Electricity Market Restructuring, Grid Reliability, and Nuclear Power Safety in the United States

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Abstract

Nuclear plants rely on electrical power from transmission grid as the preferred electrical power source to support plant safety functions. This paper investigates the impacts of electricity restructuring and competitive markets operated by Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) on grid reliability and nuclear plant safety. By studying safety events reported by nuclear plants to the U.S. Nuclear Regulatory Commission between 1990 and 2011, whose root causes are faults originated from the grid, I find that reactors operating in competitive markets are more likely to experience reactor trips that are initiated by unexpected abnormal voltages or power flow disturbance, particularly during summer months (May through September), when electricity demand is high and the grid is under higher stress. There is no increase in the hazard ratio of grid events caused by either transmission equipment failure or human error, lending no support to the concern that restructuring may causes utilities to re-prioritize or reduce their capital investment, maintenance and manpower in transmission facilities.

Keywords: Electricity Market, Restructuring, Grid Reliability, Nuclear Safety

JEL codes: L51, L94, Q48

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1. Introduction

In March 11, 2011, when a 9.0 magnitude earthquake struck Japan, the Fukushima Daiichi nuclear plant immediately proceeded to emergency shutdown based on its seismic trip settings, with no significant damage to the reactors by the earthquake. However, the earthquake damaged the adjacent transmission grid and resulted in loss of electrical power supply from grid (a.k.a. loss of offsite power, LOOP) to the plant.\(^1\) When the subsequent tsunami flooded the plant and destroyed on-site emergency diesel generators, the plant entered a Station Blackout,\(^2\) a condition with a complete loss of all alternative current (AC) electrical power.\(^3\) With no electricity to support the plant cooling functions, three reactor cores melted due to significant overheating, leading to some hydrogen explosions and releases of radioactive contamination to the atmosphere (Government of Japan, 2011; IAEA, 2012; OECD, 2012).

The Fukushima nuclear accident in 2011 illustrated how critically nuclear plants rely on the electrical power from transmission grid to maintain critical safety functions. Nuclear power reactors require robust and diverse sources of reliable electrical power supply during all modes of operation to meet fundamental safety functions,\(^4\) particularly during the period when the reactor is shutdown, since nuclear reactors, distinct from other types of electricity generating plants, continue to produce a significant amount of heat for an extended period of time after it is

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\(^1\) Upon the loss of all offsite electrical power, the emergency diesel generators started automatically and initially provided the necessary electrical power for cooling the reactors.

\(^2\) A Station Blackout involves simultaneous loss of offsite power [from the grid], loss of main generator [because of reactor shutdown], and loss of the onsite emergency power supplies [emergency diesel generators].

\(^3\) Upon Station Blackout, direct current (DC) electrical power was available from the plant’s emergency batteries to support reactor cooling for only few hours before these batteries were completely discharged.

\(^4\) The majority of operating nuclear power reactors worldwide belongs to Generation II commercial power reactors. These Generation II reactors began operation in late 1960s, use traditional “active safety features” involving electrical or mechanical operations that are initiated automatically and, in many cases, can be initiated by the operators of the nuclear reactors (Goldberg and Rosner, 2011).
The electric power transmission grid, which in general consists of the entire offsite transmission network and equipment that connects to the nuclear plants, is required by most safety regulators worldwide as the “preferred” source of electrical power for the majority of nuclear reactors currently under commercial operation.\(^5\)

This study examines the effects of electricity market restructuring on grid reliability and nuclear plant safety in the United States, an issue that has been raised by the U.S. Nuclear Regulatory Commission (NRC), the U.S. nuclear industries, and the Federal Energy Regulatory Commission (FERC), after some states in the U.S. enacted electricity deregulation in 1990s (Michal, 2000).\(^7,8\) Under regulation, generation, transmission and distribution of electricity are operated by vertically integrated electric utilities in their designated areas. Electricity market restructuring leads to establishments of competitive wholesale electricity markets, with Independent System Operators (ISOs) / Regional Transmission Organizations (RTOs) taking charge of grid operation, managing the wholesale markets, and dispatching power plants within a large unified system covering wide geographic regions. As a result, electricity is transmitted over a much longer distance with unprecedented volume, potentially creating unexpected abnormal voltages or power flow disturbance that could trigger nuclear plant protective schemes and lead

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\(^5\) The thermal power of the reactor immediately after shutdown in average is around 6.5% of the power before shutdown (IAEA, 2012).

\(^6\) For new Generation III+ reactors (e.g. Westinghouse AP1000), which are designed in the 1990s and yet under construction, these Gen III+ reactors are equipped with “passive safety systems” and their long-term accident mitigation is maintained without either operator action or reliance on offsite or onsite alternative current (AC) electrical power, but instead rely on gravity or natural convection (Goldberg and Rosner, 2011). Nevertheless, in the U.S. the Nuclear Regulatory Commission (NRC) still insists on there being a source of reliable offsite power.


\(^8\) In the U.S., the NRC regulates the operational safety of all commercial power reactors, while the Federal Energy Regulatory Commission (FERC) oversees the reliability of bulk electricity transmission grid. Since 2003, the NRC and the FERC have enhanced interagency collaboration to address the interdependence of nuclear safety and grid reliability.
to a reactor trip (also called as reactor scram i.e. sudden and unexpected reactor shutdown).\(^9\)

When a nuclear reactor trips due to some grid reliability problems, it enters an “upset” condition and its safety systems are challenged, putting itself in potential risk. Moreover, the sudden reactor trip, often the single largest contingency faced by the grid, may deteriorate the grid condition or even collapse the entire grid, which could lead to loss of offsite power at the nuclear plant, increasing the risks of Station Blackout and reactor core damage. Alternatively, severe grid disturbance could also directly lead to loss of offsite power at nuclear plants, as in the case of the August 2003 North America Blackout. In the afternoon on August 14, 2003, one large coal-fired plant and some 345-kV transmission lines tripped respectively in northern Ohio, causing local transmission grid around Cleveland and Akron in jeopardy. When no effort was made subsequently to shed load in Cleveland-Akron area, more 138-kV transmission lines began to fail, leading in turn to the loss of First Energy’s Sammis-Star 345-kV line, then triggered the uncontrollable cascading blackout and severe grid transient. The grid disturbance reaches protective feature limits in multiple U.S. nuclear reactors across New York, Ohio and Michigan, causing automatic protective actions and resulted in lost of offsite power at ten reactors. It took more than six hours to restore offsite power to these reactors.

This paper focus on grid events that were submitted by U.S. commercial power reactors to the NRC through Licensee Event Report (LER) system between 1990 and 2011.\(^10\) “Grid events” are defined as faults or problems initiated from the transmission grid that proceed to actuation

\(^9\) A reactor trip or scram is the sudden shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator (U.S. NRC Glossary).

\(^{10}\) Pursuant to Title 10 Code of Federal Regulations Part 50 Section 73 (10 CFR 50.73) – Licensee Event Report System, power reactor licensees are obligated to submit an report to the NRC within 60 days after the discovery of the reportable event defined under §50.73(a)(2), which in general involves (i) the completion of any nuclear plant shutdown required by the plant’s Technical Specifications; (ii) operation or condition which was prohibited by the plant’s Technical Specifications; (iii) any event or condition that resulted in degradation of plant safety; and (iv) any event or condition that resulted in manual or automatic actuation of engineering safety features.
(automatically activation) of plant safety features, leading to reactor trips or loss of offsite power at nuclear plants. First, we find that the hazard ratio of experiencing grid events, specifically the grid events first causing reactor trips, significantly increases after a reactor operates in a competitive market, vis-à-vis before market restructuring, using reactors always operated in areas without competitive markets as the control. Second, by distinguishing grid events based on their root causes, we find that such increased risk was primarily associated with grid events that are caused by unexpected abnormal voltages or power flow disturbance in the grid due to changes in the manner that the transmission system is operated in competitive markets, but not related to grid events that are due to either transmission equipment failure or human error, lending no support to the concerns that electricity market restructuring may cause electric utilities to re-prioritize or reduce their capital investment, maintenance and manpower in transmission facilities (Arrillaga et al., 2000; Abel et al, 2003; Joskow and Tirole, 2005). Third, we look into the seasonal distribution of the grid events in our data, and observe that the risk of experiencing grid disturbance induced reactor incidences have significantly increased during summer months (May to September) after a reactor operates in a competitive market, consistent with the fact that the transmission grid in general is more congested and under higher pressure during summer months when electricity demand is generally higher than other months of the year.

Our paper makes two interesting contributions to the literature. First, it provides a novel approach, from the perspective of nuclear plants, in assessing the impacts of market restructuring on the reliability of transmission grid. Prior studies on the reliability of U.S. electric power system have primarily focused on the probability or temporal distribution of large blackouts (Talukdar et al. 2003; Carreras et al. 2004; Hines et al. 2009), and looked into power interruptions mainly affecting the electric distribution system and retail consumers (Eto and
LaCommare, 2008; Eto et al. 2012). Studying grid reliability in the context of nuclear plants provides several interesting advantages, for both research and practical reasons. On the one hand, nuclear plants, which by design and regulatory requirement, unnoticeably consume considerable amount of electricity from the grid for fulfilling safety functions, are highly sensitive to grid transients, providing a good setting and publically available data that reflects grid reliability. On the other hand, grid reliability and nuclear plant operation are interdependent in the sense that a sudden reactor trip is often the single largest contingency faced by the transmission system operator and could in turn further impact grid reliability.

