Thus, current U.S. NPPs do not enable the Grid to absorb, adapt to, and rapidly recover from major Grid disruptions. Rather, current NPPs would actually be burdens on Grid operators during the early stages of Grid recovery and restoration activities in the wake of major Grid disruptions because most, if not all, current U.S. NPPs would ultimately require off-site power or other assistance to maintain safe shutdown cooling in the event of an extended Black Sky event[5,6] (BSE). It is evident existing U.S. NPPs are not major Grid resilience assets for such scenarios. Despite this reality, NPPs possess one unique attribute that could enable future NPPs to become transformational Grid resilience assets.

III.C. Nuclear Power's Unique Fuel Security

Nuclear power plants are unique from other steam-cycle electric power plants in one respect: their fuel security. Table I summarizes typical steam cycle power plant on-site fuel inventory in terms of the plant operating (electrical power generation) time the on-site fuel inventory enables. NPP on-site (in-reactor) fuel inventories far exceed those of other steam cycle plants. Why is this fuel security attribute such an important feature with respect to Grid and Critical Infrastructure resilience?

The answer to this question is rooted primarily in the unique role NPPs' fuel security could enable them to play in accelerating Grid recovery from BSEs (provided of course the plants could operate, synchronize with, and provide power to the Grid). A BSE is a long-duration de-energization of large geographic regions of the electric Grid, up to and including one or more of the three major U.S. Grid Interconnections that constitute the U.S. Grid. BSEs could in theory be triggered by (1) intense geomagnetic disturbances (GMDs) resulting from massive solar coronal mass ejections (CMEs), (2) high-altitude electromagnetic pulse (HEMP) attacks, or (3) cyber attacks on the nation's Grid.[5] The application of probability theory to malevolent human actions such as HEMP and cyber attacks is a controversial issue. However, the probability of massive GMDs of the magnitude of the 1859 Carrington Event is now believed to be ~0.1 on a decadal basis (i.e., such events should be expected to occur about once every 100 years) (Refs. 14 and 15). (The Carrington Event set telegraph poles and equipment in telegraph offices afire across northern North America and Europe.) Thus, the probability of GMDs that could challenge the integrity of the U.S. national Grid is higher than that of many events currently within the design basis of U.S. NPPs.

Once restarted in the wake of a widespread Grid failure, the ability of the Grid to stay energized (and the ability of other electricity-dependent Critical Infrastructure to function) will depend in part on the ability of Grid operators to refuel power generation facilities. Hydroelectric dams and fossil-fueled power plants would certainly have an important role to play in Black Sky Grid recovery. However, the on-site fuel inventory (Table I) of a fossil-fueled generation plant ranges between a few hours (gas-fired combustion turbine plants) to perhaps 2 to 3 months for coal-fired plants. BSEs would almost certainly challenge the ability of Grid

TABLE I

Typical Steam Cycle Power Plant Fuel Inventories*

Steam Plant Type	Typical On-Site Fuel Supply (day)	Fuel Replenishment Mechanism
Gas fired	<1	Pipeline
Oil fired	<7	Pipeline and truck
Coal fired	30 to 90	Truck, rail, and barge
Nuclear	~365[a]	Truck

*Reference 5.

[a] Assumes midpoint of 2-year refueling cycle.

operators to reliably resupply fuel (oil, natural gas, and coal) to fossil-fueled power plants.[5] Hydroelectric generation is, at its limit, reduced to "run of river" generating capability. Thus, the fuel security attribute of NPPs could be a differentiating Grid resilience asset in such events, provided the NPPs (1) can continue to operate through the initiating event or restart in the wake of the event and (2) interface with and power a Grid that is most likely damaged or otherwise compromised by the event.[5,6,8] This discriminating attribute of nuclear power is a great motivator for exploring what can be done to enhance the ability of NPPs to tolerate off-normal Grid conditions.

IV. RESILIENT NPPs (rNPPs)

IV.A. Definition and Key Attributes of rNPPs

The concept of rNPPs is "use-inspired," that is, one that evolves from a philosophy that NPPs can and should serve the Grid and society in ways that transcend traditional baseload electric power generation. As previously stated, "rNPPs are nuclear power plants intentionally designed, sited, interfaced, and operated to enhance Grid, Critical Infrastructure, and societal resilience."[7] In light of the definitions of generic system and Grid resilience articulated in Sec. II, two basic attributes of rNPPs have been defined[7]:

1. *rNPP Key Attribute 1*: rNPPs enhance the Grid's ability to absorb and adapt to a broad spectrum of Grid anomalies and upsets.

2. *rNPP Key Attribute 2*: rNPPs enhance the Grid's ability to recover from upsets and to restore electric service in a manner consistent with the system operator's load prioritization hierarchy.

IV.B. Six rNPP Functional Requirements

Six rNPP Functional Requirements have been defined in a preliminary qualitative manner in Table II and are discussed in detail in Ref. 7. This package of Six rNPP Functional Requirements defines a plant performance envelope that substantially exceeds that of existing U.S. commercial NPPs. (As discussed in Ref. 7, some NPPs outside of the United States do possess enhanced load-following capabilities relative to U.S. plants. Thus, a basis exists for confidence that the Six rNPP Functional Requirements are technically achievable.) While considerable work remains to be done to quantify terms such as "robust," "flexible," "immunity," and "extremely low" as employed in Table II, it is evident that a rNPP possessing all, or even some, of these functional capabilities would be capable of operating in modes and roles beyond that of baseload electricity generation, would be much more tolerant of off-normal Grid conditions than are today's NPPs, and would be capable of restarting in the wake of plant shutdowns without relying on off-site power or other resources.

IV.C. rNPP Enabling Design Features

Given the Six rNPP Functional Requirements presented in Table II, an obvious question is whether there is, from a technical perspective, a valid rNPP design trade space. In other words: Are there evident rNPP design features (system architectures and technologies) that should enable a plant to achieve the Six rNPP Functional Requirements? A preliminary analysis reveals there are indeed several design features that have the

TABLE II

Six rNPP Functional Requirements*

rNPP Functional Requirement
1. Robust real/reactive load-following and flexible operation capability 2. Immunity (extremely low vulnerability) to damage from external events (including Grid anomalies) 3. Ability to avoid plant shutdown (reactor scram) in response to Grid anomalies 4. Ability to operate in Island Mode (i.e., without connection to off-site transmission load and electric power supply) 5. Unlimited independent safe shutdown cooling capability (i.e., requiring no off-site power or resupply of diesel fuel from off site) 6. Independent self-cranking black start capability (i.e., the ability to start with no off-site power supply from the Grid)

*Reference 7.

potential to enable rNPPs (Ref. 7). Table III provides a concise description of some enabling rNPP design features together with an indication of which of the Six rNPP Functional Requirements they should enable. Reference 7 provides an in-depth discussion of potential rNPP design features summarized in Table III, along with some preliminary thoughts regarding rNPP capital cost and economic viability.

