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How Nuclear Power Can Transform Electric Grid and Critical Infrastructure Resilience

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Abstract

No element of a nation's Critical Infrastructure (CI) is more essential than the electric Grid—the system that generates and delivers electricity to power homes, businesses, industry, other Critical Infrastructure, and a nation's Strategic Asset Supply Chains (SASCs). Grid resilience—the Grid's ability to anticipate, absorb, adapt to, and recover from major disruptions, and to rapidly restore electric service in the wake of them—is a matter of paramount importance. This paper examines the potential for nuclear power (and particularly the development of a new generation of resilient Nuclear Power Plants, or "rNPPS") to transform Grid, CI, and SASC resilience via deployment of rNPPs in resilient Critical Infrastructure Islands, or "rCIIs." The nature of society's dependence on electricity and the Grid that generates and delivers electricity to consumers is briefly examined. The scope of natural hazards and malevolent human threats to the Grid are summarized. The concept of Grid resilience is next introduced. The role of current-generation nuclear power plants in the Grid and in achieving Grid resilience is assessed. The two defining attributes and Six Functional Requirements of resilient Power Plants (rPPs) and resilient Nuclear Power Plants (rNPPs) are presented. Next, the results of a small survey and preliminary evaluation of the resilience attributes of some new Small Modular Reactor (SMR) and Micro Modular Reactor (MMR) nuclear power plant concepts are described. It is concluded that some SMR and MMR concepts are likely to exhibit some or all of the Six Functional Requirements of rNPPs. Barriers to development and deployment of rCIIs and rNPPs are briefly summarized. Finally, a few recommendations for efforts that can refine our understanding of the efficacy of rNPPs and rCIIs, and enable their development and deployment, are offered.

Keywords: Electric Grid resilience, next generation nuclear power, Critical Infrastructure, Strategic Asset Supply Chain, Small Modular Reactor, SMR, MMR, rNPP, rCII

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Introduction

This paper is about electric Grid resilience and how nuclear power (embodied in a new type of nuclear power plant) can play a major role in enhancing electric Grid resilience.[1] A brief overview of the Grid and the current role of nuclear power in the Grid is presented. The portfolio of natural hazards and malevolent human threats to the Grid is then summarized. A practical, near-consensus qualitative working definition of Grid resilience is presented. With this background context in view, the concept of a resilient Nuclear Power Plant (rNPP) is then introduced. The two Key Attributes and Six Functional Requirements of rNPPs are briefly presented.

The subject of resilient Critical Infrastructure Islands or "rCIIs" is discussed. rCIIs are the key to leveraging the resilience attributes of rNPPs to enhance the resilience of other electricity-dependent infrastructure. Next, the results of a preliminary assessment of the resilience attributes of five next generation Small Modular Reactors (SMRs) and Micro Modular Reactors (MMRs) is presented. The assessment, which is based on publicly available information (corporate websites, publications or filings with the Nuclear Regulatory Commission), is an evaluation of the extent to which each reactor is likely to achieve six rNPP Functional Requirements, and the extent to which it incorporates key enabling rNPP design features. The SMR and MMR survey results discussion is followed by a brief summary of the barriers and challenges to enhancing Grid and CI resilience with rNPPs and rCIIs. The final section identifies some near-term actions that could be taken by federal, state, and private Sector entities to strengthen Grid resilience.

This is an introduction to a complex and, at times, controversial subject. The paper's intent is to inform and catalyze discussion in disciplines concerned with critical infrastructure resilience and public policy. Therefore, the paper contains a selective distillation and integration of information from a diverse range of knowledge domains. The scope is intentionally limited to the nexus of Grid resilience and nuclear power. In presenting relationships between a number of subjects, the discussion cites technical, economic, and regulatory issues that would benefit from book-length treatment. Experts in any one of the multiple subjects integrated into this discussion will no doubt be dissatisfied with the level of treatment afforded various topics. Citations and references are provided to assist those inclined to dig deeper.

What is the Grid?

The Grid (Figure 1) is a system of systems embodying some 7,700 electrical generating stations, ~700,000 miles of high-voltage transmission lines, 56,000 substa-

1 The paper draws heavily on the author's previous work in the areas of electric Grid resilience and nuclear power (Greene 2016, Greene 2017, Greene 2018a-d). Several foundational concepts developed in prior work are briefly summarized as context for examination of the ongoing evolution of nuclear power plant design—particularly that of Small Modular Reactors (SMRs) and Micro Modular Reactors (MMRs).

tions, and 6.5M miles of distribution lines connecting over 153 million customers (EIA 2019). This collection of assets is organized and geographically distributed in three regional Interconnections: the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of Texas (ERCOT). The Eastern Interconnection spans from Central Canada eastward to the Atlantic coast (excluding Quebec), south to Florida, and west to the foot of the Rocky Mountains (excluding Texas). The Western Interconnection stretches from Western Canada south to Baja California in Mexico and eastward over the Rockies to the Great Plains.

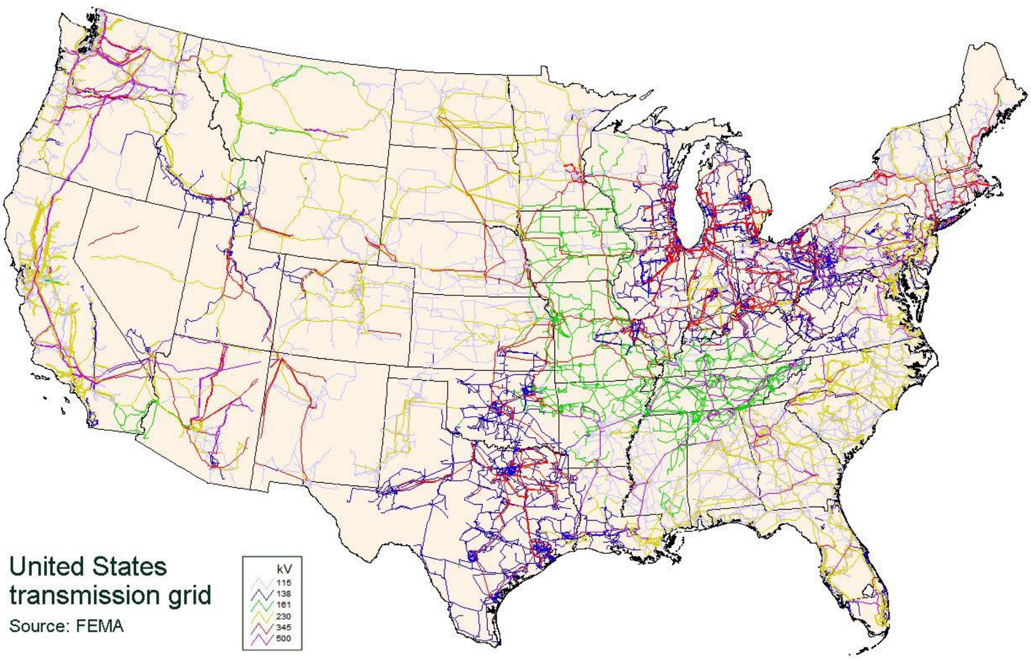

Figure 1. North American Electric Grid

Grid operations within each Interconnection are synchronized to continuously maintain system-wide electricity voltage and frequency standards within the Interconnections. A myriad of network topologies and system architectures within each Interconnection connect generation, transmission, and distribution (GT&D) assets, creating a high level of multi-dimensional functional interdependence between system components. Thus, electricity may be generated hundreds of miles away from its point of consumption.

Like most aging infrastructure, the Grid evolved during the 20th Century in response to the social, economic, political, and physical realities of that era. Despite its size, age, and complexity, the Grid has—with few notable exceptions—performed remarkably well.

Finally, electricity is big business. The Grid and its assets are owned and operated by over 3,000 different entities, including local distribution companies, rural electric cooperatives, 168 investor-owned utilities (that serve slightly over 70% of all U.S. electricity customers), public utilities, regional transmission organizations (RTOs), independent system operators (ISOs), and power generation companies. A 2017 study estimated the U.S. electric power enterprise workforce had about 2.7 million direct workers who maintain, install, and operate the Grid (BMJ 2017). The study estimated that the electric power industry contributed $880 Billion to the nation's Gross Domestic Product.

Grid Vulnerabilities

The Grid is susceptible to natural hazards and malevolent human threats that can trigger wide-spread, long-term disruptions. Cascading CI and SASC failures are difficult to bound (NIAC 2018). Superstorms and hurricanes, extreme seismic events, and naturally-occurring geomagnetic disturbances (GMDs) triggered by solar storms are natural hazards that can and have assaulted the Grid. The earth is overdue for a major geomagnetic disturbance of the magnitude of the Carrington Event, which set telegraph poles and offices across North American and Northern Europe ablaze in 1859 (Riley 2016). There has been a marked increase in the frequency, complexity, and sophistication of cyberattacks and other malevolent human Grid intrusions (INL 2016, NAS 2017). Coordinated cyber and physical attacks have the potential to challenge the Grid in ways that cannot be fully simulated or addressed in advance. In addition, a long-term, large geographic scope outage could be produced by an electromagnetic pulse (EMP) caused by a high-altitude nuclear detonation (HEMP), lower altitude detonation (SREMP), or through an intentional electromagnetic interference (IEMI) event (NCC 2019). The cascading effects of a Grid blackout of more than several months in any nation would put the lives of its entire population at risk.