Second, our paper contributes to the literature on nuclear plant safety, from the novel perspective of market restructuring and its impact on grid reliability. The literature on the effects of economic deregulation on safety performance in nuclear or airline industries primarily focuses on firm incentives and behavior due to deregulation (Golbe, 1986; Rose, 1990; Kennet, 1993; Bier et al, 2001; Hausman, 2013). The mechanism of grid reliability through which market restructuring could impact nuclear plant safety is of practical importance. For example, Exelon Generation Company decided to arrange additional power purchase agreement with other generators to ensure reliable offsite electrical power support to its nuclear plants in PJM market, after experiencing various grid events.11

Our study also has important policy implication for nuclear safety, since analyses of unexpected reactor trips during power operations due to grid disturbance provide important insights for nuclear safety risk assessments, plant evaluation, and other safety regulatory issues. For instance some have proposed that nuclear power plants should participate in automatic generation control (AGC) system to ride through grid transients without tripping the reactor

(Kirby et. al, 2007), which has been disapproved by the NRC on the ground that reactor power shall be controlled only by the nuclear plant operator, not by outside variables.\textsuperscript{12}

The remainder of the paper is organized as follow: Section 2 provides background on nuclear power plant electric power system and its interdependence with transmission grid. Section 3 discusses U.S. electricity market restructuring and its’ potential impacts on grid reliability and nuclear power plants operation, then provides specific hypothesis to be tested. Section 4 presents data and in Section 5 shows our empirical strategies and main results. Section 6 concludes the paper and discusses policy implications.

2.  Background

Nuclear power plants rely on transmission grid as the “preferred” source of electrical power to meet critical safety functions, hence have stringent requirements on grid reliability, including offsite power availability and frequency/voltage stability. Problems originated from the grid could result in reactor trips or loss of offsite power at nuclear plants, representing challenges to plant safety systems, and put nuclear plants in risks of Station Blackout and reactor core damage.

2.1 Nuclear power plants electric power system

\textit{Design principles and general arrangements}

Nuclear power reactors require robust and diverse sources of reliable electrical power supply during all modes of operation (startup; normal operation; during and after reactor shutdown) to meet fundamental safety functions, including control of reactivity, transport of heat from the core, confinement of radioactive materials, control of operational discharges, and

\textsuperscript{12} As one NRC Commissioner stated that “[A nuclear plant being brought up or down] is not the direction you would want to see it”. See the transcript, Joint Meeting of the U.S. Nuclear Regulatory Commission and the Federal Energy Regulatory Commission, dated April 24, 2006.
limitation of accidental releases (IAEA, 2012). Special attention is given during the period when
the reactor is shutdown, either planned or unexpected, since a nuclear reactor continues to
produce a significant amount of heat for an extended period of time.

Because of this reliance on electrical power, in the U.S. the NRC requires that “an onsite
electric power system and an offsite electric power system shall be provided to permit
functioning of structures, systems, and components important to safety” in all commercial power
reactors.\textsuperscript{13,14} The offsite electric power system, which in general consists of the plant main
generator, the entire transmission grid, and a minimum of two independent connections from the
transmission grid to the nuclear plants,\textsuperscript{15} is defined in the industry standards and the NRC
regulatory guides as the “preferred power system” (U.S. NRC, 1980), particularly because the
grid is generally demonstrated to have higher availability and reliability due to the diverse and
multiple generators connected to it. On the other hand, the onsite electric power system is
typically a combination of diesel generators,\textsuperscript{16} batteries and associated equipment.\textsuperscript{17} The NRC
also requires a degree of independence between these different sources of electrical power

\textsuperscript{13} It typically requires electrical power equal to 5 to 8 percent of the plant rated generation capacity to
fully load the electrical equipment of a nuclear power plant. Thus the electrical power connection to
nuclear plants must be able to supply this amount of electricity during plant startup and immediately after
reactor shutdown (IAEA, 2012).
\textsuperscript{14} The primary requirements for electrical power supplies to nuclear power plants auxiliaries are set forth
hereinafter referred to as “GDC 17”.
\textsuperscript{15} Nuclear power plants typically are connected to high voltage transmission grid at plant switchyard or
substation, with multiple physically independent transmission lines.
\textsuperscript{16} Despite there is no regulatory requirement on specific type of onsite electric power supplies to be used
at nuclear power plants, diesel generators and their proven reliability had already gained them widely
acceptance at most operating nuclear plants, which could reliably match the required response time (the
accident analysis for many reactor designs assumed emergency generator power would be available
within 10 seconds) and output power.
\textsuperscript{17} The onsite electric power supplies shall also have sufficient independence, redundancy, and testability
to perform their safety functions per GDC 17.
supplies to “minimize the probability of losing electric power from any of the remaining supplies” (GDC 17).

When nuclear plants are under normal operation, electricity output from the plant main generator is exported to the grid via switchyard, as well as being conveyed back to the plant for normal use as such will provide the cheapest electrical power. Nevertheless for the equipment and systems that are essential for emergency shutdown of the reactor, containment isolation, reactor core cooling and the removal of containment heat and reactor heat, electrical power is supplied from the grid (See Figure 1)\(^{18}\). When the main generator is not available, e.g. during reactor startup or shutdown, all electrical power is provided by the grid through high-voltage switchyards.\(^{19}\) This is the “preferred” arrangement of electrical power supply.

When neither the plant main generator nor the offsite electrical power source is available, onsite emergency diesel generators could supply electrical power to vital safety systems.\(^{20}\) Redundant and independent battery systems are arranged to provide coping period in the event of Station Blackout, i.e. simultaneous loss of main generator, offsite power and onsite emergency diesel generators.

2.2 Interfacing nuclear power plants with the grid

\(^{18}\) Starting from the left part of the Figure 1, the main generator output is linked to step-up transformers and unit auxiliary transformers (via generator output breaker and isolated phase bus). The step-up transformer increases the voltage of generator output to meet the transmission grid parameter then deliver such output into the grid via high-voltage switchyard or substation nearest nuclear plants. The unit auxiliary transformer on the other hand is the power transformer that that conveys generator output for the plant use under normal operation. In Appendix E we include a more detailed nuclear power plant electrical distribution one-line diagram.

\(^{19}\) Offsite power from the grid is provided via either (i) back-feeding through the unit auxiliary transformers; or (ii) through reserve auxiliary transformers (See Figure 1). The reserve auxiliary transformer is also supplying safety equipment during normal operation or is used whenever the unit auxiliary transformer is brought offline such as planned maintenance.

\(^{20}\) Typically one reactor is coupled with redundant emergency diesel generators, and in some plants with multiple reactors, an additional standby diesel generator may also be arranged to support either reactor when necessary.
Since nuclear power plants, by design and regulatory requirements, rely on transmission grid as the preferred source of electrical power, the degree to which the grid can maintain an uninterruptible power supply to nuclear plants with sufficient capacity, and with adequate voltage and frequency controlled within a defined narrow range,\textsuperscript{21} is the measure of grid reliability from the point of view of nuclear plants (IAEA, 2012). Faults or transients occurred in the grid may affect nuclear plants operation by tripping reactors or proceeding to various forms of loss of offsite power.

**Grid event could cause reactor trip/scram**

A large number of external reasons can cause a sharp variation in the voltage and/or frequency on the grid. When the voltage/frequency transient at the nuclear plants connecting points is beyond settings of plant protective schemes, nuclear reactors by design would automatically trip or scram. For example in February of 2000, a transmission line failure near Callaway Nuclear Plant (Missouri) resulted in sharp local grid disturbance. The plant’ reactor coolant pumps (RCP), which rely on offsite electrical power for normal operation, tripped automatically by plant protective schemes upon this electrical disturbance, resulted in a low reactor coolant flow condition and subsequently the reactor tripped.\textsuperscript{22} Similarly in 2003, a fault on 345kV transmission line neighboring Indian Point Energy Center (New York) caused the over-frequency protection at Indian Point Unit 2 to function automatically, resulted in main

\textsuperscript{21} Nuclear plants use thousands of grid operating configurations and parameters provided by grid operating or transmission entity to calculate whether nuclear plants internal voltages are within equipment ratings and the minimum voltages. These analyses are plant-specific and are revised periodically with updated parameters from the grid operating entity (U.S. NRC, NUREG-1784). There is also no systematic difference between two branches of U.S. power reactors currently in service, i.e. Boiling Water Reactors versus Pressurized Water Reactors, in terms of their analyses of the plant electric power systems (U.S. NRC, Generic Letter 79-36).

turbine trip\textsuperscript{23} and reactor trip\textsuperscript{24}. Fortunately during these events, the safety systems remain energized from offsite power after reactor trip and emergency diesel generators are not required.

\textit{Reactor trip could exacerbate grid conditions and proceed to loss of offsite power}

When nuclear power plants trip/scram unexpectedly because of transmission system faults or voltage/frequency excursions, the subsequent loss in real and reactive power support to the grid becomes a severe random test to the capacity/capability of the grid, and may exacerbate transmission events. In most cases, the sudden loss of a full size nuclear power reactor (with generation capacity over 1,000 mega-watts) is often the single largest contingency faced by the transmission system operator. Within few seconds, the grid by design should be robust and capable to recover from the voltage drop in the vicinity of the nuclear power plants and to support nuclear station loads. Otherwise if multiple contingencies have already occurred and the grid is not able to respond in a satisfactory manner, nuclear plants will be separated from the grid by its protective schemes and proceed to a loss of offsite power event (Kirby et. al, 2007). For instance in 2003, Salem Generating Station (New Jersey) Unit 1 generator tripped by design\textsuperscript{25} upon transmission fault and subsequently the reactor also tripped. The voltages at plant connections dropped below its under-voltage set-points and did not recover in a timely manner post reactor rip, resulted in the plant’s automatic disconnection from the grid, and the emergency diesel generators at Salem plant immediately started and supplied electrical power to respective safety systems.\textsuperscript{26}

\textsuperscript{23} A Turbine Trip refers to the fast closure of turbine control valves that admit steam to the turbine.
\textsuperscript{25} A generator trip refers to the opening of the output breakers from the generator. As well as plant safety equipment, nuclear plant main generators must also be protected from adverse grid conditions, e.g. degraded voltage, through various main generator protection schemes.
\textsuperscript{26} See Licensee Event Report 272/2003-002, dated September 24, 2003
**Grid event could first cause loss of offsite power and subsequently trip the reactor**