V. rNPPs AND FLEXIBLE NUCLEAR POWER OPERATIONS

Resilient NPP Functional Requirement 1 requires rNPPs to be capable of load-following operations well beyond traditional baseload operations, in terms of both real and reactive power maneuvering capability.[7] The International Atomic Energy Agency[16] and the Electric Power Research Institute[17] have evaluated the ability of

TABLE III

Potential Enabling rNPP Design Features*

Potentially Enabling rNPP Design Features	Impact	Enables rNPP Functional Requirement Number
1. Direct Current-Direct Current (DC-DC) or Variable Frequency Transformer (VFT) NPP interface with Grid	Buffers rNPP from Grid transmission load and off-site power quality anomalies	1, 2, and 3
2. High-capacity load switching and heat rejection	Substitutes alternate thermal or electrical load in case of Grid-based loss of load events	1 through 4
3. Multimodule (reactor) NPP architecture	Enables one operating reactor module to supply shutdown cooling and housekeeping electrical loads to other rNPP reactor modules Enables one reactor module to crank other reactor modules in rNPP	4, 5, and 6
4. Small reactor (module) size	Reduces cranking power requirements of individual reactor modules in rNPP Enables nontraditional cranking power supplies for rNPP Reduces individual reactor module shutdown heat removal and housekeeping electrical loads	1 and 3 through 6
5. Adaptive turbine-generator systems	Enhances rNPP load-following and flexible operation capability	1, 2, and 3
6. Passive shutdown cooling	Eliminates dependence of rNPP on consumable on-site resources and off-site assistance to maintain safe shutdown state	5
7. Inherent reactor system energy storage capacity	Buffers rNPP and individual rNPP reactor modules from electrical (transmission system) load transients	1 through 4
8. Optimized reactor core physics design	Enables rapid rNPP reactor module power maneuvering and restart across entire fuel cycle	1 through 4 and 6
9. Robust nuclear fuels	Increases rNPP reactor module's power maneuvering capability	1 through 5
10. Plant electrical, instrumentation and control, and computer technologies that are resilient in face of GMD, EMP, and cyber attack	Enables rNPP to avoid damage and continue to function in event of GMD, EMP, or cyber attack	2

*Reference 7.

current NPPs to operate outside of the baseload generation envelope and the technical implications of doing so. The conclusion of work conducted to date is that existing NPPs do generally have load-following capabilities beyond stable baseload operation. However, their use in such a manner is constrained primarily by electricity market and regulatory considerations. rNPPs with load-following capabilities beyond those of current-generation plants would have the ability to reduce power output when electricity market prices are low and shift their capacity to ancillary markets.

Analysis of the potential economic impact of rNPP flexible operations is a complex undertaking, heavily laden with assumptions regarding electricity market mechanics. Competitive merchant electricity markets actually comprise distinct submarkets for energy, capacity, and ancillary services. The Federal Energy Regulatory Commission defines six ancillary services in Order No. 888: scheduling, system control, and dispatch; reactive supply and voltage control from generation service; regulation and frequency response service; energy imbalance service; operating reserve–synchronized reserve service; and operating reserve–supplemental reserve service.[18] Similar competitive market mechanisms are utilized by Grid operators to access black start services in merchant markets.[19]

Recent investigations of the economic implications of flexible NPP operations (including roles such as Grid frequency regulation and spinning reserve capacity in a mixed-fuel generation environment) indicate "flexible operation of NPPs can increase the revenue of the nuclear units while at the same time lowering the total electric system operating costs, thus providing a win-win for the nuclear owners and rate payers."[20] Companion studies[21] also indicate that flexible operation of NPPs would enable deeper penetration and more efficient utilization of renewable energy resources. Thus, the enhanced flexible operations capability of rNPPs would enable them to provide functions beyond baseload operations and benefit from the revenue streams associated with such operations while providing a low-carbon option for enabling deeper penetration of renewable energy sources. The competitive nature of these markets would dictate whether a unit that is capable of providing an ancillary service is actually employed in that manner.

VI. rNPPs AS ELEMENTS OF HYBRID ENERGY SYSTEMS

Numerous investigations of so-called hybrid energy systems have been conducted during the past decade.[22–30] Hybrid energy systems are typically designed to leverage the operating strengths of diverse power generation sources. Hybrid Nuclear Energy System concepts (Fig. 1) would integrate the electrical and thermal power production of a NPP with power from other sources (such as wind and solar), along with energy storage technologies, to reduce reactor power maneuvering requirements and produce secondary energy products such as hydrogen, synthetic fuels, etc.

Hybrid nuclear energy systems have traditionally sought to enable the NPP to operate in a baseload mode from the standpoint of thermal power production. This typically involves modulating the combined electrical output of, and the thermal load on, the nuclear reactor and its partnered power generation facilities. This type of HNES employs load switching (rNPP Design Feature 2 in Table III) to divert the reactor's thermal energy production from electricity production to either (a) energy storage or (b) the production of some alternate energy product such as hydrogen or synthetic fuels.

Resilient NPP Functional Requirement 1 (expanded load-following capability) would enable a rNPP employed in a HNES to be more "forgiving" and adaptable to variable electricity generation by other (typically renewable) energy sources coupled to the same Grid, thus easing the challenge of balancing the output from multiple power generation facilities.

The topic of HNESs has become a specialized field of study that continues to attract global attention. The use of rNPPs as anchors of hybrid energy systems is an obvious application given the synergism between the Functional Requirements of rNPPs, the means by which these functionalities are achieved, and the functional capabilities required of NPPs that operate as elements of HNESs.

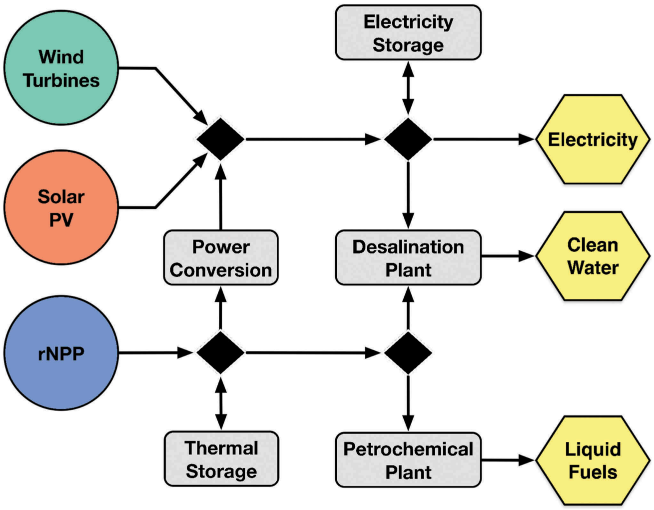

Figure 1. rNPP–anchored HNES.

