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A Frost & Sullivan White Paper

The Future of Nuclear Power Plant Operations

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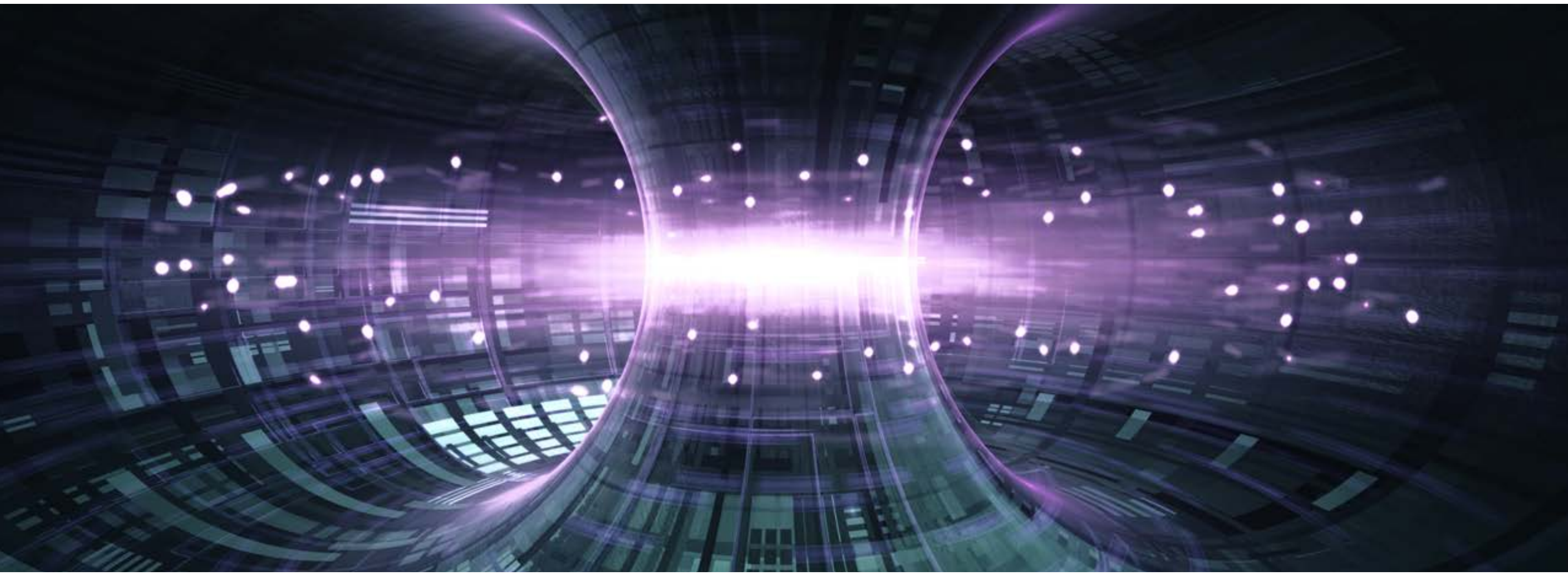
Table of Contents

The Power Sector in 2040

In 2040, the North American power sector landscape will have changed dramatically. Renewable energy will account for 60% of total electricity supply,[1] up from 22% in 2020. Deployment of energy storage systems will maximize the output of renewable energy assets when production is high and demand low. Grid stabilizing baseload power will come from nuclear power and natural gas, although operational cost pressures will have increased for natural gas as plants in the United States will likely require carbon-capture technology to minimize their carbon footprint.

The power sector will also experience major opportunities in 2040. The need to decarbonize transportation, industrial processes, and heating will result in a 70% increase in US electricity demand by 2040[2] as electric vehicles and electric heat pumps multiply in the market. This hike in demand will reflect a dramatic reversal of historic trends considering previous energy-efficiency measures had resulted in US electricity demand in 2020 matching 2006 levels. However, the widespread electrification of transportation, buildings, and certain industrial processes from 2021 on will boost electricity demand. In addition, electricity will be required to power electrolyzers that will produce the hydrogen used to decarbonize the hardest-to-reach parts of the industrial economy. This projected growth in electricity demand will turbocharge new power generation investment and provide a strong business case for the renewal of aging assets.