Grid events can also directly result in loss of offsite power in nuclear power plants, then followed by or coincided with reactor trip/scrams. For example in September of 2003, both units in Peach Bottom Atomic Power Station (Pennsylvania) scrammed automatically due to loss of two offsite power sources supplying its Reactor Protection Systems, and all four emergency diesel generators in the Peach Bottom plant automatically started and supplied electrical power to respective emergency systems.\(^{27}\) Similarly in 2004, a ground-fault occurred on a transmission line near Palo Verde Nuclear Generating Station (Arizona) first led to loss of offsite power at the Palo Verde switchyard,\(^{28}\) then caused all three Palo Verde Units' turbines tripped on over speed and subsequently all reactors tripped.\(^{29}\)

### 2.3 Safety implications of grid faults on nuclear power plants operation

The situations that grid faults or transients could most significantly impact the normal operation and potentially impair the safety of a nuclear unit, as illustrated in previous examples, are (i) reactor trip/scrams; or (ii) direct loss of offsite power, caused by grid problems. When reactors trip/scram from full power, not only the nuclear plants enter an “upset” condition and safety systems are challenged, such reactor trip could also further exacerbate grid condition and lead to loss of offsite power. Therefore we pay special attention to full or partial loss of offsite

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28 In order to prevent an unexpected degradation of the offsite power from reducing safety bus voltage to below minimum requirement that supports plant safety equipment operability while the preferred offsite power source is in use, various degraded voltage protection systems are designed and implemented in switchyard/substation to ensure nuclear power plants being separated from its offsite power upon grid disturbance and automatically transfer them to the onsite electric power system. (See American Electric Power letter to U.S. NRC, dated October 16, 2002).
power and voltage degradations below the plant specific minimum requirement, following or concurrent with a reactor trip, since these events reveal evidence of potential weakness in the grid (U.S. NRC, NUREG-1784). We are also concerned about any loss of offsite power directly caused by grid disturbance, since an increase in the likelihood of loss of offsite power constitutes a reduction in the plant's defense-in-depth and a more frequently challenge to the on-site emergency power system (i.e. emergency diesel generators). Therefore loss of offsite power events in particular are considered as precursors to Station Blackout, and probabilistic risk assessments performed for nuclear plants indicate that the Station Blackout can be a significant contributor to the reactor core damage frequency (CDF). By reducing the frequency of grid faults or transients which may lead to either unit trip or loss of offsite power, we can in turn mitigate the challenges to plant safety systems and reduce nuclear power plants operational risk.

3. Conceptual framework

3.1 Electricity market restructuring activities and its possible effects on grid reliability and nuclear power plants operational safety

Prior to electricity market restructuring, generation, transmission and distribution of electricity in the U.S. are mainly operated by investor-owned and vertically integrated electric utilities, regulated primarily by the states, delivering its services within specific geographic areas.

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30 As defined in 10 CFR 50.2, a Station Blackout (SBO) is an event/accident results in “the complete loss of all alternating current (AC) power to the essential and nonessential switchgear buses at a nuclear power plant”, which involves the simultaneous loss of offsite power, turbine trip, and the loss of the onsite emergency power supplies (typically emergency diesel generators). The loss of all AC power to reactor core decay heat removal and other support systems can result in reactor core damage within a few hours.

31 Overtime the NRC requires that all licensed power reactors shall be able to withstand for a specified duration and recover from a Station Blackout per 10 CFR 50.63, “Loss of All Alternating Current Power,” commonly referred to as the "SBO rule."

The Energy Policy Act of 1992 and Federal Energy Regulatory Commission (FERC) Order No. 888 and 889 opened transmission access to non-utility generators. In the late 1990s, many U.S. states began to restructure the electricity markets, requesting electric utilities to divest their generating assets to form independent power producers (IPPs), so as to allow them to compete for the bulk sale of power in open markets. Independent System Operators (ISOs)\(^{33}\) / Regional Transmission Organizations (RTOs)\(^{34}\) were established to take over the operation of electric power transmission system from electric utilities, in order to ensure a non-discriminatory open access to the grid for non-utility IPPs and to facilitate competitive wholesale electricity markets, while maintaining the grid reliability. Despite no longer operating the transmission grid, electric utilities in general still maintain ownership over transmission and distribution facilities, and they are reimbursed through open access transmission tariff for providing access to third parties to use their transmission networks, and in turn are required to make their best efforts to increase transmission capacity in response to requests by third parties.\(^{35}\)

For two-thirds of commercial power reactors in the U.S that eventually operated in areas having market restructuring and implementation of competitive markets, these restructuring activities could potentially degrade grid reliability and “significantly increase the probability of a NPP trip or loss of adequate offsite power supply” due to conditions caused by (1) load flow disturbance, (2) human error on operation or maintenance of transmission elements, or (3) malfunction or failure of transmission elements.\(^{36}\) In the following paragraphs we discuss how market restructuring may affect grid reliability and nuclear plants operation in greater detail.

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\(^{33}\) FERC Orders Nos. 888/889 suggested the establishment of an Independent System Operator to satisfy the requirement of providing non-discriminatory access to transmission grid.

\(^{34}\) In Order No. 2000, FERC encouraged the voluntary formation of Regional Transmission Organizations (RTOs).

\(^{35}\) See Joskow (1997 and 2005) and White (1996) for overviews of the electricity market restructuring process and transmission policy.

\(^{36}\) See NRC Generic Letter 2006-02 “Grid Reliability and the Impact on Plant Risk and the Operability of
Market restructuring may increase power flow disturbance

In competitive markets, the operable generators changes daily by matching offers from generators to bids from Load Serving Entities, which identifies where the power flows. Therefore electricity is transmitted over much longer distance and with unprecedented volume. Since it is Kirchhoff’s laws of electricity, not the power market or consumers, determine how the electricity current actually divides among different grid paths, individual transmission current flows may exceed previously established limits and cause abnormal voltages (U.S. NRC, 1999; Arrillaga et al. 2000). Exelon Generation Company, the largest independent nuclear generator in PJM market, claimed in their LER that “[The] actual operating limits have not changed, however, the probability of reaching these limits has increased and periods of lower voltage than previously predicted have occurred,” and further determined the common cause of these events was the result of changes in the manner that the transmission system is operated. Experience from August 14, 2003 North America Blackout also exploited the potential weakness of the inter-regional grid that cannot support large volume of energy trading, as some argued that the substations and high-voltage wires moving power from plants to consumers were not designed for that purpose [of wholesale electricity transaction], but intended to be a highly reliable way to move electricity relatively short distances (Abel et al., 2003; Banerjee, 2003; Berenson, 2003; Bialek, 2004).

An “offsite power inoperable” incident at the Callaway Nuclear Plant in August of 1999 is sort of a watershed event (Michal, 2000). With the plant in Hot Standby mode, offsite power

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Offsite Power” dated February 1, 2006.

37 Load Serving Entities, including traditional electric utilities or energy serving companies, obtain the electricity from generators in competitive markets, then sell to retail consumers.

voltage was observed to decrease below the minimum operability established in plant procedures for approximately 12 hours. During investigations to establish the root cause for this unanticipated voltage sag, engineering reviews determined that the competitive wholesale power market contributed to conditions that large amounts of power far excess of typical levels were being transported across the grid on the day of this event. Independent nuclear generators operating in other competitive markets, e.g. PJM and NY-ISO, also reported several similar low switchyard voltage and offsite power inoperable incidents to the NRC since 2000.

Moreover, any instantaneous redistribution of power flow by ISO/RTOs, which in general is beyond anticipation of nuclear plants in competitive markets, may also result in sizable voltage deviations and equipment overloads, then affecting nuclear power plants operation. In September of 2011, after losing a 500 kV transmission line from Arizona, the grid operator attempted to rapidly transfer electricity from the Southern California Edison (SCE) to San Diego Gas and Electric Company (SDG&E) service area via San Onofre Nuclear Generating Station (California) switchyard. The San Onofre switchyard overloaded and the protection schemes automatically separated the plant from SDG&E grid as design, resulting in collapse of the SDG&E grid voltage and then processed to dual unit reactor trip from full power.

Besides power flow disturbance, there are also concerns on the availability of offsite power since market restructuring. Defaults on generation bids in competitive markets may erode reserve capacity margins that are needed to maintain grid reliability after generation or transmission.

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41 The offsite transmission network for San Onofre Nuclear Generating Station consists of two physically and electrically independent 230 kV electrical transmission systems, provided by San Diego Gas and Electric (SDG&E) and Southern California Edison (SCE), interconnected in the San Onofre switchyard.
faults. In some other cases, utilities are selling their generating facilities that supply offsite power to the nuclear plants (U.S. NRC, 1999).