VII. rNPPs AS BLACK START RESOURCES

The author has previously described current U.S. Grid operators' approach to system recovery following major Grid disruptions.[5] As explained in that analysis, current NPPs are incapable of contributing in any meaningful way to *early* Grid restoration efforts and, in fact, place additional burdens on the Grid and Grid operators during system recovery and restoration efforts. Today's "bootstrapping" Grid recovery process typically begins with the startup of one or more small (few MVA to 200 MVA) gas-fired, coal-fired, or hydroelectric Black Start Resource [hereinafter called Black Start Unit (BSU)] generating facilities (Fig. 2) (Refs. 31, 32, and 33). Once started, these BSUs "crank" larger steam cycle plants that are typically a few hundred megawatts electric in size. The larger steam cycle plants, in turn, crank still larger steam cycle power plants and repower larger and larger segments of the Grid. NPPs are typically among the last plants to be restarted.[5] This serial method of Grid black start, recovery, and restoration is the backbone of Grid recovery procedures employed around the world. This section explores how rNPPs that achieve the Six rNPP Functional Requirements outlined in Sec. IV.B would enable improvements in traditional Grid recovery and restoration operations in the wake of major Grid disruptions.

VII.A. Derived BSU Functional Requirements

The NERC defines a Black Start Resource as follows: "*A 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.*"[34] NERC's Black Start Resource definition, along with the manner in which it is typically implemented by generating and transmission system operators, can be deconvolved into five basic Derived BSU Functional Requirements that are useful aids for examining the ability of a future rNPP to serve as a BSU.

VII.A.1. BSU Functional Requirement 1: Self-Cranking

A BSU must have the ability to be started ("cranked") multiple times[33] without support from the electric Grid (i.e., without off-site power), *or* it must be designed to operate at power without being connected to and loaded by the Grid (the Island Mode of operation). Current (nonnuclear) U.S. BSUs are typically required to be capable of startup in less than 4 h (Ref. 32), with a preference for BSUs that can successfully start up within 1 h of receiving a request to supply black start services.[33] This BSU Functional Requirement implies the possibility of three different BSU ready states as discussed Sec. VII.B. The practical implication of NERC's Black Start Resource definition is that the startup cranking power demands for today's BSUs must be supplied by dedicated on-site power supplies, typically diesel or auxiliary generators that are, in turn, cranked from batteries. rNPP Functional Requirements 4, 5, and 6 would enable a rNPP to meet this BSU Functional Requirement.

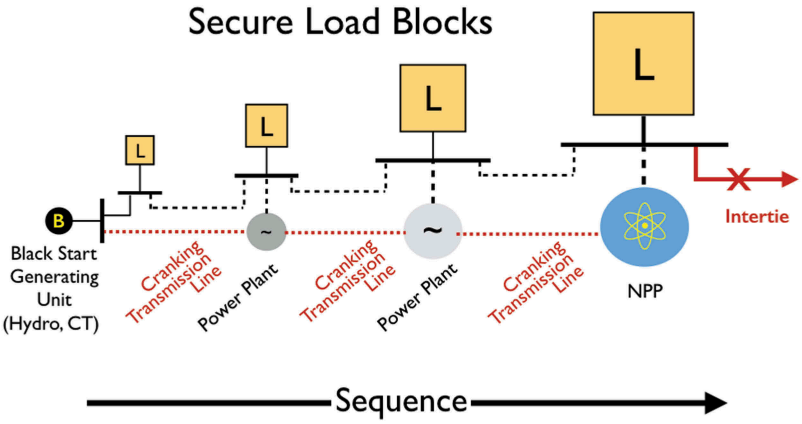

Figure 2. Current Grid black start recovery approach.
Note: Extreme simplification, CT = Combustion Turbine.
Switches, relays, circuit breakers, and isolators not shown.

VII.A.2. BSU Functional Requirement 2: Islanding/Island Mode Operation

NERC's Black Start Resource definition states that as an alternative to self-cranking capability, a Black Start Resource must be capable of "islanding." Island Mode is the state in which the plant is operating at some power level but is not connected to and loaded by the Grid. U.S. BSUs are typically required to be capable of operating in Island Mode for only 10 to 30 min (Ref. 32) after self-cranking. However, some fossil-fired generating units have the capability to manually island themselves by cutting back power and isolating from the Grid in advance of predicted threats to Grid integrity, or even to do so in real-time response to a Grid anomaly. rNPP Functional Requirements 2, 3, and 4 would provide rNPPs the same capability to achieve and operate in Island Mode.

VII.A.3. BSU Functional Requirement 3: Grid Integration

A BSU must have the ability to energize a bus that, in turn, enables the cranking of other power plants. In practice, this means the BSU's interface to the Grid must meet at least one of three configurations:

1. The BSU's switchyard is directly connected to the Grid via multiple transmission lines.
2. If the BSU's switchyard is served by a single transmission line, that transmission line is connected to a remote transmission node (bus) that serves multiple transmission lines.
3. At least one transmission line that serves the BSU is a dedicated cranking line for another generating unit.

A BSU must, in practice, be capable of energizing its assigned bus for 16 h or longer.[32,35] Among other things, this BSU Functional Requirement means that the cranking transmission lines between the BSU and the power plant(s) it will crank must either be preconfigured during normal operations or be configurable under blackout and emergency conditions. The ability of a rNPP to meet BSU Functional Requirement 3 would depend on the manner in which the rNPP is integrated into its host Grid.

VII.A.4. BSU Functional Requirement 4: Real/Reactive Power Maneuvering

A BSU must meet the Transmission Operator's restoration plan needs for real and reactive capacity, and frequency and voltage control. The capability of the BSU to fulfill this requirement is a function of its design, the manner in which it interfaces with the Grid, and the design of the Grid itself. BSUs must be tolerant of larger than normal voltage and frequency variations on both the Grid load circuits (transmission lines and cranking lines) and the power that is supplied back to the BSU once the Grid is reenergized.

Black Start Units must have the real and reactive load-following capability (Requirement 6.1 in Ref. 36) required to achieve and maintain system voltage and frequency standards. The real and reactive power load-following requirement stems from several sources intrinsic to Grid recovery operations.[37] First, the cranking of other generating units involves the startup of a multitude of large electric motor–driven auxiliary systems. During the time these motors are accelerating to speed, they can draw many times their normal operating current and present very large reactive power demand swings as their capacitive and inductive fields are energized. Second, the energization of "cold" transmission lines is accompanied by significant transient reactive power demands and voltage swings due to the Ferranti effect as various capacitive and inductive fields are established along the transmission circuit. (The Ferranti effect is a phenomenon that occurs when energizing lightly loaded AC transmission lines, whereby the current required to establish the capacitive fields around the lines exceeds that required to serve the load at the end of the line, resulting in a voltage rise along the line.) This effect can lead to BSUs absorbing reactive power and, in extreme cases, self-excitation of the BSU's generator excitation system. The cold load pickup phenomenon is another source of real and reactive power load swings on a BSU. The reenergization of loads that have been deenergized for many hours can be accompanied by inrush currents ten times larger than normal steady-state load currents.[35] Because of these factors and others, Grid operators may have limited control over the reactive power demands of the system at various points during the Grid recovery process. The BSU must be capable of handling all of these system issues while continuing to supply power to the Grid during black start and recovery operations. rNPP Functional Requirement 1 would enable the rNPP to meet BSU Functional Requirement 4.

