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The Economics and Management of Nuclear Energy Industry: Supply Chain Reliability and Safety

Ekaterina Gnedenko
Boston University
gnedenko@bu.edu

Daniel Rice
University of Massachusetts Boston
daniel.rice@umb.edu

Abstract

Nuclear energy safety is a critical issue as the world increasingly turns to nuclear energy to meet our growing needs for power and decreasing dependence on fossil fuels. Major nuclear disasters like Chernobyl (1986) and Fukushima Daiichi (2001) demonstrate the need for improved controls of these systems. The nuclear power supply chain is a critical component of the highly interconnected nuclear energy system. This paper introduces industry best practices and how these relate to the nuclear energy industry safety and reliability.

Keywords: Nuclear energy, safety, supply chain, reliability, operations costs

I. Introduction

Reliability is considered to be a branch of theory of probability and statistics. However, there is an important role that social sciences (economics, geography) can play in the development of the field of reliability. For example, a simple cost-benefit analysis of a new (contemplated) nuclear plant location will likely indicate that such a plant should be built closer to major population centers, especially those that lack local fossil fuel resources. Another economic cost-reducing feature would be to build such a plant next to the water (river, lake) in order to have a readily available source of cooling. Introducing the notion of reliability in this economic analysis would, however, indicate that such a location can be very costly in case of emergency: a nuclear disaster in a densely-populated area may result in a loss of many lives, whereas the location near the water body my result in ever-lasting pollution and loss of valuable source of drinking and irrigation water.

Although very unlikely, such disasters do occur from time to time. To list a few: Fukushima Daiichi (Japan, 2011), Chernobyl (Ukraine, 1986), Three Mile Island (USA, 1979). Located in ecologically vulnerable areas, nuclear industry receives a harsh attitude from the public. For example, the Fessenheim nuclear power plant (France) is located in a potentially seismic region, causing public safety concerns in the center of Europe. As another example, the majority of nuclear power plants in Russia are located in the densely-populated European part of the country, often in the upper reaches of Volga and other rivers. The location next to major rivers may potentially cause much more damage because the significant portion of released radiation can be spread by the strong currents over larger areas (as it was the case during the Chernobyl disaster when the radioactive pollution in the Dnieper river has affected the water basins of the adjacent rivers).

In light of development of climate-friendly technologies, economists claim that the resurgence of nuclear power would be beneficial in terms of carbon-free electricity generation and job creation. The 2009 estimate by the US National Commission on Energy Policy was about 14,360 man-years per GW installed (Har, 2009). Another immediate benefit of nuclear power is that it is very cheap comparatively to the other means of base-load electricity generation1. However, the potential danger of the nuclear power generation may well exceed its economic benefits, both in monetary terms and the cost of lost human lives. Still, caused by concern about future energy supplies, the IAEA projects the growth of the world's nuclear power generating capacity by up to 88% (IAEA, 2012; Chudakov, 2015).

The important lessons are being learned, however. For example, after Fukushima accident, Ken Buesseler together with the researchers at Woods Hole Oceanographic Institution (USA) have formed the Center for Marine and Environmental Radioactivity to help share up-to-date information about radiation from human and natural sources (Pacchioli, 2013). To have a rigorous account of the vulnerability and reliability issues, a new branch in economics has been developed several decades ago: environmental and natural resource economic analysis. However, a strong link between these two science fields is still missing. The need for bridging reliability, economics and management was brought up during the recent event organized by the Gnedenko Forum and its associates.

In April 2016 Dr. Michael Yastrebenetsky, the Honored Scientist of Ukraine State Scientific and Technical Center for Nuclear and Radiation Safety, gave a talk organized by the Gnedenko Forum at a joint Boston Chapter American Statistical Association (BCASA), IEEE Reliability Society, INFORMS Boston Chapter, and Northeastern University INFORMS Student Chapter event at Northeastern University. Dr. Yastrebenetsky began the talk by commemorating 30 years since Chernobyl nuclear power plant disaster (26 April 1986). He introduced several important nuclear energy safety and reliability concepts about instrumentation and control (I&C) systems for Nuclear Power Plants (NPP). Also, Dr. Yastrebenetsky emphasized the series of mistakes that have led to the disaster which may have been avoided if sufficient I&C systems were in place and operated correctly.