**Market restructuring may increase human errors**

Restructuring activities may result in higher frequencies of human error when operating transmission elements or performing maintenance on transmission facilities. First, market restructuring create additional interfaces between IPPs, transmission owners (e.g. electric utilities) and transmission system operators (ISO/RTOs). The operational coordination between power generation, transmission and distribution was no longer within vertically integrated electric utilities. In 2007, transmission system operator at the Connecticut Valley Electric Exchange did not recognize and follow correct operation that is necessary to maintain offsite power supply to Millstone Power Station (Connecticut), resulted in a loss of offsite power to Millstone Unit 3.\(^43\) Interface between divested nuclear plants and transmission owners (electric utilities) could also contribute to nuclear plants’ operational risk. For instance, the Vermont Electric Power Company (VELCO), which owns and maintains Vermont's electric transmission system, upgraded certain transmission equipment but failed to communicate the new parameters to Vermont Yankee Nuclear Power Station (Vermont) during its refueling outage (RFO). As Vermont Yankee plant gradually increased its power following the RFO, the plant subsequently tripped due to the difference in transmission parameter settings.\(^44\)

Second, market restructuring may also increase frequency of human errors when performing maintenance on transmission grid, possibly due to downsizing or outsourcing. For instance in September 2010, South Texas Project nuclear plant (Texas) experienced a loss of offsite power,


\(^{44}\) See LER 271/2010-001, dated July 26, 2010.
and the direct cause was attributed to personnel error of contractors during maintenance of transmission facilities.\textsuperscript{45}

\textit{Market restructuring may increase transmission equipment malfunctions or failures}

There are also concerns on re-prioritization or reduction in transmission owners’ investments in capital or maintenance that are necessary for maintaining grid reliability after electricity market restructuring (Reason, 1996; Arrillaga et al., 2000; Abel et al., 2003; Scott, 2004; Joskow and Tirole, 2005; Woo et al., 2006; Wu et al., 2006), which may result in higher frequency of transmission equipment malfunction or failures and subsequently affect nuclear plants operation. Some argued that competitive markets disincentive investments in transmission capacity when the incumbent transmission owners’ revenue depends on congestion costs (Joskow and Tirole, 2005; Woo et al, 2006). The disconnection of generation and transmission may also eliminate the economies of joint planning and coordination then contributes to reduction of investments in transmission (Scott, 2004; Wu et al., 2006). For instance at Indian Point Energy Center (New York), Unit 2 experienced automatic reactor trips twice within four months in 2003 due to repeated failure of transmission elements.\textsuperscript{46} After these events, senior levels of Indian Point management met with their counterparts of transmission owners (i.e. Consolidated Edison) to ensure that appropriate actions were to be taken.

\textbf{3.2 Hypotheses}

Open access transmission for non-utility generators and the implementation of competitive electricity markets may have changed transmission grid configurations and its daily operation.

\textsuperscript{45} See LER 498/2010-004, dated November 25, 2010.
Based on power transactions cleared in the competitive markets, electricity is transmitted over longer distance with unprecedented volume, potentially creating more abnormal voltages and power flow disturbance. The assumptions on the availability of offsite electrical power post reactor trips may also have changed, as defaults on generation bids in the markets may have eroded reserve capacity margin that is needed to maintain grid reliability.

Thus, our Hypothesis I: *market restructuring causes a higher likelihood of unit trip or loss of offsite power due to power flow disturbance.*

Interfaces created by market restructuring activities generate additional costs of coordination between power generation, transmission and distribution. Pressures to keep competitive may also potentially cause electric utilities to re-prioritize or reduce investments in capital, maintenance or manpower for transmission facilities. These factors may possibly increase the frequency of transmission equipment failure or human error during operation or maintenance on transmission elements, and subsequently affecting nuclear plants operation.

Therefore our Hypothesis II: *market restructuring causes a higher likelihood of unit trip or loss of offsite power due to transmission equipment failure or human error.*

4. **Data**

4.1 **Data description**

We focus on “grid events” reported to the NRC through Licensee Event Report (LER) system between 1990 and 2011 by 99 nuclear power reactors that have begun commercial operation prior than 1990. **Grid events** are defined as faults or transients initiated from the

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48 We choose year 1990 as the starting year for our analysis, since information on some control variables
grid then affected nuclear plants operation by causing actuation of plant safety features, reactor trips or various forms of loss of offsite power (Appendix C provided a complete list of LERs included in this research). The data contains clear and narrative description of each event, allowing us to determine the root causes of grid faults and how nuclear plants operation were affected.

Our data includes a balanced panel of 99 nuclear power reactors that submitted a total of 119 “grid events” to the NRC between 1990 and 2011. Table 1 summarizes these grid events by (1) root causes, and (2) season of events occurrence (summer/winter), over four panels, including: (i) events first cause unit trips; (ii) events first cause full loss of offsite power (LOOP); (iii) events eventually involve either reactor trips or full LOOP; and (iv) all events. Categorizing our data into panel (i) and (ii) has practical safety implications, since the nuclear industry uses “Reactor Trip-Consequential LOOP Event Tree” and “LOOP Event Tree”, in which a reactor trip or a full LOOP is the first incidence in respective event trees, to assess the reactor core damage risk in the context of Station Blackout (U.S. NRC, NUREG-1784). In panel (iii) we consider grid events eventually involve either reactor trips or full LOOPS. In our data we not only have Reactor Trip-Consequential LOOP events, but also have full LOOP events occurred when reactors already in shutdown condition for refueling and maintenance, which could have been in Reactor Trip-Consequential LOOP category if these grid events occurred during reactors’ power used in our analyses, such as yearly electricity sale at the state level was not available until 1990.

Distinct from other NRC assessments, we only include grid events that are originated on the transmission grid beyond plant switchyard/substation in this research. We also exclude “plant-centered” events, which were events due to equipment failure or operation errors occurred within nuclear plants but also proceeding to reactor trips or loss of offsite power.

We further cross referenced with the NRC preliminary notification reports (PNs), North American Electric Reliability Corporation (NERC) System Disturbances Reports and U.S. Department of Energy (DOE) Electric Disturbance Events (OE-417) to identify major grid disturbance affecting one or multiple nuclear power plants.

Including reactor trips followed or coincided with loss of offsite power.

Upon full loss of offsite power, in general a reactor also immediately trips, unless such reactor is already in shutdown condition, e.g. during refueling outage.
operation. Therefore in panel (iii) we do not differentiate “trip first events” with “full LOOP first events” while these two types of events both represent significant challenges to nuclear plant operation. Finally in panel (iv) we include several other grid events resulting in less significant safety challenges, including events resulting in partial loss of offsite power (only one train of plant safety features is disconnected from the offsite grid and reactors in general do not trip), and events only involving actuation of specific plant safety features and the reactors remain under normal operation. These events provide valuable insights on plant responses during grid disturbances.

A closer observation of grid events distribution in Table 1 reveals several interesting insights. From the aspects of root causes and seasons, Table 1 shows that power flow disturbance and equipment failure \(^53\) were the dominant causal factors for grid events across all four panels. In terms of grid events caused by power flow disturbance, whether including events occurred during August 2003 Blackout, \(^54\) the frequency is always much higher during summer months (May through September) than in winter months (October to April), possibly due to higher grid stress conditions and equipment overloads in summer months. In contrary, the frequency of transmission equipment failure is about equally weighted between summer and winter seasons. Grid events caused by human error, including personnel error during maintenance activities and mis-operation or inadequate coordination of transmission system, have much less happenings than grid events due to previous two root causes, but have much higher likelihood to occur during winter months. This seems expectable since nuclear plants often schedule their refueling outage and maintenance in winter months, and electric utilities or transmission owners in general

\(^{53}\) Most of the grid equipment failures and malfunctions were in high-voltage circuit breakers, protective relays, and 345kV transmission lines.

\(^{54}\) During August 2003 Blackout, nine U.S. nuclear power reactors tripped and proceeded to full loss of offsite power, while one other reactor only tripped but did not lost offsite power. Another one reactor had full LOOP while already in shutdown mode.
would also plan their maintenance or upgrade of nearby transmission facilities accordingly during same time frames. Finally we also have certain number of grid events caused by severe or extreme weather conditions, which about equally distributed between summer and winter months. Nevertheless we will exclude these weather induced events from our regression analyses since the occurrence of extreme weather conditions is not correlated to market restructuring activities.

In terms of how grid events that affect nuclear plants operation in a chain-like fashion, Panels (i) and (ii) in Table 1 show that grid problems most likely would first cause reactor trips, instead of directly result in full loss of offsite power. Panels (iii) is the sum of Panel (i) and (ii), and Panel (iv) shows that grid faults also cause several less significant events (around 25 percent of our sample) in terms of plant responses.

Table 2 further distinguishes the grid events reported by reactors based market restructuring status (reactors eventually operate in areas having competitive markets versus reactors never operate in competitive markets) and by two time periods (1991 to 1998 versus 1999 to 2012, roughly before- versus after-implementation of competitive markets). For fifty-nine reactors that eventually operated in areas having competitive markets, the frequency of grid events caused by power flow disturbance has significantly increased during 1999-2011, consistent with the idea that the manner which the transmission system is operated in competitive markets may potentially create more unexpected grid conditions.\(^{55}\) In contrary we do not have a higher occurrence of grid events caused by either equipment failure or human error during 1999-2011, lending no support to concerns on possibly reduction or reprioritization of investment, maintenance or manpower for transmission facilities after market restructuring.

\(^{55}\) If we include events during the Aug 2003 Blackout, such increase is even much higher.
For the other forty reactors that never operate in areas having competitive markets, the occurrence of grid events, as we may expect, are with roughly equal frequencies between two periods for all root causes.

4.2 Indicator for market restructuring

To test the impacts of market restructuring on grid reliability and nuclear plants operational risk, we construct a time varying binary indicator, Market, which takes the value of one if a reactor operated in areas having ISO/RTOs managing an organized wholesale electricity market; and zero otherwise. We construct another binary indicator, Transition, to identify the periods when ISO/RTOs have already took over the operation of transmission grid but yet implemented the competitive markets.

Our Market indicator differs from two alternative indicators of market restructuring that have been used in other studies. In her study on the impacts of electricity restructuring on nuclear plants’ capacity factors during the period of 1992-1998, Zhang (2007) uses an indicator of STATE_RESTRUCTURE, whose value changes from zero to one when the state where a reactor is located enacted or implemented electricity market restructuring. However this STATE_RESTRUCTURE variable is a noisy indicator for whether a reactor operates in an organized market. For example, in Iowa, Minnesota and Wisconsin where state-level restructuring has not been enacted, electric utilities in these states still joined competitive markets in Midwest ISO. Furthermore, in states including Illinois and Ohio, state-level

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56 We take very careful effort, looking into Federal Energy Regulatory Commission orders and State of Market reports of relevant ISO/RTOs to identify information on (1) transfer of transmission grid operation from utilities, and (2) implementation of wholesale electricity markets. See Appendix D for details.
restructuring was enacted since 1998, but nuclear reactors in these states began operation in competitive markets after 2004. 57

Davis and Wolfram (2012) uses another indicator, \textit{DIVEST}, defined as utilities selling nuclear power plants to independent power producers, in their study on the effects of divesture on nuclear plants’ operation efficiency. We consider the \textit{DIVEST} variable to be less appropriate than the \textit{Market} indicator for our study. In Michigan where all reactors operated in competitive markets, only one reactor was divested. 58 Similarly in California, all four power reactors are still owned by electric utilities but operated within the territory of California ISO.