The Grid's behavior during normal circumstances is a carefully choreographed balance between spatially dependent, continuously changing, electric load and electricity generation. Yet the system's overall behavior is difficult to simulate at the desired level of granularity because it embodies so many distinct and competing physical phenomena, geospatial and electrical relationships, network scales, interdependencies, and failure modes.

Most disruptions of electric service in the U.S. occur at the local distribution level. Damage to distribution system power lines and transformers caused by animals is a leading cause of these more frequent localized power outages (APPA 2019). More serious problems arise when these anomalies flow upstream into the remainder of a local distribution company's service territory or into the bulk power energy system (BES) and bulk power system (BPS) to impact much larger regions and human populations.

The highly discussed cascading 2003 Northeast Blackout that interrupted electric service for two days to about 50 million customers, illustrates the rapid spread of an outage (USC 2004, IEEE 2005). The voltage and frequency perturbations from the event rippled in real time across most of the Eastern Interconnection and parts of the Quebec Interconnection. Seventy-one nuclear power plants and almost 200 other power plants experienced a disturbance in their interface to the Grid. Some of these disturbances were recognized during the event, while others were only discovered by investigation in the weeks and months after the blackout. This is often the case with complex systems: the failure mechanisms lie dormant within the system until the right set of externalities and internalities coalesce to produce a cascading failure.

The Grid cannot be subjected to meaningful stress tests or taken out of service for testing at any significant spatial scale due to society's continuous dependence on the Grid. Therefore, Grid preparedness for a variety of threats and contingencies relies almost completely on simulation, very limited (in terms of system architecture and spatial dimensions) validation testing, and on forensic collection of outage information. This approach does offer very useful information. However, as the statistician George E. P. Box is credited as saying, "All models are wrong, some are useful." Experienced engineers know the only way to differentiate between useful models that reveal truth, and misleading models, is to validate them with real-world data. That simply isn't possible at any significant scale with the Grid.

Grid Resilience Defined

The study of Critical Infrastructure and Grid resilience is an embryotic, expanding research field. (NAS 2017) The concept and definition of system resilience—and "Grid resilience" in particular—continue to evolve. Adapting terminology originally articulated by the U.S. National Infrastructure Advisory Council in 2009 (NIAC 2009), the U.S. National Academies defined resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NAS 2012). The Federal Energy Regulatory Commission (FERC), which regulates only the BPS / BES elements of the Grid, proposed a generalized definition of resilience in 2017: "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from" disruptive events (FERC 2017). Thus, a system is more resilient to the extent that it achieves high situational awareness and anticipation, is prepared by design and operational procedures for disruptive events, and responds to such events by absorbing, adapting, recovering, and restoring operability to pre-disturbance levels in as timely a manner as possible.

The application of FERC's generic definition of Grid resilience is a subject of ongoing debate, the nuances of which exceed the scope of this paper (see Greene 2017 and Arghandeh 2016). However, FERC's generic definition of Grid resilience will be used in the discussion that follows.

Nuclear Power's Current Grid Roles

Only 96 of the 7,700 electricity generating stations in the U.S. are commercial nuclear power reactors. However, these 96 reactors, located at 58 nuclear power plant (NPP) sites, are responsible for approximately 20% of all U.S. electricity generation, and over 50% of the U.S. carbon-free electricity generation (EIA 2020b). Nuclear power stations have extremely high unit availability, typically operating over 93% of the time, compared with wind (~ 35% availability) and solar energy systems (~25% availability). Unlike wind and solar energy, nuclear energy is directly "dispatchable"—Grid operators can call on NPPs to generate electricity day or night and regardless of weather. Nuclear power plants add diversity and fuel security to the mix of fuels utilized by U.S. electricity generating plants. These NPPs have repeatedly demonstrated their value during extreme weather events that forced the shutdown of fossil and renewable energy generators across wide geographic regions of the U.S. (Greene 2017).

Despite these benefits, the current generation of commercial NPPs are not significant Grid resilience assets. The operational characteristics of these plants do not enhance the ability of the Grid to absorb, adapt to, or recover from major Grid anomalies. Today's NPPs do not have very robust real and reactive power load following capabilities, and have little inherent island mode operational capability. Indeed, there are a number of scenarios in which current NPPs are actually Grid resilience liabilities (Greene 2017, Greene 2018b). Today's NPPs tend to have brittle interfaces with the surrounding Grid. They are intolerant of Grid disruptions and external events (such as Grid voltage anomalies, seismic events, etc.), frequently responding by isolating from the Grid, tripping off-line, and shutting down. Once shutdown, these large NPPs become priority loads Grid operators must supply with electric power for safe shutdown cooling before other loads are served. Assurance of safe shutdown cooling is distinct from being an asset restoration priority. Today's NPPs require as much as a few tens of MWe of cranking power from the Grid in order to restart. Since such large cranking loads cannot be met by traditional onsite diesel generators, the value of the NPPs as Grid restart/recovery assets is minimal. As a result of NPP unit size and cranking power requirements, current generation NPPs would often be the first plants to drop offline and the last plants to return to service in the event of major Grid disruptions.

While future *large* LWRs could incorporate technologies to address many resilience short-comings, the unavoidable need for large cranking power supplies for large reactor prevents them from being black start-capable with current technologies. Additionally, because the safety case for existing large LWRs depends on the availability of electric power, traditional NPPs are required by the U.S. Nuclear Regulatory Agency to have independent onsite and offsite power sources available to them at all times. This regulatory requirement effectively prevents today's NPPs from black starting and operating in island mode, even if the technical challenges previously discussed were overcome (Greene 2018b).

The characteristics of present-day NPPs are largely artifacts of designs optimized during the 1960s–1980s for objectives different than those of today. There is nothing inherent in nuclear reactor and nuclear power technology requiring this to remain the case. Indeed, many intrinsic attributes of nuclear power can enable resilience improvements if the approach to NPP design and deployment can be reimagined and reengineered in light of modern technologies and realities. Nuclear power plants have proven their ability to safely and reliability deliver affordable electricity twenty-four hours a day. Now, as we enter the third decade of the 21st century, it is time for nuclear power to deliver more fully on the vision of its early developers by enabling a more resilient Grid and Critical Infrastructure for the nation.

Towards Resilient Power Plants (rPPs)—Non-Nuclear and Nuclear

Characteristics of Resilient Power Plants (rPPs)

Resilient Power Plants or "rPPs" have been defined (Greene 2018a) as power generation facilities that are intentionally designed, sited, interfaced, and operated in a manner to enhance electric Grid resilience. rPPs would exhibit two primary attributes: (1) rPPs enhance the Grid's ability to absorb and adapt to a broad spectrum of Grid anomalies and upsets; and (2) rPPs enable the Grid to recover from upsets and restore electric service in a manner consistent with the system operator's load prioritization hierarchy.

Two rPP Attributes would be manifested in six rPP Functional Requirements defined in Table 1 (Greene 2018c). The six qualitative functional requirements are a reasoned and carefully-crafted set of requirements rooted in a the perspective that power generation facility is a servant of the Grid. The Two rPP Attributes and Six rPP Functional Requirements are technology neutral. Any fossil-fueled, nuclear, or renewable power generation facility that possesses the Two rPP Attributes and achieves the Six rPP Functional Requirements would be considered an rPP. While much work is still required to derive quantitative lower-level functional requirements (e.g., to quantify the real and reactive power load following and flexible operating requirements), the two rPP Attributes and six rPP Functional Requirements provide a sound conceptual and intellectual framework for development of enhanced Grid resilience strategies.