This talk highlighted the importance of I&C in the nuclear energy industry and motivated the investigation of important issues related to the reliability of the nuclear energy supply chain. The nuclear supply chain is critical to the safe operation of the world's nuclear energy providers. Sometimes, However, nuclear suppliers can be unreliable and even unsafe such as the recent investigators findings of Areva SA and Le Creusot Forge, two major French nuclear suppliers. These companies have been cited by a team of international inspectors and the French Nuclear Safety Authority for extensive management weaknesses, safety failings, and a decades long cover-up of major manufacturing problems, underscoring the extent of problems in the supply chain of the world's crucial nuclear power components. This highlights the need for improved management and reliability of the worldwide nuclear supply chain and the nuclear industry. (Dalton, 2017).

Supply chains require close coordination of various components to reliably deliver value. A supply chain, as defined by the American Production and Inventory Control Society (APICS), is a system of organizations, people, technologies, activities, information and resources involved in moving materials, products and services all the way through the manufacturing process, from the original supplier of materials supplier to the end customer. (http://www.apics.org/) Integrated supply chains increase the confidence and trust between organizations, provide closer linkage and better communications, and boost the overall reliability of the supply chain. (Heizer, Render, & Munson, 2017). The supply chain in the nuclear industry is characterized by several very specific features. The extreme level of health risk is, of course, one of them. The other feature of the nuclear industry supply chain is its tendency to power plant consolidation under one ownership (in the market economies). The inherent reason for that is the need for some infrequent maintenance services such as refueling outages that need to be done once in 1.5 years and require a company to hire a contractor team for short periods of time.

[1] "The 104 nuclear reactors operating in the United States provide the lowest-cost baseload electricity, averaging 1.83 cents per kWh," (Har, 2009)

When instead a company manages several power plants, it may hire a single permanent team of highly skilled employees to service its various power plants throughout the year to make maintenance and refueling operations less costly and more reliable (Davis and Wolfram, 2012). In economics, this phenomenon is referred to as the economies of scale. Even with the recent creation of nuclear reactors of a smaller scale, this feature of nuclear supply chain will remain an important part of increasing worldwide competitiveness of nuclear power generation firms and therefore will persist in the long run.

Besides these recent positive economic trends to consolidate and deregulate nuclear industry, driven by market forces, there have been infrequent but highly significant failures that have led to disasters causing entire nations rethinking the prospects of the future of nuclear energy. These failures are perplexing as the nuclear energy industry is compelled to put reliability and safety first. This includes the requirement for an ultra reliable global sourcing of materials while meeting strict international (e.g., World Nuclear Association) and national (e.g., U.S. Nuclear Regulatory Commission, French Nuclear Safety Authority, Australian Radiation Protection and Nuclear Safety Agency, etc.) guidelines and regulations leading to an extremely complex supply chain. Nuclear supply chain reliability is often a major obstacle for developing new nuclear energy capabilities; however, by applying Integrated Supply Chain best practices and by measuring and monitoring supply chain operations using tools such as the Supply Chain Operations Reference (SCOR) model, these obstacles can be greatly reduced increasing the visibility and reliability of the nuclear supply chain.

II. Overview - Nuclear Energy Industry Supply Chains

Building new nuclear energy power plants requires a robust supply chain due to the large number of components and sub-components and depend on nuclear manufacturers to deliver the high-quality supplies needed to include concrete, pumps, electronics, wiring, instrumentation, piping, and specific equipment. A “cradle to grave” approach demands that each new build nuclear energy plant have multiple supply chain elements include pre-build, construction, operation, and decommissioning components. Moreover, reliability and safety considerations drive emerging measures for the global standardization for the raw material supply chain.