5. Effects of market restructuring on grid reliability and nuclear plants safety

5.1 Empirical strategies

\textit{Multi-failure duration analysis with time-varying regressors}

Our empirical strategy to investigate the impacts of market restructuring on grid reliability and reactors operational safety is a survival analysis with time-varying regressors. As shown in Table 3, more than two-thirds of the reactors in our data did not experience any grid events caused by either root causes through the study period of 1990-2011, and the remainder encountered only up to three grid events during twenty-two-year time span. Given such sparsely distributed data points, we employ a multi-failure duration analysis that focuses on the years elapsed for a reactor to encounter a grid event and analyze whether market restructuring activities increase the hazard rate or likelihood. The multiple-failure Cox Proportional Hazard model we use involves time varying regressors, where the “hazard” or likelihood of the reactor

\begin{footnotesize}
\footnote{57 Due to changes in ISO/RTOs’ operational territories.}
\end{footnotesize}
being affected by a grid event (due to one of the root causes) at year $t$, given that it had not been affected before year $t$, is assumed to be:

$$h_i(t) = h_{0,i}(t) \exp(X_{i,t} \beta + \varepsilon_{i,t})$$  

(1)

where $h_{0,i}(t)$ is the baseline hazard of reactor $i$, and

$$X_{i,t} \beta = \beta_1 \text{Market}_{i,t} + \beta_2 \text{Transition}_{i,t} + \beta_3 \text{GridStress}_{i,t} + \beta_4 \text{Upgrade}_{i,t}$$

$$+ \beta_5 \text{Characteristic}_{i,t} + \gamma \text{Year}_t$$

The key explanatory variable is $\text{Market}_{i,t}$, whether the reactor operates in areas having ISO/RTO operating competitive electricity wholesale markets. The time interval in the analysis is counted by years, starting from 1989; and year indicators are included in the regressions. The second control variable $\text{Transition}_{i,t}$, as mentioned earlier, is to control for transitional periods when ISO/RTOs have already took over the operation of transmission grid but yet launched the competitive markets.

We then include a number of time varying control variables that could potentially impact reactors’ likelihood of experiencing grid events. The first set of control variables $\text{GridStress}_{i,t}$ are: (1) $\text{StateSales}_{i,t}$, the yearly electricity sales (in MWh) in the state of reactor $i$, to proxy the effect of increasing electricity demand on grid;\(^{59}\) (2) $\text{PeakLoad}_{i,t}$, including $\text{SummerPeakLoad}_{i,t}$ and $\text{WinterPeakLoad}_{i,t}$, are non-coincident annual peak loads (in megawatts) by North American Electric Reliability Corporation assessment areas where reactor $i$ is located, to control for any potential impact of increasing peak loads on grid reliability.\(^{60}\)


Another set of control variables $Upgrade_{i,t}$, includes $ExtensionApproval_{i,t}$, $SPUApproval_{i,t}$ and $EPUApproval_{i,t}$, are to indicate major upgrades/uprates that reactor $i$ have been applied. $ExtensionApproval_{i,t}$ is to indicate if a nuclear power plant has been approved by the NRC for plant life extension. $SPUApproval_{i,t}$ and $EPUApproval_{i,t}$ on the other hand indicate if either Stretch Power Uprates (SPUs) or Extended Power Uprates (EPUs) had been approved by the NRC for reactor $i$. Whenever a reactor seeks plant life extension, SPUs, or EPUs, plant owner would significantly upgrade/replace their plant equipment when applying these major plant overhauls, and the settings or parameters in plant protective schemes responsive to grid disturbance would have been changed or updated.

The last set of control variables $Characteristic_{i,t}$, includes $Capacity_{i,t}$ and $BWR_{i}$, to control for reactor characteristics that may be related to its vulnerability to grid events. $Capacity_{i,t}$ is the maximum core thermal capacity approved by the NRC (in Megawatts-thermal) of reactor $i$ in year $t$. As discussed earlier, nuclear power plants have multiple protective devices to sense any current imbalance or frequency oscillations. Set-points in these protective schemes are plant specific and correlated to reactor thermal capacity. As nuclear power plants in general are operated at steady full load (IAEA, 2012), we use $Capacity_{i,t}$ as a proxy when we are unable to observe actual values of these protective parameters. Finally we include $BWR_{i}$, to distinguish Boiling Water Reactors with Pressurized Water Reactors, despite these two branch of reactors have similar designs of electrical power systems.

5.2 Results

*Grid events first cause reactor trips*

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61 We exclude 5 reactors that had not begun commercial operation before 1990. We also exclude 11 grid events during August 2003 Blackout.
We first investigate the effects of market restructuring on the likelihood of having grid events first causing reactor trips at nuclear plants. We focus on the hazard ratio, the exponential of the estimated coefficient $\beta_1$ for the key explanatory variable, $Market_{i,t}$, by running multiple-failure Cox Proportional Hazard regressions based on Equation (1). An estimated hazard ratio of greater than one indicates an increase in the likelihood of encountering a grid event for reactors operate in areas have launched competitive markets (a change from zero to one in the $Market_{i,t}$ variable), conditional on that it has not yet experienced any grid events up to year $t$.

*Grid events by root causes:* In Panel A of Table 4, we focus on grid events caused by power flow disturbance. The results in Columns 1-4 suggest that the hazard ratio of experiencing grid events more than decuples after the effectiveness of competitive markets, which support our argument that in open markets the manner that the transmission grid is operated may have changed and resulted in a higher frequency of abnormal grid conditions. In contrast, for grid events caused by transmission equipment failure or human error (Panel B of Table 4), results in Columns 1-4 suggest no significant change in hazard ratio after the implementation of competitive markets, lending no support to concerns on possibly reduction in transmission maintenance or manpower.

*Grid events by summer and winter months:* We further examine if the likelihood of having grid events differs by seasons, i.e. summer versus winter months, given that the transmission grid in general is already more congested and under higher pressure during summer. By separating our data into two panels based on season of grid events occurrence, results in Panel C of Table 4 suggest that the hazard ratio of encountering grid events more than quintuples during summer.

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62 Since there are fewer grid events caused by human errors, we group them together with events caused by equipment failure.
months (May through September), while results in Panel D show no significant change in the likelihood of experiencing grid events during winter months (October through April). These results are consistent with the notion that the transmission grid in general is under higher stress during summer months. Our findings also have important implication to the assessment of grid reliability. Nuclear power plants are critical base load generators that contribute to both the stability and integrity of the grid. Their large steam turbines could provide inertia and voltage support to reinforce local grid balancing efforts (NERC, 2013). Therefore in several NERC reliability regions that have implemented competitive markets and have long-term concerns of declining summer reserve margins, it is essential to have continuous and stable nuclear power operation during summer months. Otherwise the grid may not be able to respond in a satisfactory manner post reactor trips and may have higher probability of proceeding to grid collapse and large blackouts.

*Grid events occurred during summer months due to power flow disturbance:* In the last row of Table 4, we specifically focus on grid events caused by power flow disturbance during summer months. Results in last row of Table 4 again suggest that the hazard ratio of encountering abnormal power flow almost quintuples during summer months, consistent with our previous estimations. Our results also highlight the primary channel of grid faults and its impact to reactors in competitive markets.

*Grid events first cause full loss of offsite power*

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63 We include either $\text{SummerPeakLoad}_{t,t}$ or $\text{WinterPeakLoad}_{t,t}$, instead of both variables in the regression, when analyzing grid events occurred during summer or winter months, respectively.
64 For example in Midwest ISO, the anticipated summer reserve margin may decline from 18.28% in 2014 to 3.44% in 2023, fall below reserve margin targets. Moreover in Northeast Power Coordinating Council (NPCC)-New York ISO, losing the Indian Points nuclear plant after 2015 would result in immediate violations of resource adequacy criteria (See NERC 2013 Long-Term Reliability Assessment).
We then investigate the effects of market restructuring on the likelihood of having grid events first causing full loss of offsite power at nuclear plants, since full LOOP in particular is considered as precursors to risks of Station Blackout and reactor core damage. Our results in Panel A and Panel B of Table 5 suggest that there is no significant increase in the likelihood of first having full LOOP during grid events, due to either root causes. Panel C and Panel D of Table 5 provide other evidence that there is also no significant hazard of directly having full LOOP during either summer or winter months. In the last row of Table 5, we also do not have any significant estimates for first having full LOOP caused by power flow disturbance in summer. Together with our estimates in Table 4, these results hint that the reactors in competitive markets are more likely to be affected by grid events through “Reactor Trip-Consequential LOOP” event sequences.