Resilient Nuclear Power Plants (rNPPs)

A resilient *nuclear* power plant or "rNPP" would exhibit the two rPP Attributes and achieve the six rPP Functional Requirements presented in Table 1. Like non-nuclear rPPs, rNPPs would be intentionally designed, sited, interfaced, and operated

Table 1. Six rPP Functional Requirements (Greene 2018c)

rPP Functional Requirements
1. Robust real/reactive load-following and flexible operation capability
2. 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 offsite transmission load and electric power supply)
5. Unlimited independent safe shutdown cooling capability (i.e., requiring no offsite power or resupply of diesel fuel from offsite)
6. Independent self-cranking black start capability (i.e., the ability to start with no offsite power supply from the Grid)

in a manner that enhances overall Grid and infrastructure resilience. Table 2 presents a list of nuclear reactor and nuclear power plant technologies and design features that could enable an NPP to achieve the six rNPP Functional Requirements presented in Table 1. This table demonstrates that rNPPs are not beyond our technical reach today. Indeed, once released from the objectives and constraints prevalent in the 1960s through the 1980s, when the current fleet of nuclear power plants were designed, contemporary nuclear power plant designers have access to a mix of technologies and design approaches that place achievement of the six rNPP Functional Requirements within their grasp.[2, 3]

A nuclear power plant is a complex machine for generation of power and the management of power flow to a customer—the design and operation of which is subject to a variety of practical constraints, safety requirements, and economic

2 See (Greene 2018c) for a detailed discussion of the content of Tables 1 and 2.

3 The ability to achieve these functional requirements is an artifact of the reactor and nuclear island design, the manner in which multiple reactor units or modules within an NPP interact with each other, the manner in which the nuclear island is integrated with the non-nuclear island within the NPP, and how the plant interfaces with the Grid and/or customers for the NPP's process heat product. Achievement of the six rNPP functionalities via passive and inherent means (as opposed to active means) is the preferred approach when possible.

Table 2. Enabling rNPP Design Features (Greene 2018c)

Potentially Enabling rNPP Design Features	**Impact**
1. DC-DC[a] or VFT[b] NPP interface with Grid	• Buffers rNPP from Grid transmission load and offsite power quality anomalies
2. Robust seismic isolation and below-grade siting	• Buffers rNPP from seismic events and external events / attacks
3. High-capacity load switching and heat rejection	• Substitutes alternate thermal or electrical load in case of Grid-based loss-of-load events
4. Multi-module (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
5. Small reactor (module) size	• Reduces cranking power requirements of individual reactor modules in rNPP • Enables non-traditional cranking power supplies for rNPP • Reduces individual reactor module shutdown heat removal and housekeeping electrical loads.
6. Adaptive turbine-generator systems	• Enhances rNPPs load-following and flexible operation capability
7. Passive shutdown cooling	• Eliminates dependence of rNPP on consumable onsite resources and offsite assistance to maintain safe shutdown state • Reduces or eliminates need for redundant Class 1E electrical power sources for safety assurance
8. Inherent reactor system energy storage capacity	• Buffers rNPP and individual rNPP reactor modules from electrical (transmission system) load transients
9. Optimized reactor core physics design	• Enables rapid rNPP reactor module power maneuvering and restart across entire fuel cycle
10. Robust nuclear fuels	• Increases rNPP reactor module's power maneuvering capability and accident tolerance
11. GMD[c] / EMP[d] hardened electronics	• Increases rNPP tolerance of GMD events and EMP attacks
12. Hack-Resistant computer and process control systems	• Reduces rNPP vulnerability to cyber attack

realities. Figure 2 is a greatly simplified, one-line drawing depicting a generic rNPP that can produce both electricity and thermal energy ("process heat"). Decisions regarding the presence or absence of the various processes depicted in Figure 2, and the choice of technologies employed to accomplish them, is the art and craft of nuclear power plant design and optimization. The rNPP design features summarized in Table 2 can be deployed in a variety of ways and locations within the plant topology depicted in Figure 2, to optimize the plant's performance and resilience attributes.

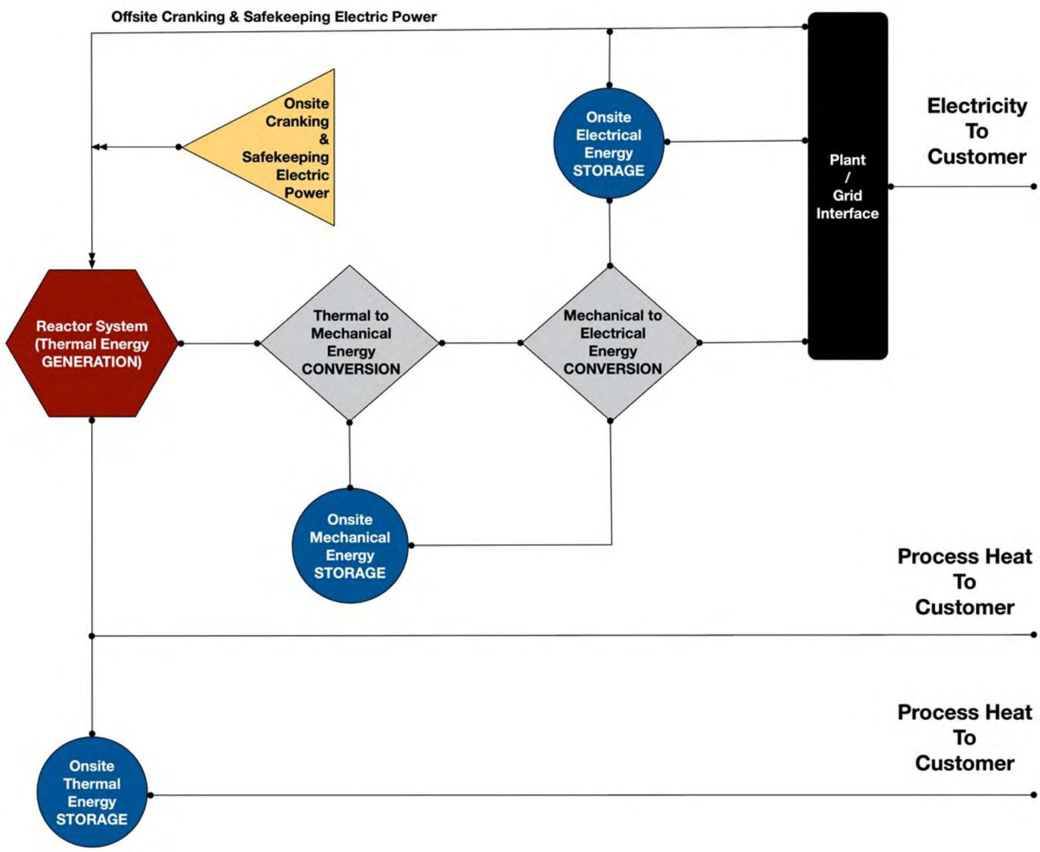

Figure 2. Generic rNPP Energy management Architecture

It is important to note that, like rPPs in general, rNPPs are not defined by their size or the specific type of nuclear technology they employ. Rather, rNPPs are defined by their functionality—their ability to enhance electric Grid resilience. Reactor and plant technology, system architecture, and sizing choices work in unison to achieve or impede achievement of the Six rPP Functional Requirements. Application of the two rPP Attributes and six rPP Functional Requirements in an rNPP do not *a priori* dictate a certain reactor size or technology suite (e.g., nuclear fuel, coolant, plant configuration, etc.).

How rPPs and rNPPs Can Enhance Grid Resilience

There are several ways in which rPPs and rNPPs, if intelligently deployed, could provide significant Grid resilience benefits. These benefits relate to their ability to supply emergency and backup power to larger traditional reactors, their flexible operations capabilities (EPRI 2014), their greater tolerance to Grid anomalies, their ability to serve as variable-capacity black start units, the likelihood that small rNPPs could be sited much closer to the electrical loads they serve, and the unique "fuel security" attributes of nuclear power in general. Each of these benefits is briefly discussed in this section.

By Enhancing the Resilience of Existing NPPs

Small rNPPs could provide assured shutdown cooling power and cranking power to today's large NPPs if the rNPPs were co-located onsite or very near existing NPPs. This approach mirrors that currently employed by the Tennessee Valley Authority (TVA) at their Watts Bar Nuclear Generation Station in Tennessee and Duke Energy at its Oconee Nuclear Station in South Carolina. In both cases, electric power from co-located or effectively co-located hydro generation facilities (dams) can provide priority power to neighboring NPPs. In addition to the technical challenges that must be overcome to integrate the co-located rNPP and NPP, the regulatory challenges to island mode and black start operation of existing NPPs previously discussed would have to be overcome to reap the full benefits of the integrated rNPP / NPP facility.

By Enhancing NPP's Flexible Operations Capability

A rNPP would have significantly enhanced load following and "flexible operations" capabilities compared to existing NPPs. Thus, if economically competitive with other non-baseload generating capacity, the rNPP would not be captive to baseload operations during "normal" operations as is the case for current generation NPPs in the U.S. The economics of NPPs operating in non-baseload modes as providers of "ancillary services" (regulation, spinning reserve, black start, etc.) are complex (Helman 2008, ANL 2016). Recent studies of NPP flexible operations during normal (non-emergency) conditions indicate such operations have the potential to lower power system operating costs, increase reactor owner revenues, and substantially facilitate the use of renewable energy sources (Jenkins 2018).