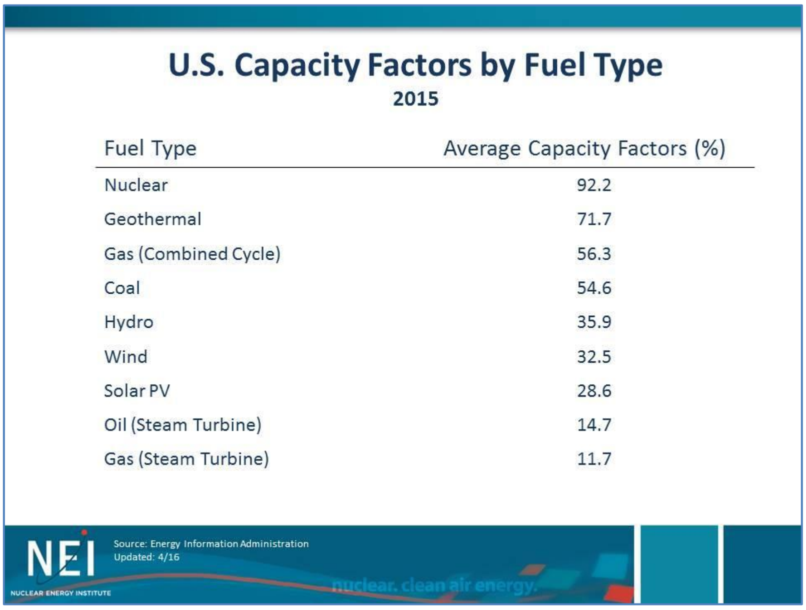
The use of uranium, required for creating plutonium needed for use as fuel in nuclear reactors, introduces intricacies into the supply chain for the operation of nuclear energy plants. Additionally, spent uranium and plutonium fuel needs to be recovered and recycled for reuse in the creation of fresh reactor fuel or, in the case that nuclear materials that are not recycled, they must be responsibly disposed. Safety and reliability of the supply chain is an important issue at every point in the nuclear energy life cycle.

Moreover, shipping and delivery of nuclear materials is under strict international standards and controls. International shipping standards are in place for the transport of these materials, including rules for packaging and marking the materials, and shipping practices must be closely monitored and enforced. Shipping containers are monitored throughout the shipping process (e.g., inspected and weighed) and these measures must comply with the International Atomic Energy Agency (IAEA) requirements as well as the European Atomic Energy Community.

III. Reliability of the Nuclear Energy Supply Chain

While many today take the reliability of energy supply for granted in the major nuclear nations, this has not always been the case in many parts of the world. In this highly interdependent and interconnected world, we are becoming increasingly more dependent on the availability of electrical power. Power to heat and cool our homes, store and prepare the food we eat, purify and deliver the water we drink, transport ourselves and the goods we come to depend on being delivered, power up the devices we use to work, communicate, and entertain ourselves. Nuclear power generates about 11 percent of the worldwide electrical power, with France generating 72.3 percent of its electrical power (Nuclear Energy Institute, https://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics).

Nuclear power also operates at an extremely high capacity (92.2 percent in the US nuclear power generation in 2015) in comparison to other fuel types. Operating at this level of capacity requires an extremely reliable system with minimal scheduled downtime for maintenance and repair without unexpected interruptions and this system must be continuously maintained if we are to expect the energy supply to be there to meet our needs.



U.S. Capacity Factors by Fuel Type
2015

Fuel Type	Average Capacity Factors (%)
Nuclear	92.2
Geothermal	71.7
Gas (Combined Cycle)	56.3
Coal	54.6
Hydro	35.9
Wind	32.5
Solar PV	28.6
Oil (Steam Turbine)	14.7
Gas (Steam Turbine)	11.7

Figure 1 - Average Energy Capacity Factors by Fuel (U.S. only)

The nuclear energy supply chains, like other similar supply chains including medical use nuclear materials, “have unique features and characteristics due to the products’ time sensitivity along with their hazardous nature” necessitating improved modeling to include “multicriteria decision-making and optimization to capture the operational and waste management costs as well as risk management.” (Nagurney, Yu, Masoumi, & Nagurney, 2013). Optimized supply chains are needed but difficult to achieve with the unique features and complexities of the nuclear energy chain of supplies (for various reasons).