VII.A.5. BSU Functional Requirement 5: Grid Restoration Plan Integration

A BSU must be included in the Transmission Operator's restoration plan as a Black Start Resource. That is, the transmission system operator must have a specific plan and functional capability for Grid recovery that enables use of the BSU in the Grid recovery process. The details for use of a specific BSU within the Transmission Operator's restoration plan relate both to the specific BSU's characteristics and those of the Grid into which it is interfaced. One obvious impact of rNPP functionality (specifically rNPP Functional Requirement 5) is that unlike current NPPs, restoration of off-site power for shutdown cooling would no longer be among the Grid operator's highest priorities during Grid recovery and restoration efforts.

VII.B. Three rNPP BSU Ready States

Figure 3 depicts the three possible BSU ready states for a rNPP (or any other BSU) that could function both as a normal power generation unit and as a BSU, along with the pathways for transition among the three ready states. Figure 4 is a more detailed version of Fig. 3 that depicts the BSU ready state logic embedded in the five BSU Functional Requirements and the manner in which the Six rNPP Functional Requirements ("rNPPFR" in Fig. 4) enable a rNPP to operate in all three BSU ready states. The three BSU ready states are discussed below.

VII.B.1. BSU Ready State 1

The rNPP is operating in Ready State 1 (shutdown) but is capable of rapid startup by self-cranking (without the aid of off-site power) into Ready State 2 Island Mode (via P_{12} in Fig. 3) until loading and repowering the Grid (via P_{23} in Fig. 3) from Ready State 3. Ready State 1 is the state in which conventional gas turbine BSUs function. The rNPP would presumably only be in Ready State 1 if it were forced to shut down due to some internal or external issues associated with a Grid anomaly. As previously stated, current U.S. BSUs are typically required to be capable of multiple black start cranking attempts and to be capable of restarting in less than 4 h when called upon to provide black start services. rNPP Functional Requirements 5 and 6 would enable a rNPP to reside in this BSU ready state and self-crank into Ready State 2.

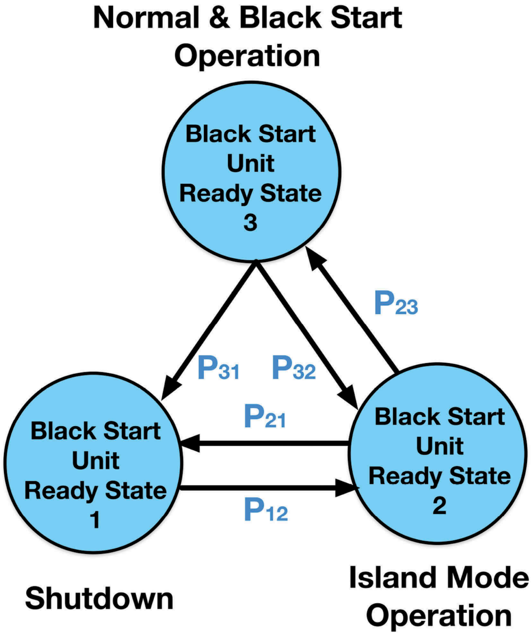

Figure 3. Three BSU ready states.

VII.B.2. BSU Ready State 2

A rNPP operating in this BSU ready state is operating at or above housekeeping power level in an Island Mode. Island Mode is an operating mode in which the plant is completely isolated from the Grid until called upon to synchronize with, load, and repower the Grid from Ready State 3 (path P_{23} in Figs. 3 and 4). Island Mode is similar in some respects to a "spinning reserve" state—albeit one in which the unit is not connected to the Grid and dispatched until called upon to function as a Black Start Resource. In order to have a legitimate capability for Ready State 2 operation, the plant (a) must be capable of achieving stable Island Mode operation by self-cranking from Ready State 1 (via path P_{12} in Figs. 3 and 4) or executing a load rejection/islanding maneuver from Ready State 3 (P_{32} in Figs. 3 and 4). All units transition to Ready State 3 from Ready State 2. Thus, all BSUs must be capable of operating in Ready State 2 (Island Mode). A BSU must also be capable of maintaining a stable Island Mode operation (stable power level, voltage, and frequency) as long as required to function effectively as a Black Start Resource within the framework of system operators' Grid Recovery Plan. rNPP Functional Requirements 2, 3, and 4 would enable a rNPP to achieve and reside in this BSU ready state for much longer periods of time than is typically required of current U.S. BSUs (i.e., only 10 to 30 min).

VII.B.3. BSU Ready State 3

A rNPP operating in Ready State 3 is supplying power to the Grid either in a normal power generation mode or in black start operations mode. When operating as a normal power generation facility, the plant would ideally be capable of quickly isolating from the Grid and transitioning to BSU Ready State 2 Island Mode (via path P_{32} in Figs. 3 and 4). A variable-output rNPP that could accomplish this load rejection (P_{32}) maneuver would be of great utility in a