By Reducing Vulnerability To Grid Anomalies

The resilience enhancing capabilities of rNPPs (Table 1) means they would be more tolerant of Grid anomalies, and therefore less likely to trip offline when such conditions occur. These qualities would enable the rNPP to remain available to stabilize the Grid (from the voltage and frequency perspective), reducing the potential for additional load flow perturbations and voltage collapse transients that can result from the sudden tripping offline of a generating facility during periods in which the Grid is stressed.

By Serving As Variable Capacity Black Start Units

The present strategy for protection and restoration of the Grid in catastrophic national scenarios—such as black sky events that might be caused by cyber or EMP attacks on the —is to first restore mini-Grid Islands of stable, matched load, and generation capacity. Once these Islands are stabilized with respect to voltage and frequency parameters, they are grown and merged via secure transmission lines with proximate Islands to restore Grid operability and electric service over sequentially larger geographical regions (NERC 2012). Generation capability is recovered by first activating black start generating units (typically 10s of MWe to a few hundred MWe in size), which in turn crank larger generating plants, which in turn crank even larger generating plants in a "daisy-chain" restart approach. These Grid recovery Islands are today defined on the basis of BPS topologies (and to some extent chance), and in most cases have little to do with defined geopolitical boundaries. This BPS recovery strategy offers a practical path forward for enhancing Grid resilience with rNPPs by strategically locating rNPPs and utilizing them as anchors for Grid recovery Islands.

Small rNPPs Can Be Sited Closer to Their Customers

Nuclear power plants have traditionally been strictly viewed as Bulk Power System assets—larger power generation facilities typically located far from the electricity customers they serve. While there have been multiple reasons for this, one revolutionary aspect of small rNPPs is the potential for embedding them in the Distribution element of the Grid (much closer to the customers they serve) as the hub of "mini-" or "micro-" Grids. This should be possible because: (a) their size and technology relaxes the requirements for access to large bodies of water that traditionally service as heat sinks for the plants; (b) their generating capacity more closely matches that of many of today's Distribution system loads; and (c) their safety characteristics are such that traditional regulatory siting restrictions (e.g., emergency planning zone or "EPZ" requirements) can be relaxed (NRC 2020a).

Fuel Security—The Added Resilience Benefit of rNPPs vs. Non-nuclear rPPs

rNPPs would also provide an additional benefit compared to non-nuclear rPPs. rNPPs provide a "fuel security" value that is unachievable by other current energy production technologies. This fuel security value is manifested as around-the-clock, *dispatchable*, long-term energy production capability that is not dependent on fuel resupply to the plant site. The onsite fuel storage capacity of power plants varies and in some cases is being extended due to growing concerns about fuel supply fragility. Table 3 summarizes traditional onsite fuel storage capacities for various conventional power generation facilities. A fuel-secure rNPP could offer unique benefits in the wake of a black sky event—wide-spread, long-term (weeks to months) Grid failure. An rNPP would have the capability to operate for months—perhaps even years—in such scenarios, when other types of generating stations could be inoperable due to fuel supply depletion, inability to black start, or inability to meet (disrupted) Grid interface requirements.

Table 3. Fuel Security Attributes of Various Power Generation Facilities (Greene 2016)

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 (assumes mid-point of 2-yr refueling cycle)	Truck

It is likely that renewable energy sources, *if* paired with adequate electricity storage capacity, could offer many of the fuel security benefits of NPPs. It is difficult to compare the fuel security attributes of renewable energy sources such as wind and solar, with that of traditional power plants such as those in Table 3—particularly if one is concerned primarily with their performance during long-term Grid failure scenarios. Effective fuel security, for a renewable energy system coupled to energy storage devices, is a complex issue involving factors such as: the equivalent generating capacity of the energy storage device (i.e., MWe) when it is discharging into the Grid, (2) the amount of energy (MWe-days) actually stored in and recoverable from the storage system that can be dispatched into the Grid, and (3) the integrated system's charge-discharge cycle characteristics (e.g., how quickly it can discharge at rated capacity and recharge to rated capacity). Traditional hydro-generation facilities associated with impoundments do, of course, have rated generation capacities (MWe) and intrinsic storage capability (MWe-days). The effective generating capacity (MWe) and energy storage value (MWe-days) of hydroelectric generating plants during black sky scenarios would ultimately be limited to their so-called "run-of-the-river" capacity once reservoirs are drawn down. In any event, it is not within the scope of this paper to compare the relative technical feasibility and Grid operational and resilience impacts, nor the economic and environmental merits of the "renewables plus storage" vs. rNPP approaches.

Resilient Critical Infrastructure Island (rCIIs)

How might rNPPs be leveraged to enhance the resilience of other Critical Infrastructure? Each of the nation's sixteen Critical Infrastructure sectors (PDD 2013) embodies its own geospatial "grid" or network of essential facilities (e.g., natural gas and petroleum refineries, pumping stations/compressors and pipelines, the internet, air traffic control radars, etc.). These CI grids are often intertwined and interdependent (DOE 2017). The dependence of power generation facilities on the transportation sector for delivery of fuel, and the dependence of the water/wastewater infrastructure on the Grid are two simple examples. Siting and integration of rNPPs with other Critical Infrastructure in resilient Critical Infrastructure Islands (rCIIs) at the geospatial intersections of these *existing* CI Sector grids could provide significant near-term Grid and CI resilience benefits. rCIIs are defined as "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 km) geographical area" (Greene 2018d). Figure 3 depicts a generic rCII.

Facilities (such as factories, internet hubs and data centers, fuel refineries, military bases, etc.) located within the rCII would use the electricity and thermal energy produced by the rNPP in a "mini- or micro-grid" configuration capable of operating in isolation (hence the "island" terminology) from the surrounding electric Grid for months, or even years if necessary. This could occur following major Grid disruptions in which other CI and SASC would be dysfunctional. By enduring the initial disruptive event and continuing to operate, rCIIs would enable a radial "build-outward" national Grid, CI, and SASC recovery and restoration strategy in the wake of national catastrophes of both natural and man-made origins.

The safety characteristics of rCIIs should enable smaller plant footprints and public exclusion zones—allowing their location closer to facilities utilizing their thermal energy and electricity products. Some rCIIs might operate in an air gap mode in which no rCII cyber or power transmission interfaces are connected to external entities during normal operations – thus reducing the vulnerability of the rCII to cyberattack and Grid disruptions. This mode of operation would enhance the likelihood that the rCII would remain operational in the wake of major Grid disruption. It would also assure that the rNPP, and infrastructure elements within the rCII could reconnect to the world outside the boundary of the rCII to bootstrap surrounding Grid, CI, and SASC. If geographically dispersed, optimally sited, and appropriately integrated into the Grid, rNPPs and rCIIs could be the foundation of a national "hub and spoke" Grid/CI/SASC resilience strategy with enormous potential economic and national defense implications.

Finally, it is noted that the unique fuel security attributes (the capability for long-term, dispatchable, electricity production) of rNPPs is particularly critical for maximizing the value of rCIIs as strategic Grid and national resilience assets.

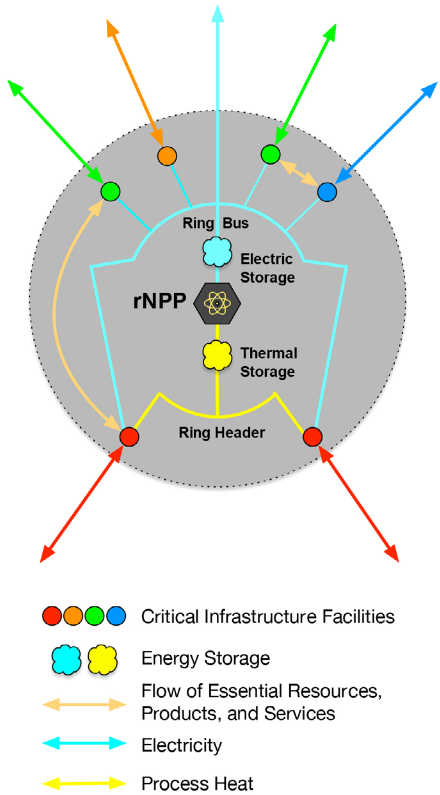

Figure 3. Generic resilient Critical Infrastructure Island (rCII)

It is evident that the question of whether ongoing developments in NPP design are likely to deliver rNPPs capable of enhancing Grid and CI resilience is a matter of some importance. This issue is examined in the next section.

Will Next Generation NPPs be rNPPs?

The U.S. has at least two dozen private sector entities aspiring to develop and field the next generation of nuclear power plants in the U.S. (DOE 2020). The Nuclear Regulatory Commission (NRC) has characterized these new reactors as: (1) Large Light Water Reactors (LWR) greater than 300 MWe, which employ traditional LWR technologies and are sized similar to existing commercial NPPs; (2) Small Modular Reactors (SMRs) that use traditional LWR technologies but are sized no larger than 300 MWe; and (3) Advanced Reactors that do not utilize light water reactor coolant technology and may be of any reactor size (NRC 2020b). The Advanced Research Projects Agency - Energy (ARPA-E) has adopted the term Micro Modular Reactor (MMR) to refer to modular reactors of any technology that are less than 10 MWe in size (Zhao 2016).