Therefore, nuclear energy best practices include the “establishment and reinforcement of the supply chain” to ensure viability, reliability, and safety throughout the nuclear power plant (NPP) life cycle from construction to decommissioning. (van der Hoeven & Magwood, 2015) The NPP supply chain has a large impact on the economics of nuclear power because it has a very high contribution to NPP capital costs. For example, equipment supply has been estimated to “constitute around 48% of overnight costs (i.e. the cost of construction excluding financing costs).” (NEA and OECD, 2015) NPP viability is threatened when supply chain costs are high and the danger to the industry is clear as recently evidenced in the bankruptcy of Westinghouse Electric Co., the U.S. nuclear unit of Japan's Toshiba Corporation. There continue to be key questions raised about the future of four nuclear reactors under construction in Georgia and South Carolina, and specifically about at Plant Vogtle in Georgia. (Foody, 2017) Industry trends indicate a localizing NPP supply chains to control costs; however, this brings into focus safety and reliability issues that can never be compromised. (Beutier, 2013)

Therefore, one of the key recommendations in the Technology Roadmap for Nuclear Energy is that “safety culture needs to be enhanced and monitored across the nuclear sector” including the NPP supply chain. “Safety culture” can be defined as a “set of characteristics and attitudes in organizations and individuals that ensures that nuclear safety issues receive appropriate attention as an overriding priority over other considerations.” In this roadmap, the need for promoting a safety culture across organizations is emphasized through a case study of the Fukushima Daiichi NPP accident. (van der Hoeven & Magwood, 2015)

Controlling nuclear energy supply chain costs, safety, and reliability requires the application of industries best practices, as well as new approaches, to model, analyze, implement, and then measure supply chain performance. New analytical methods are needed to model and understand the intricacies of nuclear energy supply chain networks. Safety considerations must be a primary consideration in all decisions made about the supply chain. Finally, metrics for the measurement of nuclear supply chain performance must be in place to monitor and react to changes in the supply chain, marketplace, and regulatory environment. The next section will discuss industry best practices for measuring nuclear energy supply chain performance.

IV. Measuring Nuclear Energy Supply Chain Reliability

Industry best practices should be adopted for measuring supply chain performance first by customizing the methods for nuclear energy supply chain performance measurement and monitoring. The Supply Chain Operations Reference (SCOR) model is an excellent reference model that is widely used by firms to capture and compare metrics on how they compare to other firms and other industries, and SCOR provides a useful reference point to understand the nuclear energy supply chain performance. There are five primary components to the SCOR model as depicted in Figure 2: namely (1) Plan; (2) Source; (3) Make; (4) Deliver; and (5) Return with another component, Buy, indicated. These are addressed with a focus on the nuclear energy supply chain in the next paragraphs.

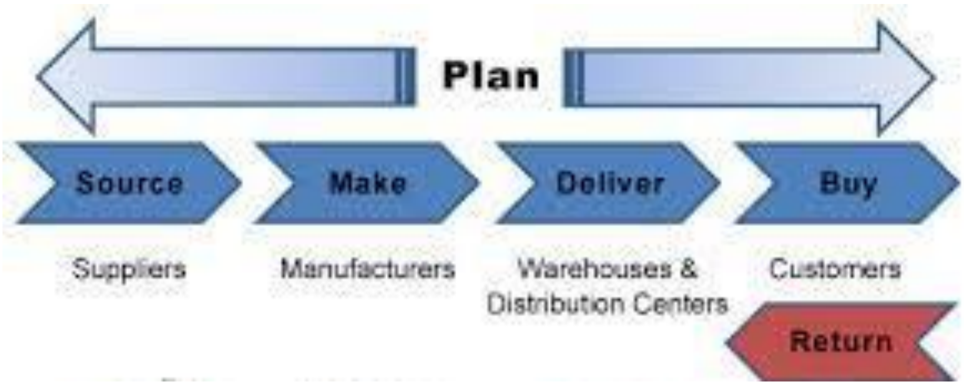


Figure 2 -A depiction of the Supply Chain Operations Reference (SCOR) Model

Plan - Planning activities

Planning for the supply and demand requirements of the nuclear power system is critical for reliability of the system, existing facilities should be able to reliably meet the demand and future construction of nuclear facilities to meet growing demand for power. The planning elements include the need to balance resources with requirements and enabling communication throughout the supply chain. Business rules should be established to measure the efficiency of the supply chain to make improvements in inventory, logistics, asset management, and compliance with federal regulations.