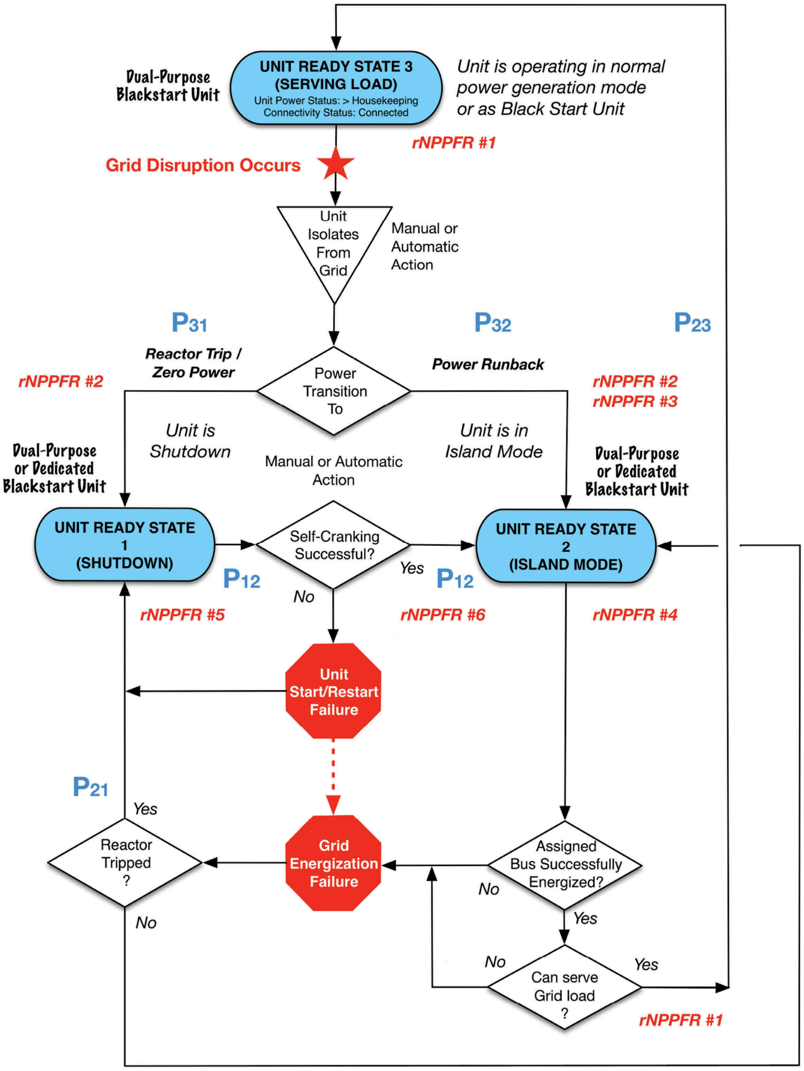

Figure 4. Black start unit ready state transition logic (rNPPFR # = rNPP Functional Requirement number).

number of Grid operation scenarios. The achievement of this capability would require the unit to detect, evaluate, differentiate, and respond appropriately to Grid anomalies in real time. Some nonnuclear steam power plants in the United States that do not have self-cranking capability do have the ability to execute this load rejection–islanding maneuver.[29]

Alternately, and as a last resort, a rNPP operating in Ready State 3 could transition to shutdown Ready State 1 (via path P_{31} in Figs. 3 and 4) if for some reason it could not execute an islanding maneuver. If a rNPP operating in Ready State 3 were forced to shut down into Ready State 1, the rNPP would be capable of meeting its own shutdown cooling requirements without any off-site power or assistance (rNPP Functional Requirement 5) and would be capable of self-cranking restart into Ready State 2 (rNPP Functional Requirement 6). Assuming the plant was not damaged (rNPP Functional Requirement 2), the time required to restart or start up a rNPP would depend on the plant's Limiting Conditions for Operations and associated surveillance requirements. The time required to restart the rNPP from Ready State 1 might limit the unit's use as a Black Start Resource to scenarios in which advance warning of an impending Grid anomaly is available (as perhaps might be the case for a CME) or when rapid black start capability is not required. Thus, the ability of a rNPP to avoid plant shutdown (rNPP Functional Requirement 3) and to operate in Island Mode (rNPP Functional Requirement 4) would greatly expand its potential value as a Black Start Resource.

VII.C. rNPP BSU Grid Interface and Grid Recovery Operational Considerations

The Six rNPP Functional Requirements assure that a rNPP would have the ability to function as a dual-purpose (normal power generation plus black start) unit, provided the plant is interfaced to and integrated with the Grid in the appropriate manner, and the surrounding Grid is, or can be, configured to enable the rNPP to crank other generating units and power critical loads during the Grid recovery and restoration process. How might the necessary Grid interface and configuration conditions be achieved?

The rNPP's robust real and reactive power maneuvering capability (rNPP Functional Requirement 1) would free the Grid operator from the traditional serial generating fleet startup approach depicted in Fig. 2. Figure 5 is a simplified depiction of a rNPP-Grid architecture that would enable such operations. The configuration is one in which the rNPP forms the "hub" of a radial arrangement of cranking lines (to other power plants) and transmission lines (to load blocks and distribution centers). Switchgear, relays, circuit breakers, and isolators are not shown in Fig. 5, but various bus configurations can be envisioned both within the generating network and the transmission/distribution network.

Such rNPP-Grid architectures should enable larger plants to be cranked sooner and/or diverse load blocks to be recovered sooner—as soon as their local loads are sufficiently stable to enable plant operation. Additionally, the rNPP hub, when accompanied by the appropriate Grid architecture, would provide the Grid operator more flexibility in terms of the order in which various transmission segments are energized and loads are recovered. Thus, a single rNPP Black Start Resource, properly sited within and interfaced with its surrounding Grid, would significantly enhance the ability of a system operator to employ a robust multipoint, multi-island approach to Grid restoration.

VIII. rNPPs AS ANCHORS OF RCIIs

Section VII discussed the potential for rNPPs to serve as versatile Black Start Resources for Grid recovery and restoration. Our focus now shifts to higher-level strategic national resilience considerations: the challenge of bootstrapping interdependent national Critical Infrastructure functionality in the wake of national calamities. A rNPP's robust operational capabilities and black start Grid recovery value can be leveraged to provide still greater strategic Critical Infrastructure and societal benefits via the thoughtful integration of a rNPP with other national Critical Infrastructure elements in a RCII. This idea is explored in this section.

VIII.A. Interconnected and Interdependent U.S. Critical Infrastructure

U.S. Presidential Policy Directive 21 (Ref. 38) defined 16 Critical Infrastructure Sectors upon which society depends (Fig. 6). Each Critical Infrastructure Sector has a distinct Grid of its own: a geospatially distributed combination of production facilities and product delivery networks (along with the required human infrastructure) that uniquely defines the architecture of that specific

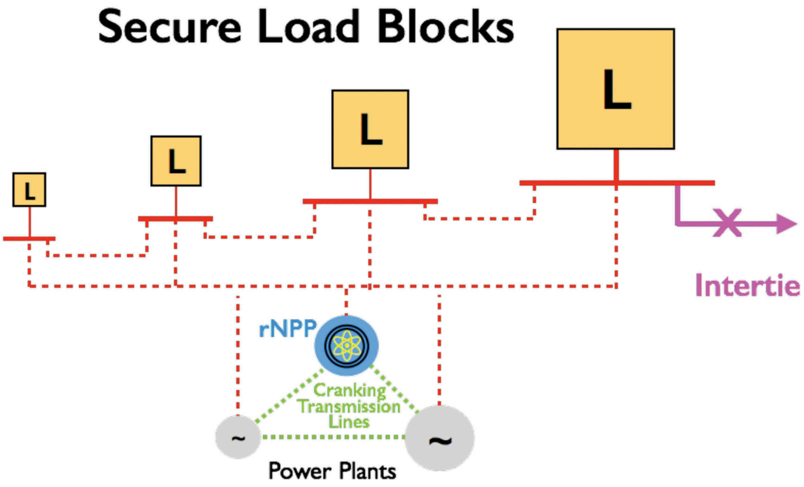

Figure 5. rNPP-based Grid black start recovery approach.
Note: Extreme simplification.
Switches, relays, circuit breakers, and isolators not shown.