A few SMR, Advanced Reactor, and MMR reactor designs have matured to the point where their developers have formally engaged with the NRC—either via submission of a design certification application (DCA), a combined operating license (COL) application, or other pre-application discussions. A preliminary review of information made public by five SMR and MMR reactor vendors was conducted to assess whether new reactor designs are progressing towards rNPP capability. The information reviewed was obtained from the developers' corporate websites, various publications, and vendor filings with the NRC. Brief design and physical characteristics descriptions, along with images of the proposed reactors/ NPPs (when available) are presented below. Importantly, the analysis includes a preliminary evaluation of each design's ability to meet the six rPP/rNPP functional requirements listed in Table 1, and the extent to which the designs incorporate the rNPP-enabling design features summarized in Table 2.

The results of this preliminary review are summarized in Table 4 and discussed below.[4] All five vendors were "likely to meet" functional requirements for three functions (FRs 2, 5, 6). At this time, only two vendors were deemed likely to meet all six rNPP Functional Requirements.

NuScale SMR

The NuScale SMR is a thermal spectrum, 200 MWt/60 MWe, natural circulation-cooled, integral pressurized water reactor (PWR). It is considered to be an evolutionary PWR in that it utilizes shortened, but traditional PWR nuclear fuel assembly designs. Each NuScale Power Module™ (NPM) vessel (Figure 4) consists of a single reactor together with its integrated steam generator. The NPM vessel is approximately 9 feet (2.7 m) in diameter and 65 feet (20 m) tall. (Note: the physical sizes of SMR and MMR vessels vary widely and depend on reactor power, the specific NPP functions integrated into the vessel, and the specific technologies employed to accomplish those functions.) Multiple NPMs would be clustered in a single NuScale NPP to deliver power to the Grid in multiples of 60 MWe (NuScale 2020a).

4 A few caveats are in order on the discussion that follows. First, it is not a technical maturity/technology readiness (to deploy) (DOD 2011) assessment of the reactor systems described. At the time of this writing, the systems discussed are at differing levels of technical maturity. The NuScale SMR is the most mature design concept at present. Some of the plant designs discussed are more likely to change than others. Second, the analysis is based solely on a review of publicly available information. There is much more public domain information available at present for some designs than others. Finally, the analysis was conducted without assistance from or the direct participation of the vendors/developers of these reactors. For these and other reasons, the results presented, and conclusions reached, are necessarily preliminary in nature and are subject to change. Readers are encouraged to examine the information available to them at the time that they review these exploratory findings in order to confirm their accuracy.

Table 4. Survey of SMR and MMR Conformance with rNPP Functional Requirements*

	NuScale SMR	Holtec (SMP Inventec) SMR-160	Oklo Aurora	Terrestrial Energy IMSR-400	X-enrgy XE-100
Likely to Meet rNPP FR 1?	yes	?**	yes	?	?
Likely to Meet rNPP FR 2?	yes	yes	yes	yes	yes
Likely to Meet rNPP FR 3?	yes	?	yes	?	yes
Likely to Meet rNPP FR 4?	yes	?	yes	yes	yes
Likely to Meet rNPP FR 5?	yes	yes	yes	yes	yes
Likely to Meet rNPP FR 6?	yes	yes	yes	yes	yes

* rNPP Functional Requirements (FR) are listed in Table 1.

** "?" = Marginal achievement of functional requirement or insufficient public information available to assess.

The NuScale NPP incorporates a number of resilience-enabling design innovations that can be characterized in three categories: technologies, system architectures, and operating modes (NuScale 2020b-d). These innovations include: small reactor size, modular architecture (NuScale Power Module, NPM), redundant array of independent reactors (RAIR), below-grade (underground) placement of NPM's shared reactor cooling pool/heatsink, extensive use of fiber optics and field programmable gate array technology in module and plant protection systems, etc. (Palmer 2018). Considered individually and collectively, the innovations should enhance the NuScale SMR's overall load following capability (rNPP FR 1), reduce its vulnerability to damage from Grid anomalies and a range of external events (rNPP FR 2), and reduce the necessity of reactor scram (shutdown) in response to Grid anomalies and external events (rNPP FR 3). The NuScale NPP is capable of operating in Island Mode (rNPP FR 4) while isolated from the Grid—maintaining the ability of the plant to meet its own power requirements and enabling the plant to be available to power the Grid in the wake of a major Grid disfunction as quickly as Grid conditions and plant-Grid interface conditions permit. The NuScale NPP

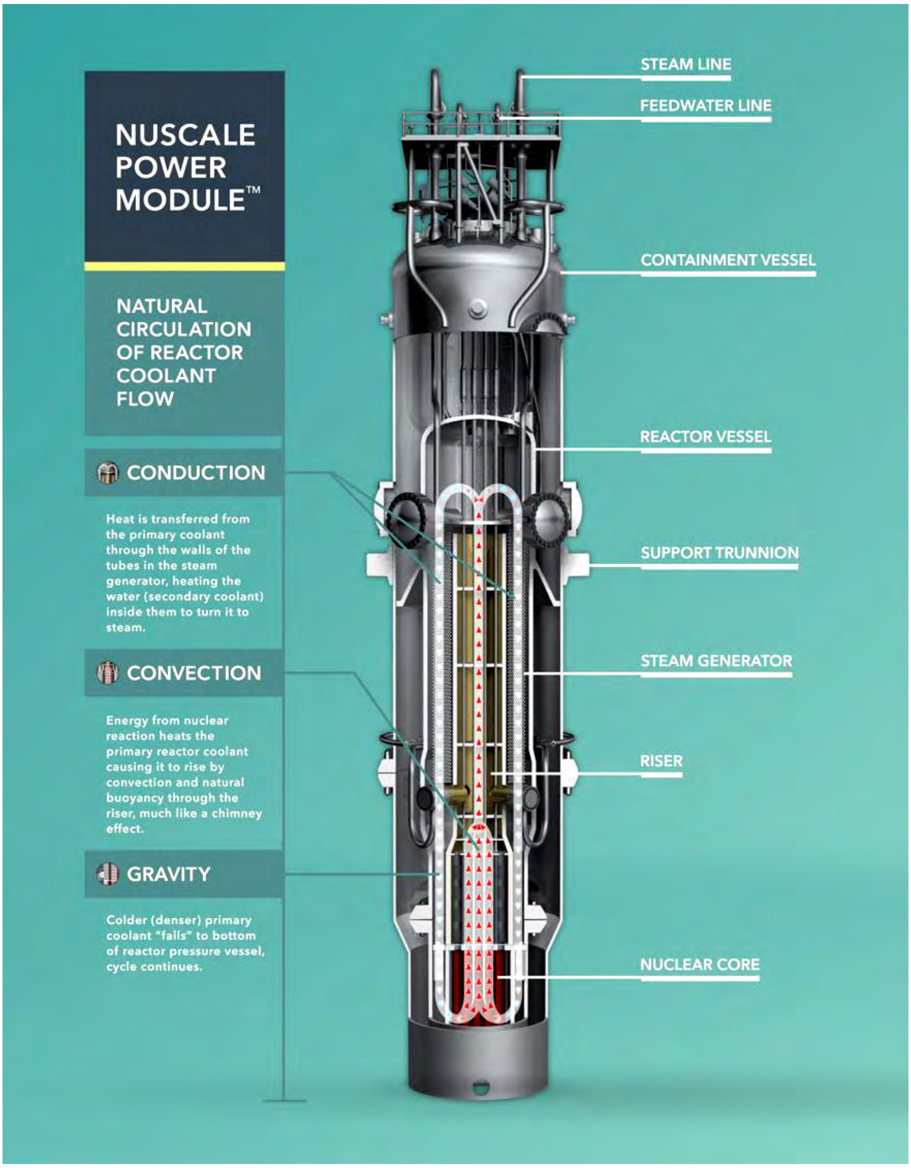

Figure 4. NuScale Power ModuleTM Vessel and Internals (Source NuScale)

requires no alternating current (AC) or direct current (DC) power for safety shutdown or cooling of its reactors (rNPP FR 5). Due primarily to its small reactor size and its RAIR configuration, the NuScale NPP is capable of black starting with no off-site power from the Grid (rNPP FR 6). NuScale's studies (Ingersoll 2014) suggest that their design could fit with a rCII concept in which electricity and low-temperature process heat enable other CI and SASCs.

The NRC announced in August 2020 that the final safety review of NuScale's reactor and NPP was completed and their intent to confer design approval (NRC 2020c, McFarland 2020). NuScale's design is the first commercial NPP design to be granted an exemption from the Class 1E redundant electricity supply requirements currently in place for all NPPs in the U.S. —a regulatory action that is necessary to enable the plant to serve as a black start unit. The NuScale SMR concept is clearly the most mature of the next-generation NPPs currently under development for commercial deployment in the U.S. While the first SMR to achieve this status, further approval must occur for a license to build and operate a NuScale NPP at a particular site.