All of these shifts in the power sector create urgency to act. Delaying investment now could mean retiring assets early from the generation mix, just at a time when electricity demand is set to increase and new revenue opportunities become available. The growth opportunities, technologies, and solutions discussed in this paper will be pivotal to future power sector cost reduction and profitability—but implementation of the energy transition expected by the year 2040 will take time and strategic planning to ensure the maximum benefits.



Future Power Sector Opportunities

Electrification of transport, heating and industrial processes will be a game-changer in North America because of the resulting increase in power demand. For perspective, US electricity demand was 4,000TWhrs in 2020. This figure could nearly double in the next twenty years according to research from Princeton University. Princeton University's report that outlines 5 pathways to a Net-Zero America forecasts 2040 demand of 6,000TWhrs in a "less high electrification" scenario and close to 8,000TWhrs[3] in a "high electrification" scenario. Frost & Sullivan forecasts total electricity demand in North America (which includes not only the US, but Canada and Mexico) in 2040 will total 9,250TWhrs, up from 5,700TWhrs in 2020.[4]

The Need for Baseload

Although renewable energy will be pivotal in meeting future electricity demand—by 2040, 5,700TWh of electricity will come from renewable energy sources—renewables are only part of the story. Natural gas will continue to play an important role in meeting power demand, particularly in supporting grid flexibility, but its carbon emissions must be limited, either through capture, low annual operating hours, or by blending natural gas with hydrogen in the turbines—most likely a combination of all three. However, what will be vital to the mix is low-carbon baseload power, and nuclear is the prime technology for satisfying this need. In a report on the Projected Costs of Generating Electricity,[5] the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA) conclude that globally, a significant number of "shovel ready" projects carry limited project risks, stating: "Electricity produced from nuclear long-term operation (LTO) by lifetime extension is highly competitive and remains not only the least cost option for low-carbon generation—when compared to building new power plants—but for all power generation across the board."[6] As electricity demand increases, operators should look again at the assets they have and prioritize those that offer the best return on investment.

> "Although renewable energy will be pivotal in meeting future electricity demand—by 2040, 5,700TWh of electricity will come from renewable energy sources—renewables are only part of the story."

Changing Dynamics of Asset Ownership

The energy transition in North America poses a number of major challenges for utilities who are facing increased competition; higher environment, social, and governance (ESG) regulatory compliance pressures; and the need to decarbonize their asset base. This is driving two big trends—a quest for greater scale within the power sector and increased private equity ownership. Consolidation will mean larger utilities that span a broader number of states and bring together a diverse base of assets.

Yet a more varied base will enable utilities to balance their power generation portfolios and mitigate dependence on one fuel. It will mean fewer nuclear power plant operators in the future, but the majority of those that do exist will have a larger fleet to operate and maintain. This should encourage utilities to maximize the effectiveness of their operations through more coordinated service investment programs. New program models will increase the attractiveness of advanced service offerings that carry an initial first-of-a-kind cost, but ultimately deliver value when scaled up.

Increased private equity ownership will be another market game-changer, bringing both greater access to capital and razor focus on efficiency. The private equity model is built on creating a highly efficient and optimized asset that will increase in value. Private equity investors will then focus on creating super-lean, highly efficient plants that can operate for the long term. They will look to achieve this efficiency with the deployment of advanced operations and maintenance (O&M) solutions that virtualize plants as much as possible.