*Grid events involve either unit trip or full loss of offsite power*

As mentioned earlier, we have several grid events first causing reactor trips but subsequently proceeding to full LOOP. We also have several other grid events first causing full LOOP when the reactors were already in shutdown condition, which should have involved unit trips if reactors were under normal operation. Therefore in Table 6 we consider grid events involve either reactor trips or full loss of offsite power, and reports our estimations of hazard ratios by performing separate multiple-failure Cox Proportional Hazard regressions. Our results in Panel A of Table 6 suggest that the hazard ratio of experiencing grid events more than triples after the effectiveness of competitive markets, and results in Panel C of Table 6 again provide evidence that the risk is higher during summer months. Results in the last row of Table 6 similarly show that the likelihood of having reactor trips or full LOOP significantly increases due to power flow disturbance during summer.
**Including all events**

Besides events involving either reactor trips or full loss of offsite power, in Table 7 we include all other grid events that only result in less significant safety impacts to nuclear plants, including grid events that only result in partial loss of offsite power, and events only causing specific plant safety features to actuate but the reactors remain under normal operation. These events provide valuable insights on plant responses during grid disturbances. Again we perform multiple-failure Cox Proportional Hazard regressions and report results in Table 7. These results similarly suggest that the likelihood of encountering grid events have significantly increased due to abnormal power flow disturbance after reactors begin their operation in areas with competitive markets, and the risk is significantly higher during summer.

**Assuming baseline hazard is reset after encountering grid events**

An important assumption in Equation (1) is that the baseline hazard $h_{0,i}(t)$ is the same when having multiple grid events during the analysis period. This assumption could be further relaxed. For instance, after a grid event caused by equipment failure in transmission system, such failed equipment will be replaced, and similar equipment will also be checked or upgraded. In such circumstance we can say the baseline hazard $h_{0,i}(t)$ is “reset”, and the duration to experience next grid event should be re-counted from zero. Hence we assume that the hazard of experiencing a grid event to be:

$$h_i(\tau) = h_{0,i}(\tau) \exp(X_{i,t}\beta + \varepsilon_{i,t})$$

where $\tau$ is the time elapsed since last grid event, and $X_{i,t}\beta$ is the same as in Equation (1).

We repeat Cox Proportional Hazard regressions and report results in Appendix A, which are mostly econometrically similar to our main results.
Addressing potential selection bias

The major difference between reactors that eventually operate in areas having competitive markets and reactors never operate in open markets is their locations, as the later reactors are mostly clustered in Southeastern states. If state-level decisions about market restructuring and formation of ISO/RTOs were influenced by some factors that are correlated with the trends in regional grid reliability, there might be an “omitted variable” problem which would threaten the identification of a causal relationship between market restructuring, grid reliability and nuclear plants operation. Nevertheless, prior published studies mostly identified that state-level restructuring decisions were driven by high electricity prices and liberal politics at the state level (White 1996; Joskow 1997). Industrial assessments neither reveal any specific long-term regional grid reliability issues prior mid-1990s.⁶⁵ The only possible area of concern may be in states of Iowa, Minnesota and Wisconsin, where electric utilities voluntarily formed Midwest ISO despite no market restructuring at state level. Excluding reactors in these states from the data, the results for Market is essentially unchanged for grid events first tripping reactors (Table B1).⁶⁶ In this case, concerns on potential selection bias at regional level may be alleviated.

We then consider the cases where decisions on joining specific ISO/RTOs (and its competitive markets) were made at the reactor level, separate from state level market restructuring. First, several independent power generators in Midwest or mid-Atlantic decided to withdraw from Midwest ISO and joined the power markets in PJM around 2004 and 2005. Excluding these reactors from the sample, the results for Market is essentially unchanged (Table B2). Second, the State of Virginia have suspended their market restructuring activities

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⁶⁶ The results are econometrically similar when including other grid events involving partial or full LOOP, therefore we do not report these results in Appendix B.
since 2004, but electric utilities there have decided to join PJM power markets in 2005. In Michigan, two reactors operated in Midwest ISO while the other two decided to participate in PJM. When these Virginia and Michigan reactors are excluded from the sample, the estimated hazard ratios for *Market* are similar (Table B3). All together, these results reassure us that the correlation between market restructuring and power interruptions experienced by nuclear reactors is not driven by selection bias.

6. **Policy implications and conclusions**

This paper studies the impacts of market restructuring and the resulting competitive wholesale markets on grid reliability and nuclear plant safety. Nuclear power plants rely on transmission grid as preferred electrical power source to support critical safety functions, and hence have stringent requirements on offsite power availability and on voltage and frequency stability. Using data on “grid events” reported to the NRC by U.S. commercial power reactors from 1990 to 2011, we find that, compared to reactors still operated by vertically integrated utilities, reactors operating in competitive wholesale electricity markets are more likely to experience reactor trips that are initiated by unexpected abnormal voltages or power flow disturbance following changes in the manner that the transmission system is operated, suggesting that there is an increase in the likelihood of grid disturbance in competitive wholesale markets, compared to regulated markets, particularly during summer months (May through September) when the grid in general is under higher stress due to higher load demand. The hazard ratio of encountering grid events due to either transmission equipment failure or human error on the other hand does not increase significantly in competitive markets, lending no support to the

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67 Only Dominion control area integrated into PJM, but not the entire state of Virginia.
concern that restructuring may cause utilities to re-prioritize or reduce their capital investment, maintenance and manpower in transmission facilities.

Our findings provide a novel perspective on the assessment of the reliability of bulk transmission grid from viewpoints of nuclear plants in the context of electricity market restructuring. Prior published investigations of U.S. electric power system reliability have primarily focused on distribution of large blackouts, and looked into power interruptions experienced by retail consumers. To the author’s knowledge, the unique feature of nuclear power plants, that they are also electricity consumers and are highly sensitive to grid transients, is unnoticed by other empirical studies to date. Our findings also help to address the interdependence of grid reliability and nuclear plant operation, while a sudden reactor trip is often the single largest contingency faced by the transmission system operator.

Moreover, our investigation has important policy implications for U.S. commercial power reactors in the aspects of its continuous safe operation and future deployments. For incumbent nuclear power reactors, our analysis provides important insights for further probabilistic risk assessments, individual plant examinations and other safety regulatory issues. Our results suggest that the analysis of plant-specific reactor core damage frequency (CDF) should incorporate the effects of market restructuring on offsite power reliability, which is beyond the scope of this research.

Our study also provides empirical insights on deployments of new nuclear power plants. The results imply that grid capability/reliability could become one of key considerations and impediments for building new full-size nuclear reactors (above 1,000 MW generation capacity) in competitive electricity markets. This might be one potential reason that currently all the new
reactors under construction are located in the southeastern region of the U.S., where electric utilities remain delivering service as regulated and vertically-integrated companies and there are no competitive markets. Our study also shed the light on the future development of Small Module Reactor (SMR), which has the advantage of grid-independence, providing an off-grid solution to consumers (e.g. military bases) who want to avoid vulnerability to the commercial electric power grid, or in locations where the transmission grid is small or not well-developed.

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68 Virgil C. Summer Units 2 and 3 (in South Carolina) and Vogtle Units 3 and 4 (in Georgia) are the only two new nuclear plants currently under construction in the U.S. See U.S. NRC “Combined License Applications for New Reactors.” Retrieved April 1, 2013 from http://www.nrc.gov/reactors/new-reactors/coll.html

69 One NRC Commissioner stated that “I wouldn’t be surprised if the selection of most of these units, is directly related to the fact that the grid is very strong, reliable, and has the capacity in this [Southeast] area.” See transcript, Joint Meeting of the U.S. NRC and FERC, dated April 24, 2006.

References


Accession No.ML041200565)  
Figure 1: Nuclear Power Plant Electrical Distribution Diagram (Simplified)
Table 1: Distribution of grid events, by root causes and seasons, between 1990 and 2011

<table>
<thead>
<tr>
<th>Root Causes</th>
<th>Seasons</th>
<th>(i) First Cause Unit Trip</th>
<th>(ii) First Cause Full LOOP</th>
<th>(iii) Involve Unit Trip or Full LOOP</th>
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<td></td>
<td>(I)</td>
<td>(II)</td>
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<td>(I-1) Disturbance</td>
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Note:
(1) We exclude five reactors that began commercial operation in or after 1990, including Comanche Peak Unit 1 & 2, Limerick Unit 2, Seabrook Unit 1 and Unit 2. (2) Summer is defined as May to September; and winter is October through April.
Table 2: Distribution of grid events, by root causes and market restructuring status, between 1990 and 2011

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<th>Root Causes</th>
<th>Periods</th>
<th>Panels</th>
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<td>(i) First Cause Unit Trip</td>
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<td>(I-2) Disturbance</td>
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<td>*Include Events in Aug 2003 Blackout</td>
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</table>

Note: (1) We exclude five reactors that began commercial operation in or after 1990, including Comanche Peak Unit 1 & 2, Limerick Unit 2, Seabrook Unit 1 and Watts bar Unit 2. (2) Summer is defined as May to September; and winter is October through April. (3) Reactors affected during August 2003 Blackout are all located in areas having competitive markets.
Table 3: Distribution of reactors, by number of grid events experienced between 1990 and 2011

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<td>(I-2) Disturbance</td>
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<td><em>(Include Events in Aug 2003 Blackout)</em></td>
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<td>(II) Equipment</td>
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<td>(III) Human Error</td>
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Note: We exclude five reactors that began commercial operation in or after 1990, including Comanche Peak Unit 1 & 2, Limerick Unit 2, Seabrook Unit 1 and Watts bar Unit 2
Table 4: The Effect of Competitive Electricity Market on Grid Events

*Events First Causing Unit Trip*

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<tr>
<td>[Market]</td>
<td>.343 (.242)</td>
<td>.281 (.222)</td>
<td>.279* (.215)</td>
<td>.271* (.211)</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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</tr>
<tr>
<td>[Market]</td>
<td>3.335** (1.557)</td>
<td>6.308*** (3.014)</td>
<td>5.932*** (2.906)</td>
<td>5.778*** (2.838)</td>
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<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
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</tr>
<tr>
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<td>.405 (.311)</td>
<td>.468 (.313)</td>
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<tr>
<td>Grid Stress</td>
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<tr>
<td>Reactor Upgrade</td>
<td>X X X X X</td>
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<tr>
<td>Reactor Characteristics</td>
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</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table 5: The Effect of Competitive Electricity Market on Grid Events