Holtec (SMR, LLC) SMR-160

Holtec International subsidiary SMR, LLC's SMR-160 is a 525 MWt/160 MWe, passively cooled (i.e., natural circulation) PWR with a unique primary cooling system architecture. The SMR-160 reactor vessel is directly connected to a second pressure vessel which houses the steam generator and pressurizer (Holtec 2020a, NRC 2020d). The reactor core is located below grade and employs traditional PWR fuel. No offsite power is required to shut down the reactor or to cool the reactor in shutdown mode (rNPP FR 5). The concept employs an innovative air-cooled condenser to enable siting of the reactor in areas with limited surface water supplies. The reactor can start/restart without the aid of off-site power (rNPP FR 6). The concept employs a distributed control system along with its below-grade siting. Holtec asserts these features reduce the vulnerability of the plant to malevolent human actions. These design features should enhance the ability of the plant to achieve rNPP FR 2. The Holtec design is "amenable for applications requiring process steam such as industrial processes, district heating, or desalination" (Holtec 2020b). The question of how multiple SRM-160 units are interfaced to provide larger effective NPP electric capacities and load following capabilities has not been addressed in the public forum. Holtec is currently engaged in pre-licensing interactions with both the NRC (NRC 2020d) and with the Canadian Nuclear Safety Commission (CNSC 2020).

Oklo Aurora MMR[5]

The OKLO Aurora (no image available) is a fast spectrum, UZr metal fueled, 4 MWt, MMR concept that utilizes heat pipes for cooling the reactor core rather than a traditional forced flow circulating fluid loop. The reactor core is coupled via multiple heat pipes to six heat exchangers—each heat exchanger mating to one-sixth of the core heat pipes, and conveying its share of the reject heat to a low-enthalpy supercritical carbon dioxide (sCO_2) secondary loop/power conversion loop via a dedicated heat exchanger. The system requires no forced cooling and no offsite AC or DC power for normal operations or for shutdown decay heat removal (rNPP FR 4 and 5). Electricity generated by the power conversion system

5 This analysis is based on the public version of the Final Safety Analysis Report submitted by OKLO Power in support of their COL Application (Oklo 2020a).

meets all onsite unit housekeeping power demands, and charges an onsite electrical energy storage system comprised of batteries and inverters. The energy storage system provides power for reactor startup and normal shutdown capabilities (rNPP FR 6). Both reactor power control and traditional turbine bypass (which transfers thermal energy to the environment) approaches are available to avoid over-charging the battery storage system if/when needed. "The Aurora provides its own power for onsite systems and treats the offsite grid strictly as a load rather than as a potential source of power" (Oklo 2020a). All offsite loads (i.e., the Grid) are served from the energy storage system—not directly from the power conversion system—thus decoupling/buffering the reactor from Grid anomalies (rNPP FR 1, 2, and 3). The energy storage system can, on a short-term transient basis, serve electrical loads greater than the rated capacity of the reactor. Thus, the use of passive heat pipes for reactor cooling, a heat exchanger system that embodies large thermal storage capacity, and an electrical storage system to provide both a constant load to the reactor and a buffer/interface to the Grid, enables all six of the rNPP Functional Requirements.

Oklo submitted a Combined Operating License (COL) Application to the NRC for construction and operation of a single unit, Aurora MMR facility at Idaho National Laboratory in March 2020 (Oklo 2020b).

Terrestrial Energy Integral Molten Salt Reactor (IMSR-400)

Many design details of Terrestrial Energy's IMSR-400 are not yet available in the public domain. The IMSR-400 is a 400 MWt/195 MWe, thermal-spectrum, molten salt fueled and cooled reactor (Terrestrial 2020, IAEA 2016). The reactor core, primary coolant circulating pumps, and primary heat exchangers are located within a shared vessel. The plant will be capable of load following down to approximately 50% of rated capacity—a modest load following capability compared (rNPP FR 1). The vendor asserts the reactor has a high degree of passive seismic robustness due to its integral design (rNPP FR 2). The reactor employs an operational and shutdown cooling approach that relies on passive, in-place, heat capacity and heat loss mechanisms that are asserted to enable passive shutdown cooling with no need for offsite power (rNPP FR 5). The cold-cranking startup load of a single IMSR-400 is ~10 MWe. Terrestrial Energy has indicated its intent for the IMSR-400 to incorporate black start capability (rNPP FR 6). Terrestrial Energy has also stated its intent that the IMSR-400 be capable of full Island Mode operation (rNPP FR 4). In addition to electricity generation, the reactor can supply high-temperature (600°C) heat to drive a variety of industrial processes. Vendor studies indicate that, when coupled to a molten salt heat transport loop, the IMSR can supply this high-temperature heat to facilities located as far as 3 km (5 mi) from the IMSR plant (Terrestrial 2020), making it a potentially attractive option for rCII applications requiring high-temperature process heat.

Terrestrial Energy submitted its IMSR-400 design to the Canadian Nuclear Safety Commission (CNSC) for a "pre-licensing vendor design review" in April 2016 (CNSC 2020). The NRC and the CNSC selected the IMSR-400 as the focus of their first "joint technical review of an advanced, non-light water nuclear reactor technology" in August 2019 (NRC 2019). The review process is on-going.

X-energy Xe-100 SMR

X-energy's Xe-100 reactor is a helium-cooled, pebble-bed high temperature gas-cooled reactor. Each reactor is rated at 200 MWt/75 MWe (X-energy 2017, X-energy 2018, X-energy 2020). With a core outlet helium temperature of 750 °C, the Xe-100 is designed to produce both electricity and process heat with high pressure steam temperatures as high as 565 °C. X-energy's NPP concept integrates a block of four Xe-100 modules. Thus a 4-pack X-energy NPP would be rated at approximately 300 MWe. Each of the four Xe-100 modules consists of a Xe-100 reactor, its helium cooling system, a steam generation system employing a single helical coil steam generator, and one turbine-generator subsystem. The pebble fuel is comprised of 15.5 % enriched Uranium Oxycarbide (UCO) kernel, tristructural-isotropic (TRISO) particle fuel in a graphite matrix. According to X-energy, the low power density of the Xe-100 (~ 30 times lower than traditional light water reactors) enables completely passive shutdown cooling of each reactor (rNPP FR 5). Therefore, the Xe-100 does not require safety-grade electric-driven reactor cooling systems. X-energy asserts that one Xe-100 design requirement is that no disruption in the conventional (non-nuclear) island of the plant can produce a reactor trip (rNPP FR 3). When coupled with other design features, it is likely this design requirement would render the plant relatively invulnerable to Grid anomalies (rNPP FR 2). X-energy also asserts the Xe-100 concept will have the ability to perform "rapid load following in real time within the power range of 100-40-100%" of rated generating capacity (modest attainment rNPP FR 1) (X-energy 2018). Each reactor module has the capacity to reject ~ 25% of its rated power as waste heat when isolated from the Grid, and the plant can be operated indefinitely at this power level in Island Mode (rNPP FR 4). A single Xe-100 can be black started from onsite diesel generators with no need for offsite power (rNPP FR #6), and a single Xe-100 module can provide all the housekeeping electric loads for the other three modules in the X-energy NPP (X-energy 2018).

X-energy has is engaged both with the U.S. NRC (NRC 2020e) and the Canadian Nuclear Safety Commission (CNSC 2020) in pre-licensing discussions and vendor design reviews.

Major Barriers and Challenges to Development and Deployment of rNPPs and rCIIs

There are a number of cultural, technical, institutional, economic, and regulatory barriers to enhancing Grid and CI resilience, regardless of the path and technologies pursued to achieve it. These generic barriers include issues such as lack of consensus on the quantitative metrics of Grid resilience and the value of Grid resilience; the absence of market mechanisms for compensating Grid asset owners for the resilience value they provide; fragmented federal, state, and local regulation of electricity markets and Grid assets; fragmented Grid enterprise business structures; etc. Indeed, every path to enhancing Grid and CI resilience has a specific subset of obstacles and challenges. The rNPP/rCII approach is certainly no exception. A few of the more obvious challenges associated with the development and deployment of rNPPs and rCIIs are discussed here. The intent of this section is not to provide a comprehensive inventory, nor a detailed analysis of these challenges. Rather, the aim is merely to highlight a few of the more important challenges.