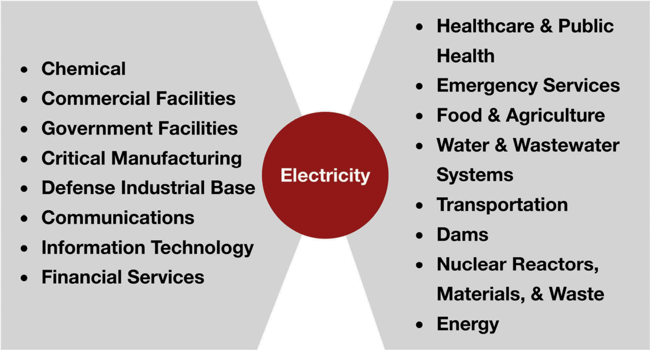

Figure 6. Sixteen Critical Infrastructure sectors defined in U.S. Presidential Policy Directive 21 (Ref. 38).

Critical Infrastructure Sector. The physical architecture of each of these Critical Infrastructure Sectors has evolved over the past century in response to a complex set of geospatially dependent supply-and-demand factors. Chief among these factors are natural resource location (closely related to siting of production centers), human population dynamics (closely related to demand center location), and topology/geography (a major driver for distribution and delivery network routing).

Each of the 16 Critical Infrastructure Sectors either is involved in the generation and distribution of electricity or requires electricity to perform its critical functions. Indeed, a survey conducted by the U.S. Department of Homeland Security of 3352 sites across all 16 Critical Infrastructure Sectors revealed that 90% of the sites depend on electric power for their core operations.[40]

The present-day geospatial topology of the integrated system of 16 Critical Infrastructure Grids can be viewed as a three-dimensional, 16-layer stack of interconnected and interdependent two-dimensional Critical Infrastructure Sector Grids (Fig. 7). Though beyond the scope of this paper, even a casual analysis of the 16 individual U.S. Critical Infrastructure Sector Grids reveals there are regions of the United States (and presumably other nations) where key elements of multiple Critical Infrastructure Sectors are found in close proximity to each other (i.e., colocated within relatively short distances of a few to a few tens of kilometers).

VIII.B. Critical Infrastructure and Societal Resilience in “Very Bad Day” Scenarios

Societies and nations are examples of large-scale, complex social-physical systems. Thus, societal resilience can be defined as the ability of a nation, population, or society to anticipate and prepare for major stressors or calamities and then to absorb, adapt to, recover from, and restore normal functions in the wake of such events when they occur. A nation’s dependence on its Critical Infrastructure systems, and the resilience of those systems, are therefore major components of national and societal resilience.

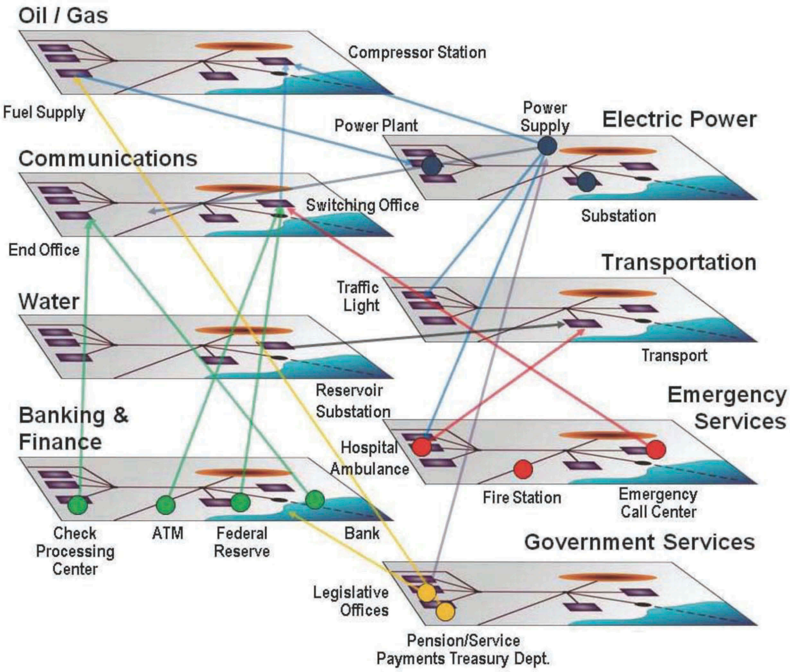

Figure 7. Interconnected and interdependent Critical Infrastructure.[39]

There are a variety of events that could deal crippling blows to a nation's Grid, Critical Infrastructure, and social fabric. The types of catastrophes under consideration here are "very bad day" scenarios that might result from severe GMDs induced by solar CMEs, HEMP attacks, cyber attacks, etc.[5]

As briefly discussed in Sec. III.C, the probability of a GMD of the magnitude of the 1859 Carrington Event is now believed to be on the order of 1%/year. The Earth narrowly missed (by only several days) intercepting a CME stream in July 2012 that would have created a GMD equal to or larger than the Carrington Event.[41] Lloyd's, in its 2013 report, "Solar Storm Risk to the North American Electric Grid,"[42] stated the following: "A Carrington-level, extreme geomagnetic storm is almost inevitable in the future…The total U.S. population at risk of extended power outage from a Carrington-level storm is between 20-40 million, with durations of 16 days to 1-2 years…The total economic cost for such a scenario is estimated at $0.6-2.6 trillion USD."

Analyses conducted subsequent to the Lloyd's assessment indicated the geographical area impacted by the CME would be larger than that estimated in Lloyd's analysis (extending farther northward along the New England coast of the United States and in the state of Minnesota),[43] and that the actual consequences of such an event could actually be greater than estimated by Lloyd's.

Based on "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures" to Congress in 2008 (Ref. 39), a HEMP attack over the Central U.S. could impact virtually the entire North American continent. The consequences of such an event are difficult to quantify with confidence. Experts affiliated with the aforementioned Commission and others familiar with the details of the Commission's work have stated in Congressional testimony that such an event could "kill up to 90 percent of the national population through starvation, disease, and societal collapse."[44,45] Most of these consequences are either direct or indirect impacts of the predicted collapse of virtually the entire U.S. Critical Infrastructure system in the wake of the attack.

Last, recent analyses by both the U.S. Department of Energy[46] and the U.S. National Academies of Sciences, Engineering, and Medicine[47] have concluded that cyber threats to the U.S. Grid from both state-level and substate-level entities are likely to grow in number and sophistication in the coming years, posing a growing threat to the U.S. Grid.

These three "very bad day" scenarios are not creations of overzealous science fiction writers. A variety of mitigating actions to reduce both the vulnerability and the consequences of these events has been identified, and some are being implemented. However, the fact remains that events such as those described here have the potential to change life as we know it in the United States and other developed nations in the 21st century, whether the events occur individually, or simultaneously, and with or without coordinated physical attacks on Critical Infrastructure assets.