Events First Causing Full Loss of Offsite Power

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<tr>
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<td>.390</td>
<td>.154**</td>
<td>.148*</td>
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<tr>
<td></td>
<td>(.636)</td>
<td>(.319)</td>
<td>(.112)</td>
<td>(.149)</td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<tr>
<td>[Market]</td>
<td>1.031</td>
<td>.192*</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>(.659)</td>
<td>(.180)</td>
<td>-</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<td>.891</td>
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<td>(.663)</td>
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<tr>
<td>Grid Stress</td>
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<td>X</td>
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<td>Reactor Characteristics</td>
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</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table 6: The Effect of Competitive Electricity Market on Grid Events  
*Events Involve Either Unit Trip or Full Loss of Offsite Power*

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<td></td>
<td>(2.316)</td>
<td>(2.406)</td>
<td>(2.345)</td>
<td>(2.358)</td>
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<td>.298**</td>
<td>.299**</td>
<td>.300**</td>
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<td>(.249)</td>
<td>(.180)</td>
<td>(.178)</td>
<td>(.177)</td>
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<td><strong>By Season</strong></td>
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<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<tr>
<td>[Market]</td>
<td>1.913*</td>
<td>2.693***</td>
<td>2.628**</td>
<td>2.546**</td>
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<td>.552</td>
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<td>(.305)</td>
<td>(.329)</td>
<td>(.332)</td>
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<tr>
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<td>3.331**</td>
<td>3.413**</td>
<td>3.670**</td>
<td>3.390**</td>
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<td>(1.910)</td>
<td>(1.976)</td>
<td>(1.706)</td>
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</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator *Market* in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table 7: The Effect of Competitive Electricity Market on Grid Events

All Events

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<td>4.837***</td>
<td>2.906</td>
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<td><strong>By Season</strong></td>
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<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<td>1.891*</td>
<td>2.373**</td>
<td>2.330**</td>
<td>2.187**</td>
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<td>(.883)</td>
<td>(.885)</td>
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<td>.996</td>
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<td>(.481)</td>
<td>(.477)</td>
<td>(.503)</td>
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<td>3.331**</td>
<td>3.288**</td>
<td>3.545**</td>
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<td>(1.820)</td>
<td>(1.890)</td>
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<td>Grid Stress</td>
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Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Appendix A: Additional Cox Proportional Hazard Regressions, assuming the baseline hazard is reset after grid events

Table A1: Events First Causing Unit Trip

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

<table>
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<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<tr>
<td>[Market]</td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<tr>
<td>[Market]</td>
<td>.179*** (.151)</td>
<td>.131** (.129)</td>
<td>.133** (.127)</td>
<td>.133** (.128)</td>
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<tr>
<td><strong>By Season</strong></td>
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<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<tr>
<td>[Market]</td>
<td>3.280** (1.604)</td>
<td>5.988*** (2.902)</td>
<td>5.797*** (2.883)</td>
<td>5.694*** (2.838)</td>
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<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
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<tr>
<td>[Market]</td>
<td>-</td>
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<td>-</td>
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<tr>
<td><strong>Power flow disturbance during summer months</strong></td>
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<td><strong>Control Variables</strong></td>
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<td>Grid Stress</td>
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Note: This table reports hazard ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions, assuming the baseline hazard is reset after having grid events. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table A2: Events First Causing Full Loss of Offsite Power

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<td>.845</td>
<td>.407</td>
<td>.143***</td>
<td>.153*</td>
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<td></td>
<td>(.660)</td>
<td>(.332)</td>
<td>(.096)</td>
<td>(.167)</td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<td>1.069</td>
<td>.187*</td>
<td>.220</td>
<td>.214**</td>
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<td></td>
<td>(.688)</td>
<td>(.176)</td>
<td>(.212)</td>
<td>(.153)</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<td>(.484)</td>
<td>(.519)</td>
<td>(.435)</td>
<td>(.604)</td>
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<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
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<td></td>
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<tr>
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<td>1.341</td>
<td>.855</td>
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<td>(1.429)</td>
<td>(.959)</td>
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<td>(.210)</td>
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<td>(.796)</td>
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</table>

Note: This table reports hazard ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions, assuming the baseline hazard is reset after having grid events. All regressions are with year dummies, and robust standard errors reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Table A3: *Events Involve Either Unit Trip or Full Loss of Offsite Power*

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

<table>
<thead>
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<th>(1)</th>
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<tbody>
<tr>
<td><strong>By Root Causes</strong></td>
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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<tr>
<td>[Market]</td>
<td>-</td>
<td>4.195*</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>(3.213)</td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<tr>
<td>[Market]</td>
<td>.489</td>
<td>-</td>
<td>.215**</td>
<td>.215**</td>
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<tr>
<td></td>
<td>(.221)</td>
<td></td>
<td>(.142)</td>
<td>(.139)</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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</tr>
<tr>
<td>[Market]</td>
<td>1.951*</td>
<td>2.808***</td>
<td>2.853**</td>
<td>2.793***</td>
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<td></td>
<td>(.744)</td>
<td>(1.071)</td>
<td>(1.183)</td>
<td>(1.093)</td>
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<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
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<tr>
<td>[Market]</td>
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<td>.430</td>
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<td></td>
<td></td>
<td>(.299)</td>
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<tr>
<td><strong>Power flow disturbance during summer months</strong></td>
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<tr>
<td>[Market]</td>
<td>3.585**</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td>(1.993)</td>
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</tbody>
</table>

**Control Variables**

- Transition: X
- Grid Stress: X
- Reactor Upgrade: X
- Reactor Characteristics: X

Note: This table reports hazard ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions, assuming the baseline hazard is reset after having grid events. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table A4: *All Events*

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

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<td></td>
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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
<td>6.002***</td>
<td>4.249**</td>
<td>-</td>
<td>4.105**</td>
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<td>[Market]</td>
<td>(3.372)</td>
<td>(2.860)</td>
<td>-</td>
<td>(2.669)</td>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
<td>.628</td>
<td>.348*</td>
<td>.309*</td>
<td>.308*</td>
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<tr>
<td>[Market]</td>
<td>(.248)</td>
<td>(.199)</td>
<td>(.192)</td>
<td>(.193)</td>
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<tr>
<td><strong>By Season</strong></td>
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</tr>
<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
<td>1.787</td>
<td>2.240**</td>
<td>2.219*</td>
<td>2.095*</td>
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<tr>
<td>[Market]</td>
<td>(.636)</td>
<td>(.912)</td>
<td>(.917)</td>
<td>(.863)</td>
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<tr>
<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
<td>1.170</td>
<td>-</td>
<td>-</td>
<td>.847</td>
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<td>[Market]</td>
<td>(.536)</td>
<td>-</td>
<td>-</td>
<td>(.386)</td>
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<td><strong>Power flow disturbance during summer months</strong></td>
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<td>[Market]</td>
<td>-</td>
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<tr>
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<td>Grid Stress</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reactor Upgrade</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Reactor Characteristics</td>
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</tr>
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</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions, assuming the baseline hazard is reset after having grid events. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Appendix B: Addressing concerns about potential selection bias

Table B1: Excluding reactors in Midwest ISO

Events First Causing Unit Trip

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

<table>
<thead>
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<th>(1)</th>
<th>(2)</th>
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<th>(4)</th>
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<td><strong>By Root Causes</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<tr>
<td></td>
<td>(6.755)</td>
<td>(8.498)</td>
<td>(7.759)</td>
<td>(8.235)</td>
</tr>
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<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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<td></td>
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<tr>
<td>[Market]</td>
<td>.360</td>
<td>.286*</td>
<td>.284*</td>
<td>.262*</td>
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<td></td>
<td>(.248)</td>
<td>(.216)</td>
<td>(.210)</td>
<td>(.198)</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<td></td>
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<tr>
<td>[Market]</td>
<td>3.394***</td>
<td>5.810***</td>
<td>5.464***</td>
<td>5.399***</td>
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<td></td>
<td>(1.558)</td>
<td>(2.613)</td>
<td>(2.528)</td>
<td>(2.505)</td>
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<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
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<tr>
<td>[Market]</td>
<td>.539</td>
<td>.426</td>
<td>.485</td>
<td>.525</td>
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<td></td>
<td>(.383)</td>
<td>(.316)</td>
<td>(.317)</td>
<td>(.334)</td>
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<td><strong>Power flow disturbance during summer months</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(5.552)</td>
<td>(5.758)</td>
<td>(5.624)</td>
<td>(5.378)</td>
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<tr>
<td>Transition</td>
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<tr>
<td>Grid Stress</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Reactor Upgrade</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reactor Characteristics</td>
<td>X</td>
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</tbody>
</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table B2: Excluding reactors withdraw from Midwest ISO and join PJM

Events First Causing Unit Trip

Cox Proportional Hazard Regressions on the likelihood of experiencing grid events