Growth of as-a-Service Business Models

As-a-service leasing-based business models are becoming a de facto form of ownership in industrial industries. For example, this business model is being rapidly adopted by the aerospace and defense sector, enabling airlines to keep high-capital-cost assets off their balance sheets. For the power sector, this is still a relatively new concept; but in 2040, these offerings will have matured significantly to become a substantial form of ownership, particularly in the nuclear sector where construction costs pose a challenge, yet longer-term returns are attractive. Under an as-a-service model, utility companies would remain accountable for the regulatory compliance of the plant, the trading of power, and the relationships with the customer supply base. The O&M of the plant, however, would be outsourced through an outcomes-based contractual relationship. It would fall to the O&M solution providers to take the lead in the design and execution of programs for the modernization of existing assets, as part of their contract. Plant operators would benefit from this relationship shift in that their incentives would now directly align with those of the service provider, driving greater efficiencies and encouraging co-creation initiatives.

Hydrogen Economy

Under the IEA's Sustainable Development Scenario,[7] global hydrogen demand is forecast to reach 287 million tonnes in 2050, more than quadruple the 71 million tonnes required in 2020. The North American market is likely to see comparable levels of growth. Currently, 99% of all hydrogen produced comes from unabated fossil fuels,[8] which is totally incompatible with the global decarbonization agenda. In 2040, hydrogen will need to be produced with electricity from low-carbon sources, termed clean hydrogen. Renewables will be a significant part of this story, but to meet the required capacity, the industry will struggle to scale up fast enough. The most effective way to increase the penetration of clean hydrogen within total hydrogen output is to utilize existing power assets. Operational nuclear power plants—with high availability and no intermittency—are the perfect generation technology to fill the impending electricity demand gap.

> **"Even the most extreme scenario combining high electrification and 100% renewables assumes the nuclear fleet achieves a minimum life of 60 years."**

Small Modular Reactors

According to an IEA study published in 2020,[9] 74 small modular reactor (SMR) projects are underway globally and at stages ranging from conceptual design to construction, based on 6 different technologies (excluding the 5 SMRs already in operation). By 2040, the winning technologies will be clear, and they will have been fully commercialized and deployed. The size of the reactors will vary depending on the power output need. Larger units (100MW – 300MW) will be in permanent locations; relatively easy to construct; and able to compete against solar, wind, and gas-fired power plants. The smallest units, known as micro-reactors, will be containerized on trucks and able to relocate on relatively short notice if needed, meaning they can be deployed to situations where the grid infrastructure needs additional support. This flexibility will create significant business opportunities for both new construction and new servicing business models targeted toward the needs of smaller nuclear units.

These future SMRs will complement existing nuclear fleets, not replace them. Whilst the business case for SMRs in a low-carbon electricity future will be strong, an even stronger business case is to keep investing in conventional nuclear plants where operational lifetimes of 100 years are now achievable. Princeton's Net-Zero America Project[10] has modelled 5 pathways to net-zero carbon emissions by 2050. Four of these scenarios assume that at least 50% of the current US nuclear fleet has a minimum 80-year operational life. Even the most extreme scenario combining high electrification and 100% renewables assumes the nuclear fleet achieves a minimum life of 60 years.

In the next section of this paper, focus shifts to some of the fundamental technological and operational developments that will be the mainstay of long-term operational strategies in 2040.

Operations Autonomy

Much of the automation technology the nuclear power industry has adopted today will be obsolete twenty years from now. This means that inaction is not a viable strategy for safeguarding the future performance of key assets. Considering the potential of future cognitive automation and advancements in quantum computing, three key shifts are expected to take place in the lead-up to end-to-end automation of nuclear power plant operations: system-of-system optimization, pervasive knowledge optimization, and quantum cybersecurity.

> "Ultimate automation will make our modern industry as primitive and outdated as the stone age man looks to us today."[11]
>
> —Albert Einstein

System-of-System Optimization

System-of-system optimization refers to the remote probabilistic risk assessment (PRA) of multiple interconnected plant systems, meaning more than one plant system will be remotely monitored in unison, such as a cooling water system and a steam turbine system in a nuclear power plant. At present, the most advanced PRA model that solution providers are seeking to implement is designed so that a single physical plant system and its PRA model (digital twin) are integrated to form a closed-loop channel. At this advanced level, any parameter changes made on the PRA model will reflect on the physical system's operational performance.