VIII.C. Enhancing Critical Infrastructure and Societal Resilience with RCIIs

The potential magnitude of the consequences of the events discussed in Sec. VIII.B is a compelling reason to consider what might be done to improve the ability of the Grid and electricity-dependent Critical Infrastructure to absorb, adapt to, and recover from such events. Every element of the interconnected and interdependent matrix of 16 Critical Infrastructure Sectors is a candidate for examination and improvement. However, the close physical proximity of diverse electricity-dependent Critical Infrastructure Sector elements (Fig. 7), along with the unique performance characteristics and fuel security of rNPPs, suggests that a combinatorial approach might provide one effective option for significantly improving the nation's ability to endure and more rapidly recover from "very bad days."

A Resilient Critical Infrastructure Island or "RCII" is an engineered network of multiple Critical Infrastructure Sector facilities and their interconnections (electric power, internet, pipelines, rail, etc.), powered by a fuel-secure rNPP, and co-located within a small (a few to tens of kilometers) geographical area. A RCII is not simply an electric Grid or a "micro-Grid." The electric Grid is but one of the Grids that constitute the RCII. From the topographic perspective, RCIIs are essentially three-dimensional overlays and interconnections of an electric Grid and selected elements of multiple Critical Infrastructure Sector Grids (Internet, pipelines, railways, etc.) in a defined geographical region (Fig. 8). *While the architecture and functionality of each RCII would differ based on its assigned functions, the "backbone" of all RCIIs is a fuel-secure supply of electric power provided by a rNPP.*

Imagine a future in which selected assets of different Critical Infrastructure networks are configured into a number of RCIIs. Resilient Critical Infrastructure Islands would be regional hubs of Critical Infrastructure functionality in a "hub and spoke" national Critical Infrastructure recovery strategy in the event of national catastrophes. The approach envisioned is conceptually similar to the current U.S. electric Grid recovery strategy discussed in Sec. VII, in which Grid islands are restarted and stabilized, then expanded, and ultimately merged with other islands until the entire Grid is recovered. While that Grid restart/recover process can be considered a two-dimensional process constrained within one Critical Infrastructure Sector (or layer in the context of Fig. 8), the RCII extends the concept to a three-dimensional, multisector (layer) process involving carefully selected assets within different Critical Infrastructure Sectors.

Figure 9 is a notional depiction of a RCII anchored by a rNPP. The RCII is itself configured in a hub and spoke topography in which the rNPP is the hub. As depicted in Fig. 9, elements of Critical Infrastructure within RCIIs might utilize both electricity and nuclear process heat. Thus, rNPPs operating for combined electricity and process heat production would be desirable in some circumstances. The hub and spoke topology depicted in Fig. 9 envisions the use of a "ring bus"/ "ring header" concept for distribution of electricity and thermal energy from the rNPP to its companion Critical Infrastructure facilities within the RCII. Thermal energy storage could be incorporated into the rNPP design to enhance its functionality as a process heat source, and elements of the RCII could be configured as HNESs as discussed in Sec. VI.

The idea of employing nuclear power to enable critical national functionalities is, of course, not a recent epiphany. However, the emergence of multilayered, interdependent, national Critical Infrastructure networks; along with continuing evolution of hazards and threats to the Grid; coupled with the transformational performance attributes of rNPPs; provide significant motivation for exploring the potential for rNPPs and RCIIs to enhance national Critical Infrastructure and societal resilience in the 21st century.

VIII.D. RCII Siting Considerations

Resilient Critical Infrastructure Islands could be hubs from which national multisector Critical Infrastructure functionality could be restored in the event of major Critical Infrastructure disruptions, i.e., foundational building blocks for recovering and restoring essential societal functions in the wake of national catastrophes. Intelligent siting of RCIIs would be essential to extracting maximum Critical Infrastructure and societal resilience value from them. But, where should RCIIs be sited to maximize their ability to accomplish this function?

Many events of concern with respect to Critical Infrastructure resilience (e.g., GMDs, EMP attacks, cyber attacks, etc.) would simultaneously compromise or disable multiple Critical Infrastructure Sectors. Even if the required human resources were available, physical damage to Transportation Sector assets, or the inability to deliver fuel to Transportation Sector assets, could undermine the delivery of supplies and goods across even modest distances for extended periods. Thus, the

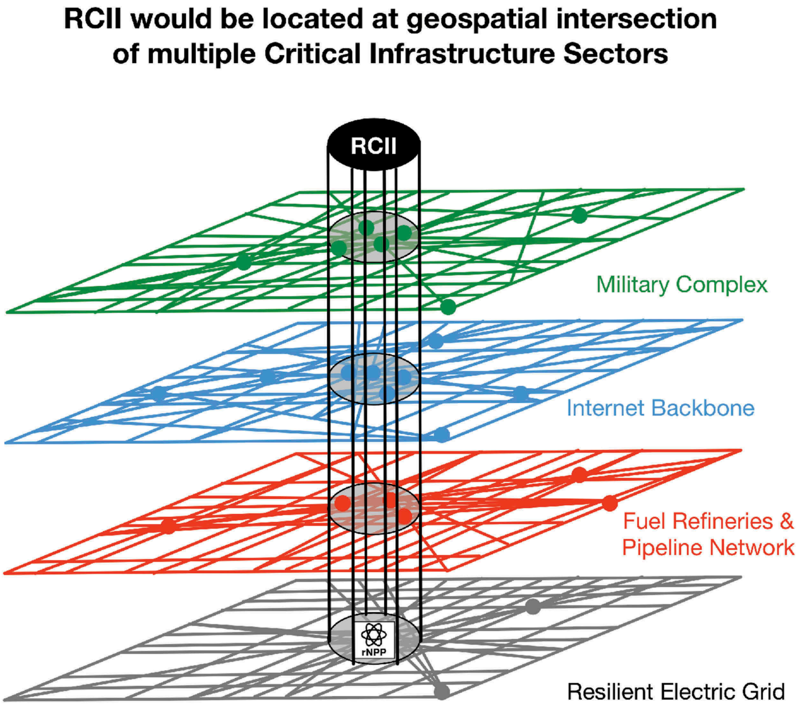

Figure 8. Siting of RCIIs.