The Capital Cost of Nuclear Power Plants

The high capital cost of today's large (~ 1 GWe) NPPs and the cost uncertainty of plant construction, has become the chief obstacle to the continued deployment of nuclear power—especially in an era where natural gas prices are at historic lows. The nuclear industry's recent experience in construction of (large) NPPs does not provide a basis for optimism that there is a future for GWe-class NPPs. The cost of new GWe-class NPPs has become so large, only a handful of current private sector power generation entities have sufficient market capitalization to finance their construction. Developers of advanced reactors, SMRs, MMRs, and rNPPs must, therefore, break the established pattern of high intrinsic (size-dependent) costs, construction mismanagement, and delay-driven cost escalation, if nuclear power in the U.S. is to remain a significant part of its energy mix in the 21st Century.

SMR developers are claiming a number of capital cost advantages over traditional large LWRs. These advantages include factors such as factory fabrication/mass production of reactors; reduction in the number of safety-grade structures, systems, and components in the plants; adoption of advanced instrumentation technologies that reduce complex wiring strategies; modular construction; reduction of basic commodities (concrete, steel, copper, etc.) employed in the plant; and daisy-chained build/commissioning of reactor modules that reduces both the amount of capital that must be financed before a revenue stream results, and the time period over which a reactor module must be financed. These claimed financial advantages will need to be confirmed by actual experience.

NPP capital cost ($/kW of plant capacity) and busbar cost of electricity (mils/kWh of energy produced) metrics have traditionally been employed as primary investment and build/no-build decision criteria for nuclear power plants. These evaluation metrics will, most likely, need to be expanded if rNPPs (indeed nuclear power in any form) are to play a role in enhancing U.S. Grid resilience. The reason is simple: all kilowatts and all kilowatt-producing assets are not the same in terms of their Grid resilience value. For example, a 300 MWe rNPP would be of much greater Grid resilience value than a 1 GWe traditional NPP that achieves none of the six rNPP functional requirements in Table 1. This issue, of course, is a subset of the general over-arching reality that electricity markets do not explicitly value resilience. The flexible operations capabilities of rNPPs and their potential for providing ancillary services other than baseload electricity could enable rNPPs to increase their revenue streams relative to today's NPPs.

Nuclear Energy Regulation Barriers

After some experimentation in the 1950s and 1960s, the electric power industry rapidly narrowed its focus to Light Water Reactor technology and build on-site/economy of size paradigms as the guiding principles for harnessing the atom. This dynamic led to a commercial nuclear power fleet characterized by medium-to-very large LWRs. The reasons for this are complex, controversial, and beyond the scope of this paper. However, there are two aspects of this history that are very relevant to the development and deployment of rNPPs and rCIIs.

All regulatory frameworks employ assumptions (some explicit, some implicit, some unrecognized) with respect to that which they regulate—technologies allowed or disallowed, acceptable approaches and procedures for meeting/demonstrating regulatory compliance, etc. The maintenance of technology-neutral regulatory processes is inherently more challenging than technology-specific processes. In the case of the nuclear power industry, the NRC's regulatory framework evolved over several decades to one that largely assumed LWR technology.

A LWR-dependent regulatory structure creates immense regulatory and cost uncertainty for any entity wishing to develop and deploy non-LWR technologies. With this in mind, the NRC launched an effort in 2002 to develop a risk-informed, technology-neutral, performance-based regulatory framework of future reactors (NRC 2002). The regulatory processes and protocols that have emerged from this two-decade effort have evolved in conjunction with NuScale's SMR design certification effort, and are receiving more extensive testing via the NRC's ongoing interactions with SMR, Advanced Reactor, and MMR vendors. Still, the new regulatory framework is largely untested for non-LWR concepts, and is likely to evolve as lessons are learned from ongoing SMR, MMR and Advanced Reactor licensing activities. Thus, entities seeking to develop and deploy novel LWR and non-LWR technologies will continue to face elevated regulatory uncertainty for the foreseeable future.

Regulatory-induced technology-lock or "lock-in" (Cowan 1990) is a phenomenon in which the cost and uncertainties associated with regulatory compliance create an environment where "good-enough is the enemy of better"—an environment that is hostile to innovation. It is the "other side of the coin" of technology-dependent regulation. This dynamic has been in play in the commercial nuclear power industry in the United States for most of the industry's history. Additionally, the nuclear power industry has, along with the aerospace, pharmaceutical and other industries, been highly dependent on federally funded research and development since its inception (Dooley 2008). Partly as a result of the factors discussed above, the nuclear power industry has historically had one of the lowest rates of private research and development investment of any major technology-intensive societal endeavor.

Incompatible Design / Build / Commissioning Schedules

Finally, the time required to (and cost/schedule uncertainty associated with) licensing, construction, and commissioning of an NPP can be much longer than that required for non-nuclear facilities that might utilize the products (electricity and process heat) of an rNPP in a rCII. Consider, for example, a rCII in which an rNPP powers large data centers, manufacturing facilities, refineries, etc. Major misalignments between the permitting, construction, and licensing times of the rNPP, and the facilities that would rely on it present a host of practical regulatory, construction, and financial challenges to the rCII's developer (Greene 2009). The adoption of accelerated nuclear reactor regulatory review processes, accelerated rNPP construction schedules, and realization of step-wise reactor module commissioning, are some potential avenues for resolving this dissonance in nuclear/non-nuclear facility design/build/commissioning schedules.

Recommended Next Steps

This preliminary analysis suggests that the resilience attributes and other benefits of rNPPs and rCIIs could be harnessed by federal, state, and private sector entities to enhance Grid, CI sector, and SASC resilience at multiple scales. Much work remains to confirm these initial findings and to implement a workable strategy to realize the potential benefits of rNPPs and rCIIs, presuming that future work confirms the initial conclusions. Some recommended next steps are briefly discussed below. It is recognized that some current activities relate in some manner to this prescription. However, space limitations do not permit a survey of those efforts nor an analysis of the extent to which any such efforts are responsive to recommendations presented here.

Quantify rNPP Functional Requirements

Substantial work is needed to translate the *qualitative* attributes and functional requirements of rNPPs presented in Table 1 into *quantitative* derived rNPP requirements, and to identify the best approaches for interfacing rNPPs with the Grid (Table 5, Item 1). These derived quantitative requirements (e.g., real and reactive power load following capability, flexible operation capability, etc.) must address a wide range of rNPP-Grid interface issues if the Grid is to truly "harvest" the potential benefits of rNPPs. The question here is what, precisely, does each of the six rPP/rNPP Functional Requirements translate to in terms of quantitative functional requirements on the rNPP? How much real and reactive load following capability is needed and what ramp rates are required? Which specific types of flexible operations are required and are the time frames, relative power levels, ramp rates, etc. required to fulfill flexible operations needs? How long must the rNPP be capable of Island Mode operation, and what are the conditions for transfer into and out of Island Mode operation? Quantitative answers to these questions and many others are required to enable the design and evaluation of specific rNPP concepts.

Table 5. Recommended Next Steps to rNPPs and rCIIs

	Recommended Actions
1	Derive quantitative rNPP functional requirements and Grid interface strategies
2	Develop virtual Grid resilience quantification and assessment models
3	Demonstrate promising rNPP and rPP-Grid interface technologies
4	Develop the business case for rNPPs and rCIIs
5	Map U.S. Critical Infrastructure and Strategic Asset Supply Chains to identify existing high-value siting opportunities for rNPPs and rCIIs
5	Create rNPP market pull by implementing resilient power purchase agreements for select Federal facilities
7	Develop and obtain NRC Design Certification of at least one pathfinder SMR rNPP and one pathfinder MMR rNPP design

Developing Virtual Grid Resilience Assessment Model

Both coarse and highly granular computer simulations of actual Grid systems or synthetic Grid test systems are needed to assess the reliability, operability, and resilience implications of insertion of rNPPs into the Grid (Table 5, Item 2). Such simulations can illuminate a number of important issues such as: optimal rNPP / Grid siting strategies; promising rNPP-Grid interface approaches; the impacts of rNPPs on Grid reliability, availability, load flow, and stability during normal operations and extreme Grid events; optimal approaches for maximizing the black start value of rNPPs; and Grid transmission and distribution system modifications that would enhance the overall utility of rNPPs. The use of synthetic virtual test systems (such as IEEE Bus test systems) certainly have their place in such studies. The need also exists to examine the use of rNPPs as actual elements of today's integrated

Grid. The use of highly granular models of actual Grid topologies (e.g., the island of Puerto Rico, the Tennessee Valley Authority's service region, the portion of the Grid with the State of Florida, etc.) could begin to bridge the gap between theoretical possibilities and actual rPP/rNPP deployment opportunities and strategies.