Although current industrial computing technology provides the high level of performance support that is required to achieve a closed-loop digital twin of a single system, it is not yet able to achieve a closed-loop mechanism for multiple systems. Yet in 2040, PRA models will be able to optimize multiple plant systems as a result of quantum computing technology. This technology will allow real-time data sourcing, analysis, and insights derivation by processing data at quantum speeds to facilitate the needed level of digital sophistication. In practice, this means plant operators will be able to optimize condenser and steam turbine performance at once, without any manual intervention, as optimization will take place in under a second of initial action. Moreover, physical plant systems will be supported by customized self-learning and self-optimizing nuclear-industry-specific AI algorithms that will be trained with numerical and symbolic AI inputs to adapt to and predict changes in asset performance.

For nuclear power plant operators, this means they can remotely optimize physical systems in real-time from the PRA model without getting physically closer to the assets, thus guaranteeing worker safety while decreasing overhead O&M costs. At present, most modern nuclear power plants that have been commissioned in the past twenty years have the basic technology foundation of digital sensors, asset performance management systems, and rudimentary PRA models installed to scale up for system-of-system optimization. However, to make this vision a reality, plant operators must continue to modernize their plants' data engineering and analytics while investing in cutting-edge digital technology through partnerships with proven technology solution providers in this space.

Pervasive Knowledge Optimization

AI is becoming pervasive across industries, evident in the increasing number of smart devices that can recognize an environment and react to it. These smart devices, from robots to industrial-grade cameras to automated guided vehicles, run on customized algorithms designed to achieve a specific outcome with minimal human intervention. In a nuclear plant, smart devices are expected to supplement existing critical and non-critical assets to increase overall operational efficiency.

In addition to this shift, as AI algorithms continue to evolve, increased opportunities will emerge for plant systems to be augmented by cognitive AI. These algorithms will be developed specifically for nuclear power plant assets and will have the potential to self-learn and adjust parameters on their own, to use plant energy efficiently, and to respond automatically and with foresight to events. In practice, for example, this would potentially mean that a plant's coolant system will automatically readjust its supply frequency if it observes abnormal variations from the reactor while safety systems are being alerted at the on-site monitoring center, all without any human intervention. Furthermore, the algorithm will take note of this instance and store the response measures that are produced so that it can predict this event if a similar pattern of anomaly takes place within the reactor on a future date. If cognitive AI is adopted across a plant, it would significantly decrease the degree of human intervention required, provide operators with cause-and-effect knowledge of plant events, and guarantee a faster return on investment.

At present, the adoption of AI-based systems is marginal in nuclear power plants as interest from operators has been geared more toward supplementing AI smart devices than toward augmenting plant systems with AI. On the technology end, solution providers have lacked the willingness to design and test such capabilities due to concerns about regulatory approval and safety. Nevertheless, as AI continues to evolve and becomes ubiquitous across the industry, opportunities for constructive collaboration between OEMs, plant operators, and regulatory bodies will make this vision a reality.

Quantum Cybersecurity

Securing digital plants of the future using next-generation cybersecurity will be essential. Quantum cybersecurity will tackle cyberattack risks by utilizing computing technology that can break algorithm encryptions. At present, there are two main ways with which computers encrypt algorithms. The first approach is symmetric encryption, which uses the same key to encrypt and decrypt a piece of data. This is utilized for decrypting bulk encryption tasks such as enciphering major databases. Second is asymmetric encryption, which uses one key to encrypt data and a different key to decrypt data. With quantum computing, symmetric and asymmetric encryption and decryption of algorithms will be completed within a matter of seconds using the principles of quantum mechanics. In practice, if a malicious entity is looking to gain access to a plant's communication system, quantum computing solutions will initiate automated response mechanisms to break the entity's algorithm and thwart it from gaining access. Likewise, operators will have the capability to enforce quantum encryption on algorithms, potentially making them unbreakable. This means critical and non-critical algorithms that run on AI-driven machines are safeguarded to the limit.