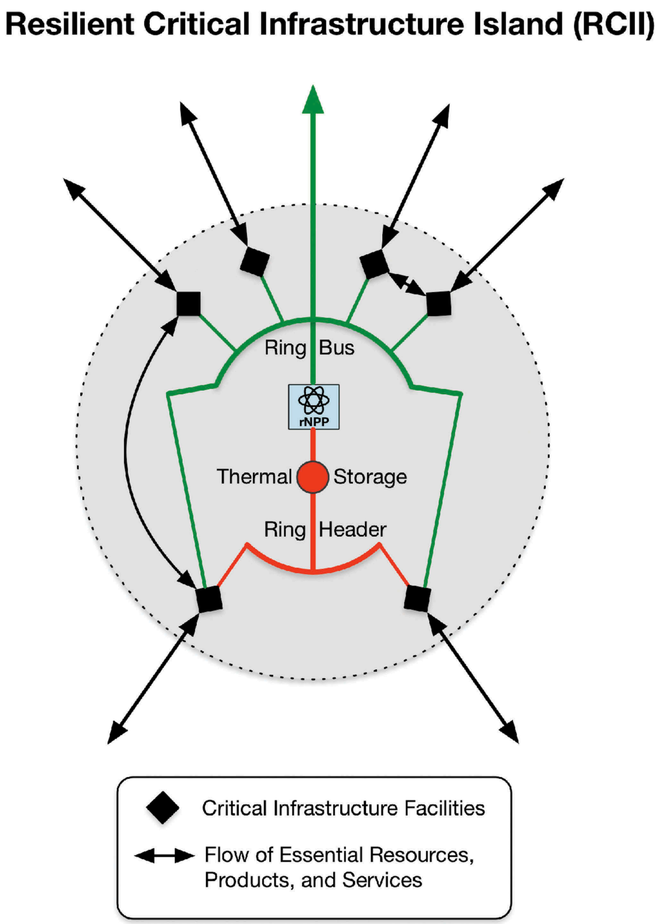

Figure 9. Resilient Critical Infrastructure Island architecture.

feasibility and value of the RCII concept rests in part on the ability to securely intertie key Critical Infrastructure assets whose individual physical supply chains do not extend beyond, or far beyond, the geographic boundaries of the RCII itself. Otherwise, dysfunctionalities in the Transportation Sector could prevent Critical Infrastructure assets within the RCII from functioning despite having ready access to electricity and process heat. This supply chain dependency consideration would therefore be an essential element of RCII planning, design, and siting. For this reason, RCIIs focused on the support of military bases or the provision of essential services (such as Internet, communications, telecommunications, etc.) that do not employ long physical supply chains are perhaps easiest to envision.

The design and performance attributes of rNPPs should enable some relaxation of current NPP siting constraints,[7] making it possible to site the rNPPs closer to their electricity and process heat "customers" than is the case with today's commercial NPPs. For instance, one version of a RCII might comprise colocated configurations of rNPPs, Internet, e-commerce/finance, and telecommunications hubs; rNPPs and water supply systems; rNPPs and military bases, etc. Other examples might include colocated petroleum/petrochemical refineries, petroleum pipeline/pumping stations, and rNPPs. Each RCII would be strategically designed to retain its assigned critical functionalities in the event of a major national catastrophe. The RCII, having survived the initial event, could enable more rapid recovery and restoration of our nation's Critical Infrastructure Sectors.

There are many potential strategies for selecting high-priority sites for RCIIs. Most of these strategies are coupled closely to assumptions regarding the specific hazard and threat scenario adopted as the basis of the analysis. One general strategic RCII siting strategy would be to site one RCII in each of the three major U.S. Grid Interconnections or in each of the seven NERC Regions (Southeastern, Midwest, Northeast, etc.). Other approaches would site RCIIs as closely as possible to human population centers or major military bases and defense installations. In any case, the next step would be to search for locations within that Grid Interconnection, NERC Region, or near the chosen population center that would enable high Critical Infrastructure interconnection density. This search would involve the construction of detailed topographic overlays (similar to the notional overlays depicted in Fig. 7) of the 16 U.S. Critical Infrastructure Sectors, with the goal of identifying regions where key assets from multiple Critical Infrastructure Sectors already exist. These locations would be prime candidates for development of the first RCIIs. In the long-term, RCIIs might be developed at locations based on a rigorous analysis of national hazard and threat portfolios, along with scenario-specific societal recovery and restoration priorities. The ideas presented here are but the simplest and most obvious of many possible RCII siting strategies.

IX. rNPPs AND MONETIZATION OF GRID AND SOCIETAL RESILIENCE

The dialog concerning the definition and value of Grid resilience is in its infancy. Beyond the question of what societal benefits rNPPs might deliver are the questions of (1) who benefits, (2) who pays for the benefit, and (3) how the benefit is monetized. These are challenging issues. Critical Infrastructure resilience in general, and Grid resilience in particular, are currently "tragedy of the commons" issues in which there are many stakeholders, little consensus, and no obvious means to secure desired outcomes for all those affected once such outcomes are articulated. Most of the Critical Infrastructure in the United States is owned and operated by the private sector. Deregulation of the electricity market in the United States has resulted in a fragmented patchwork of Grid asset owners and regulators focused on the day-to-day generation and regulation of electricity as a commodity rather than as an essential strategic national resource.

Electric-generating facilities (and NPPs in particular) in the United States today receive no economic compensation in exchange for their contribution to enhancing overall generation system reliability or to reducing greenhouse gas emissions. The development of market and competitive mechanisms to guide private sector enterprises toward achievement of strategic national goals is a complex process. A market that does not compensate current NPPs for their reliability or carbon avoidance benefits is unlikely to compensate future plants for their resilience contribution. Significant work will be required to develop appropriate market incentives and structures to enable the development and deployment of rNPPs. The development of mechanisms for monetizing the day-to-day Grid resilience contributions of rNPPs can only proceed as a better understanding of Grid resilience and its role in enabling Critical Infrastructure and societal resilience evolves. On the other hand, a good argument can be made that the strategic resilience contribution of rNPPs and RCIIs to homeland and national security in "very bad day" scenarios should stand apart from consideration of the day-to-day Grid resilience value of rNPPs. Thus, it is not unreasonable to consider federal financing of RCIIs to be justified as an investment in strategic Critical Infrastructure resilience and national security.

X. SUMMARY

This paper is the fourth in a series detailing the results of a study conducted to examine the role of nuclear power in achieving and sustaining U.S. Grid, Critical Infrastructure, and societal resilience. The definition and functional capabilities of rNPPs defined in those papers is the basis for identification and characterization of four potential rNPP applications discussed in this paper. Two applications—the use of rNPPs to enable flexible electricity generation operations of NPPs and as anchors of HNESs—leverage ideas and concepts currently under investigation in the nuclear power industry and in academia. Two of these applications—the use of rNPPs as Grid Black Start Resources and as anchors of RCIIs—are new concepts introduced here for the first time.

Resilient NPPs could extend the value proposition of nuclear energy beyond baseload electricity generation in the 21st century. rNPPs could enhance Grid, Critical Infrastructure, and societal resilience in ways current electricity generation technologies cannot. The realization of rNPPs and the benefits they offer will depend on the outcome of a dialog that is just beginning regarding the value of Grid, Critical Infrastructure, and societal resilience; how resilience should be monetized; and who pays for each resilience benefit. The outcome of this debate is of great importance given modern society's growing dependence on the Grid and the evolving portfolio of natural hazards and malevolent threats to the Grid. The conceptual work described in this paper is intended to catalyze and inform this forward-looking dialog in which every citizen is a stakeholder. A variety of actions at the individual, local, state, and federal levels is prudent and necessary to address Grid and Critical Infrastructure resilience concerns. The path will be long and the obstacles many. The good news is that the development and deployment of rNPPs can and should proceed—and the time to do so is *now*.

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