Source - Sourcing and purchasing activities

Nuclear power sourcing a procurement of necessary materials for the construction and continuous operation of nuclear power plants includes the sourcing of infrastructure and material acquisition, and describes how to manage inventory, supplier network, agreements, and performance including supplier payments and timing, verify, and transfer of receipts.

Make - Production activities

Production of nuclear power involves all power generation and plant operations activities that depend heavily on nuclear power supply chain reliability. Production activities includes managing the production network, equipment and facilities, and transportation.

Deliver. Distribution activities

Delivery includes order management, warehousing, and transportation of nuclear power supplies, plant, and equipment to include customers' power demands and invoicing for delivery of power. This step includes energy distribution to customer.

Return. Closed-loop supply chain activities.

Nuclear power plant supply chain reliably handles spent fuel and materials related to the safe disposal of spent fuel, containers, packaging, and other items. Handling of these involves the management of business rules, inventory handling, assets, transportation, and regulatory requirements.

The SCOR model enables understanding of the nuclear energy supply chain from "cradle to grave", that is from pre-construction planning through decommissioning of plants and everything in between such as ongoing disposal and recycling of nuclear materials that includes nuclear waste. NPPs have an operating life of approximately 25 years and the decommissioning may take more than twenty years. NPP decommissioning is an extremely complex process that includes the removal and disposal of radioactive materials and elimination of radioactive hazards. All materials must be removed and properly disposed. Frequently, the nuclear waste disposal involves crossing national borders and operating in different legal environments. The SCOR model can give NPPs a framework for managing all aspects of the nuclear energy supply chain and SCOR metrics, such as those shown provided by the Supply Chain Council shown in Figure 3, provide the measurements needed to understand nuclear energy supply chain performance. SCOR metrics should be tailored for the nuclear energy industry to provide solid supply chain measures in various dimensions including speed, flexibility, cost, and reliability.

Performance Attribute	Performance Attribute Definition	Level 1 Metric
Supply Chain Reliability	The performance of the supply chain in delivering: the correct product, to the correct place, at the correct time, in the correct condition and packaging, in the correct quantity, with the correct documentation, to the correct customer.	Perfect Order Fulfillment
Supply Chain Responsiveness	The speed at which a supply chain provides products to the customer.	Order Fulfillment Cycle Time
Supply Chain Flexibility	The agility of a supply chain in responding to marketplace changes to gain or maintain competitive advantage.	Upside Supply Chain Flexibility
		Upside Supply Chain Adaptability
		Downside Supply Chain Adaptability
Supply Chain Costs	The costs associated with operating the supply chain.	Supply Chain Management Cost
		Cost of Goods Sold
Supply Chain Asset Management	The effectiveness of an organization in managing assets to support demand satisfaction. This includes the management of all assets: fixed and working capital.	Cash-to-Cash Cycle Time
		Return on Supply Chain Fixed Assets
		Return on Working Capital

Figure 3 - SCOR Metrics (provided by the Supply Chain Council)

V. Discussion

This paper has introduced some of the challenges of managing the nuclear energy supply chain to account for the complexities introduced by regulatory and other factors as well as critical cost, reliability, and safety considerations. In summary, we recommend three challenges that can be addressed by the reliability community; namely:

1. Develop new supply chain models and methods to improve nuclear energy supply chain modeling by introducing multi-criteria decision modeling to include cost, reliability, and safety considerations
2. Create and maintain a "safety culture" in global and local nuclear energy supply chains.
3. Introduce new cost, reliability, and safety metrics into industry supply chain best practices such as the SCOR model providing new ways to measure, understand, and improve nuclear energy supply chain performance.

Dr. Yastrebenetsky brought up many ideas to consider about what could have been done differently that may have spared the nuclear power industry and world the Chernobyl and Fukushima disasters, including nuclear energy safety and reliability concepts that should have been well understood and under control. However, it appears that building safety and reliability into the nuclear energy processes is difficult at best. The nuclear energy supply chain is a substantial part of the world's nuclear energy processes, and a critical spot to rethink nuclear energy safety. By continuously building reliability and safety into the nuclear energy supply chain, perhaps we can help to avoid future disasters while ensuring the enduring viability of nuclear power as an alternative energy solution that will provide the citizens of the world with safe and dependable power they need to live their lives.

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