Demonstrate rPP / rNPP Technology

Those familiar with the challenges of technology development and deployment know that simulation can be extraordinarily helpful, but it is often not sufficient. Ultimately, something must be built and tested to achieve "ready to deploy" technology maturity. The fielding of physical (as opposed to virtual) rPP and rNPP technology test beds would do much to move rNPP development forward (Table 1 Item 3). Much relevant and useful work could be done outside the direct nuclear sphere, focusing or generic rPP-Grid interface issues without the need for the reactor (presuming alignment of rPP and rNPP functionalities as expressed in Table 1). Comprehensive rNPP—Grid testbeds would, of course, necessitate the construction and operation of the reactor (most likely a MMR rNPP) embedded in a mini- or micro-Grid testbed. Such activities might proceed as public/private sector collaboration or partnership at one or more of DOE's national laboratories. Some proposed SMR demonstration activities could be adapted to function as, or provide a template for, rNPP testbeds. Public/private sector cost sharing, federal innovation prizes, and tax incentives can be effective mechanisms to accelerate these demonstrations.

Develop the Business Case for rNPPs and rCIIs

Quantification of the functional capabilities of rNPPs and rCIIs will, in turn, enable assessment of the economics of, and the business case for rNPP and rCIIs (Table 5, Item 4). The business case for deployment of an rNPP or an rCII will rest on many factors. These include the capital, operating, and maintenance costs of the rNPP and the rCII, the value of the products (Grid resilience, resilient electricity and process heat, ancillary Grid services, etc.) provided by the rNPP to its customers (within or outside an rCII), and the specific user applications incorporated in a particular rCII. Competition from other alternative rPP technologies will, of course, also be a factor. Can—and if so, how—can rNPPs and rCIIs anchor resilient local and regional economies? A number of government- and privately-funded studies have been conducted in the U.S. and abroad in recent years to examine the economics of SMRs and Advanced Reactors. Though not aimed at addressing specific rPP/rNPP issues, selected studies provide a template for examining the economic case for deployment of rPPs, rNPPs and rCIIs. These studies also illuminate potential financial incentives that can be constructed to catalyze and enable the development and deployment of rNPPs and rCIIS. Federal, state, and local entities are all stakeholders in this proposition.

Map CI and SASC Networks to Identify High-Value rNPP and rCII Sites

As previously noted, each U.S. Critical Infrastructure (CI) and Strategic Asset Supply Chain (SASC) Sector has an established physical network (a "grid") of its own. Natural gas and petroleum pipelines and the Internet are but two prime examples. Locations in which these networks physically "overlap" are natural candidates for high-value deployment of rNPPs and rCIIs. As noted, co-location of MMR rNPPs with existing conventional reactors, and rNPPs of diverse sizes with other CI such as Internet hubs and data centers, refineries, etc. are rather very promising possibilities. Granular knowledge of the geospatial topology of these CI networks has become sensitive and (typically) tightly held information. Nevertheless, there is a need to identify immediate, high-value opportunities for siting of rNPPs and rCIIs (Table 5, Item 5). This type of exercise should be conducted out of public view as a prudent precaution against misuse of the information by malevolent actors.

Create rNPP Market Pull

Firm, first-mover customers in the SMR and Advanced Reactor market are difficult to find outside the venues of strategic planning meetings and casual conversation. Market pull will be needed if new reactors in general and rNPPs in particular, are to become reality. The Federal government is in a unique position to create pathfinder market pull by implementing long-term resilient power purchase agreements at major Federal facilities (Table 5, Item 6). Some relevant preliminary discussions in this direction have occurred between the private sector, Department of Defense facilities, and Department of Energy National laboratories. However, these discussions have, to date, focused on SMRs, rather than rNPPs (Kutakrock 2017). Such discussions should be expanded to explicitly incorporate the rPP/rNPP resilience attributes and functionalities discussed here.

Distinct from power purchase agreements are the various tax and siting incentives federal, state, and local governments can wield to stimulate investment in rNPPs, rCIIs, CI, and SASCs. Investment tax credits, guaranteed loans, and land transfers are examples of such incentives.

Develop Certified rNPP Designs

It is clear SMR and MMR developers are making progress towards development of new reactors and NPPs that achieve at least some of the six rNPP Functional Requirements. But more intentional effort is needed (Table 5, Item 7). The U.S. Department of Energy is currently co-sponsoring or stimulating in some manner the development of a limited number of SMR and Advanced Reactor designs. But these activities are not explicitly aimed at assuring the resulting reactor and NPP concepts embody the two rPP/rNPP Attributes and six rPP/rNPP Functional Requirements. These design development/certification efforts should be modified as necessary to incorporate the goals of achieving these rNPP attributes and functional requirements. Maximum use of public/private sector cost sharing, federal innovation prizes, and tax incentives can be effective mechanisms to accelerate progress in development and demonstration of rNPPs and rCIIs by all parties.

Conclusions

Twenty-first century society is reliant on the continuous flow of electricity from the point of generation to end use. The system for generating and delivering that electricity to consumers is the Grid, arguably the most complex human-engineered system. Most U.S. Critical Infrastructure and Strategic Asset Supply Chains are completely dependent on the Grid. The current world is replete with natural hazards and human threats that could trigger wide-spread, long-term Grid disruption, with resulting CI and SASC failures that are difficult to bound. Such events pose an existential threat to our way of life. Every citizen and every institution is a stakeholder in Grid resilience.

The Grid has evolved into a system optimized for delivery of low-cost electricity in a context of stable social, cultural, and natural environments with somewhat predictable natural calamities and limited human threats. We now know that major natural disasters of continental and regional scope are more likely than once believed. At the same time, the ability of malevolent human agents to inflict Grid damage is expanding. A key to national survival in such events, and regional recovery from less-extreme scenarios, is to substantially enhance Grid resilience. Again, a resilient Grid is one that has the ability to anticipate, absorb, adapt to, recover from such disruptions, and rapidly restore electricity service to essential societal functions. Recognizing its essential, life sustaining roles, Grid resilience must be considered a "local" end-user issue. A Grid that is optimized to deliver the lowest cost electricity is unlikely to deliver the most resilient electricity supply.

Nuclear power has the potential to play a unique enabling role in achieving the level of Grid resilience needed for the remainder of the 21st Century. The development and deployment of resilient Nuclear Power Plants (rNPPs) and resilient Critical Infrastructure Islands (rCIIs) anchored by rNPPs, could transform Grid, CI, SASC, and societal resilience in an uncertain world. Current trends in nuclear power plant design suggest evolution towards more resilient NPPs. There are many technical, economic, regulatory, and policy barriers to achieving the levels of Grid resilience needed to secure public health and welfare, economic prosperity and national defense objectives. Steps should be taken on an expedited basis to further examine and to potentially deploy the use of rNPPs and rCIIs to enhance U.S. Grid, CI, and SASC resilience.

Abbreviations and Acronyms

AC	Alternating Current
ARPA-E	Advanced Research Projects Agency - Energy
BES	Bulk Energy System
BPS	Bulk Power System
CI	Critical Infrastructure
COL	Combined License
DC	Direct Current
DCA	Design Certification Application
DOE	U.S. Department of Energy
DOD	U.S. Department of Defense
EMP	Electromagnetic Pulse
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FR	Functional Requirement
GMD	Geomagnetic Disturbance
GT&D	Generation, Transmission, and Distribution
GWe	Gigawatt Electric
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operators
LWR	Light Water Reactor
MMR	Micro Modular Reactor
MW	Megawatt
MWe	Megawatt Electric
MWt	Megawatt Thermal
NAERM	North American Energy Resilience Model
NPM	NuScale Power Module
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
PPD	Presidential Policy Directive
PURPA	Public Utilities Regulatory Policies Act
PWR	Pressurized Water Reactor
RAIR	NuScale Redundant Array of Independent Reactors
rCII	resilient Critical Infrastructure Island
rNPP	resilient Nuclear Power Plant
RTO	Regional Transmission Organizations
SASC	Strategic Asset Supply Chain
SCADA	Supervisory Control And Data Acquisition
SMR	Small Modular Reactor
SRC	System Resilience Curve
TRISO	TRi-structural-ISOtropic
TVA	Tennessee Valley Authority
UCO	Uranium Oxycarbide
VFT	Variable Frequency Transformer

Author Capsule Bio

Sherrell Greene is President of Advanced Technology Insights in Knoxville, TN. His career in nuclear energy research and technology development spans over four decades in such diverse fields as electric generation system expansion planning, commercial nuclear power safety, and advanced reactor development. During his thirty-three years at Oak Ridge National Laboratory (ORNL), he served as Director of Nuclear Technology Programs and Director of Research Reactor Development Programs, with leadership responsibilities for over a $100M/yr. research, development, and demonstration program portfolio sponsored by eleven offices in four federal agencies. He has extensive experience working with senior leadership in the U.S. Department of Energy (DOE), U.S. National Nuclear Security Administration (NNSA), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. National Aeronautics and Space Administration (NASA). He has conducted pioneering analyses of the current and potential role of nuclear power in assuring electric Grid and Critical Infrastructure resilience and is an internationally recognized expert in commercial nuclear power severe accident safety. He holds a B.S. and M.S. in Nuclear Engineering, and a PhD in Energy Science and Engineering from the University of Tennessee, Knoxville.

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