<table>
<thead>
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<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
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</thead>
<tbody>
<tr>
<td><strong>By Root Causes</strong></td>
<td><strong>By Root Causes</strong></td>
<td><strong>By Root Causes</strong></td>
<td><strong>By Root Causes</strong></td>
</tr>
<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
</tr>
<tr>
<td></td>
<td>(6.420)</td>
<td>(7.751)</td>
<td>(7.487)</td>
</tr>
<tr>
<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
</tr>
<tr>
<td>[Market]</td>
<td>.415</td>
<td>.289</td>
<td>.245*</td>
</tr>
<tr>
<td></td>
<td>(.285)</td>
<td>(.223)</td>
<td>(.190)</td>
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<tr>
<td><strong>By Season</strong></td>
<td><strong>By Season</strong></td>
<td><strong>By Season</strong></td>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
</tr>
<tr>
<td>[Market]</td>
<td>3.083**</td>
<td>5.892***</td>
<td>5.338***</td>
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<tr>
<td></td>
<td>(1.433)</td>
<td>(2.746)</td>
<td>(2.442)</td>
</tr>
<tr>
<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
<td><strong>Panel D – Initiated during winter months (October - April)</strong></td>
</tr>
<tr>
<td>[Market]</td>
<td>.684</td>
<td>.528</td>
<td>.496</td>
</tr>
<tr>
<td></td>
<td>(.505)</td>
<td>(.428)</td>
<td>(.366)</td>
</tr>
<tr>
<td><strong>Power flow disturbance during summer months</strong></td>
<td><strong>Power flow disturbance during summer months</strong></td>
<td><strong>Power flow disturbance during summer months</strong></td>
<td><strong>Power flow disturbance during summer months</strong></td>
</tr>
<tr>
<td></td>
<td>(5.270)</td>
<td>(6.122)</td>
<td>(5.364)</td>
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<td><strong>Control Variables</strong></td>
<td><strong>Control Variables</strong></td>
<td><strong>Control Variables</strong></td>
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<tr>
<td>Transition</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Grid Stress</td>
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<td>X</td>
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<tr>
<td>Reactor Characteristics</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Table B3: Excluding Michigan and Virginia

Events First Causing Unit Trip

<table>
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<th>(1)</th>
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<td><strong>By Root Causes</strong></td>
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<tr>
<td><strong>Panel A – Caused by unanalyzed or unexpected power flow disturbance</strong></td>
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<tr>
<td><strong>Panel B – Caused by equipment failure or human error</strong></td>
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</tr>
<tr>
<td>[Market]</td>
<td>.349</td>
<td>.270</td>
<td>.272*</td>
<td>.264*</td>
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<tr>
<td></td>
<td>(.238)</td>
<td>(.217)</td>
<td>(.214)</td>
<td>(.212)</td>
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<tr>
<td><strong>By Season</strong></td>
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<tr>
<td><strong>Panel C – Initiated during summer months (May - September)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>[Market]</td>
<td>3.194**</td>
<td>7.070***</td>
<td>-</td>
<td>6.752***</td>
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<td>(1.478)</td>
<td>(3.437)</td>
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<td>(3.448)</td>
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<td>.543</td>
<td>.443</td>
<td>.573</td>
<td>.601</td>
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<td>(.384)</td>
<td>(.343)</td>
<td>(.411)</td>
<td>(.437)</td>
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<td>(5.311)</td>
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</table>

Note: This table reports hazardous ratio estimates corresponding to binary indicator Market in Equation (1) by running Cox Proportional Hazard Regressions. All regressions are with year dummies, and robust standard errors reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Appendix C: Grid Events

Appendix C provides Table C-1 of grid events that affected U.S. commercial nuclear power plant performance from 1990 through 2011. The events were identified and summarized from licensee event reports (LERs) through the U.S. NRC Licensee Event Report Search (LERSearch) system. Table C-1 provides the LER number, plant name, the date the event occurred, the reactor power level, and event classification in relation to the grid and the NPP.

In a few events, Table C-1 references the NRC preliminary notification reports (PNs), North American Electric Reliability Corporation (NERC) System Disturbance Reports, and U.S. Department of Energy Electric Disturbance Events (OE-417) reports. The LERs, PNs, NERC and OE-417 event dates were cross-referenced to identify the major grid disturbance affecting one or multiple NPPs. The NERC System Disturbance Reports and DOE OE-417 filings helped to identify when the event was part of a larger grid disturbance.

Grid events were defined as events initiated from the grid and causing reactor trips or various forms of loss of offsite power (LOOP), and events initiated by a loss of electric power from any remaining power supplies as a result of, or coincident with, a reactor trip. For the purposes of this study and distinct from NRC NUREG-1784 “Operating Experience Assessment – Effects of Grid Events on Nuclear Power Plant Performance,” a line of demarcation was drawn between the plant and the grid at the high voltage switchyard or substation nearest the NPP. The grid was defined to include the transmission and generation system beyond the switchyard or substation. The boundary between the NPP and the grid is also consistent with typical organizational responsibility for equipment design, maintenance, and operational control. In a deregulated environment this boundary is typically the borderlines between the ISO/RTO and the deregulated nuclear generating company.

A full LOOP was indicated by the start and loading of ALL emergency diesel generators (EDGs). A partial LOOP was indicated by the start and loading of one or more, but not all the EDGs. Momentary LOOPs and partial LOOPs were indicated by the start of the EDGs; however, the voltage quickly recovered so the EDGs did not load. For the purposes of this assessment, partial or momentary LOOPs were used to identify potential NPP sensitivities to a grid-related event, despite less risk significant than full LOOPs.

The grid events were categorized by its event sequences and consequences as follows:

I events: grid event is the first event in the sequence of events leading to actuation of Engineered Safety Feature (ESF), including Emergency Diesel Generators (EDGs), but did not involve a unit trip, LOOP, or partial LOOP. These events provide insights into the plant response in the grid events.

T events: when grid event is the first event in the sequence of events leading to the reactor trip, but did not initiate or coincide loss of electric power from any remaining power supplies.

R events: when grid event is the first event in the sequence of events leading to the reactor trip, then followed by or coincided with losses of electric power from any remaining power supplies. Losses of electric power include any LOOPs, partial LOOPs, or voltage degradations below the technical specification low limit.

L and PL events: when the first grid event in the sequence of events leading to full LOOPs or partial LOOPs was in the transmission network. LOOPs at zero power are indicated by a zero suffix.
- L events: full LOOPs.
- PL events: partial LOOPs

**C-1 Explanation of Column Headings in Table C-1**

**C-1.1 LER**
The Licensee Event Report (LER) number describing the grid event.

**C-1.2 Plant Name**
The name of the plant experiencing the grid event.

**C-1.3 Date**
The date of the grid event (mm/dd/yy).

**C-1.4 Operation Mode**
The operational mode when the grid event occurred. The two operational modes are described as follows.

- **Power Ops** – The grid event caused a plant trip during power operation. If the grid event leads to LOOP, the plant has to cool down without the aid of the power conversion system which is lost due to the LOOP, and these events are applicable to full power risk assessments.
- **Shutdown** – The grid event occurred during plant hot or cold shutdown or during plant startup. The event characteristics and plant configuration apply to shutdown conditions (e.g., the low-pressure shutdown cooling system is currently supplying cooling and if the system is lost, shutdown cooling can be put on line without much cool down, or decay heat is very low).

**C-1.5 Grid Event Class**
The classification used to determine which grid events to include in the frequency and duration calculations.

- **I** events – Grid events occurred but did not involve a reactor trip, LOOP, or partial LOOP
- **T** events – Grid events is the first event in the sequence of events leading to the reactor trip.
- **R** events – Grid events leading to the reactor trip, then followed by or coincided with losses of electric power from any remaining power supplies.
- **L** events – Full LOOPs
- **L0** events – Full LOOPs occurred when reactor in shutdown mode
- **L-NT** events – Full LOOP but reactor remained connected to the grid
- **PL** events – Partial LOOPs
- **PL0** events – Partial LOOPs occurred when reactor in shutdown mode

**C-1.6 EDG Status**
The response of plant emergency diesel generators (EDG) after the grid event occurred.

- **NA** – The EDGs are not required to start as the plant is still connected to the grid
- **EDG loaded** – All or one of the EDGs started and loaded
- **EDG started** – one of the EDGs started but not loaded to the buses

**C-1.7 Restoration Time**
The duration, in minutes, from the event initiation until offsite electrical power was restored to a

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71 This information could be used to determine which events are applicable to full-power risk assessments and which are applicable to low-power and shutdown risk assessments. The dividing line between these two risk assessments is whether the plant can use low pressure shutdown cooling (shutdown) or if it requires the power conversion system to safely shutdown and cool down (power operations).
safety bus. This is the actual time taken to restore power from an offsite source to a safety bus. The restoration time is not available when during the grid events the safety buses remained supplied from offsite grid.

C-1.8 Grid Event Root Causes
The root causes of grid events used to determine which grid events to include in the frequency calculations.

Disturbance – momentary or sustained grid voltage transient in the vicinity of NPP.
Equipment – malfunction or failure of a transmission element.
Human Error – human error occurred during operation or maintenance of transmission elements.
Weather – Local, severe or extreme weather conditions affecting the vicinity of NPP and caused grid events, including lightning, hurricane, high wind, winter storm, snow and ice, and earthquake.

C-1.9 Reference
Cross-reference from the U.S. NRC preliminary notification reports (PNs), North America Electric Reliability Corporation (NERC) System Disturbance Reports, and the U.S. Department of Energy Electric Disturbance Events (OE-417) reports for identifying the major grid disturbance events affecting one or multiple nuclear power plants.

NYPP 96 – New York Power Pool Disturbance, dated October 30, 1996
USCA 03 – U.S.– Canada Blackout, dated August 14, 2003
WSCC 94 – WSCC System Disturbance, dated December 14, 1994
WSCC 96 – WSCC System Disturbance, dated August 10, 1996
WECC 11 – WECC California-Arizona Transmission/Distribution Interruption; Load Shed and Generation Inadequacy, dated September 8, 2011
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Note:
1. Information on effectiveness of ISO/RTO and implementation of competitive markets come from State of Market Reports of relevant ISO/RTOs, and SEC filings of the reactors involved. These information were cross-checked against data on Federal Energy Regulatory Commission website at: [http://www.eia.gov/electricity/policies/restructuring/restructure_elect.html](http://www.eia.gov/electricity/policies/restructuring/restructure_elect.html).
2. “Year in ISO/RTO” indicates the year of a reactor begin its operation within an ISO/RTO; “Year in Competitive Market” indicates the year of a reactor begin its operation within a competitive market. These two dates may be different due to: (1) In some ISO/RTOs, the energy markets were implemented in a later year; or (2) some independent power generators/electric utilities decided to join specific ISO/RTO in a later year.
Appendix E: Nuclear Power Plant Electrical Distribution One-line Diagram