Pervasive knowledge optimization, system-of-system virtualization and optimization, and quantum cybersecurity have the potential to transition a present-day nuclear power plant into a semi or completely autonomous nuclear plant that can function securely with minimal human intervention. The benefits of this transition include the ability to drive superior asset optimization that streamlines O&M services to ultimately increase the profitability of nuclear power plants.

The Future of the Nuclear Workforce

Today's workforce in the industrial and energy markets is entering a universal era of technological advancement across all aspects of daily activity. From use in augmented reality/virtual reality (AR/VR) systems to simulation systems to machine vision systems, technological advancements are having a profound impact on factory floor and plant operations. Within nuclear power plants, the future will be no different. As the adoption of a multitude of automation capabilities, AI, robotics, and other technologies increases steadily within nuclear power plants, four notable shifts will take place that need to be capitalized on by nuclear plant operators to strengthen their workforce-supported operational efficiency.

Shift towards a Technology-driven Integrated Workforce Environment

Four key technologies will be integrated into the nuclear workforce environment by 2040: cognitive systems, systems with machine vision, collaborative robotics (cobots), and exoskeletons.

1. **Cognitive systems** are designed to self-learn and interact with the frontline workforce to collect knowledge and information about nuclear plant operations. These systems will be vital when recollection of event knowledge is required to resolve critical issues on plant floors, to train plant apprentices, and to converse with fellow plant workers wirelessly. For example, workers operating in the control room would be able to communicate wirelessly with fellow plant workers about a particular situation.
2. **Systems with machine vision** use digital sensors protected by industrial-grade cameras to capture the environment and analyze equipment faults with assistance from plant workers for informed decision-making. These systems could potentially be used in automated vehicles, crawling robots, or inventory recognition tools. The technology can be deployed to analyze coolant systems, steam generation systems, or inventory management systems to detect faults.
3. **Cobots** are collaborative robots that can relieve frontline workers from performing dangerous, repetitive, and tiresome tasks. These robots are not intended to replace humans, but to become an advanced safety mechanism. For example, cobots can work alongside workers to carry out quality inspection, welding, and material handling activities within the nuclear power plant.
4. **Exoskeletons**, general or customized, can be used by workers to carry out routine and ad-hoc long-duration tasks within a nuclear power plant with ease and efficiency, such as completing maintenance activities in low radiation areas.

Complementing this workforce environment shift will be the creation of on-site and centralized remote monitoring centers that will help with the delivery of solution services and monitoring from solution providers. The core objective of these providers will be to ensure that cross-disciplinary technology solutions are operating within the programmed parameters, heeding given instructions, and rectifying anomalies without comprising any aspect of safety. The potential benefits of monitoring centers include having holistic oversight of plant functions, an additional systems safety net, and potential to decrease O&M overhead costs.

Together, these changes will mean that the workforce environment of 2040 will be highly integrated with and enhanced by a multitude of technologies so that fewer workers will be required to accomplish the tasks of many, freeing them to use their talent on creative, strategic, and innovative initiatives, rather than tying them to completing rote or routine tasks.

Required Workforce Skill Sets of the Future

To operate and supervise functions that have been integrated with diverse emerging technologies, plants will require the addition of new roles and responsibilities.

The primary responsibilities of senior management will include, but are not limited to, the following:

- Chief Intelligence Officer: Overseeing technology and robotics functions within several divisions of the plant, including O&M and inventory management
- Director of Solutions Advancement: Liaising with solution providers to continuously upgrade technology systems and ensure operational security
- Human-Technology Resources Manager: Ensuring that the plant workforce is highly familiar with advanced technology systems

The primary responsibilities of operational personnel will include, but are not limited to, the following:

- Running plant AI, automation, and robotics systems within their respective plant divisions
- Liaising with plant AI managers, data scientists, on-the-ground workers, and OEMs to routinely discuss critical issues and pain points within systems
- Training new plant workers in the handling of emerging technology-driven systems while ensuring operational security
- Handling machine repairs and working with OEM personnel to minimize downtime

Digital Upskilling

To work and thrive in a successful AI-integrated nuclear industry environment, continuous digital upskilling of the frontline workforce will be of paramount importance. Rather than treating it as a training program, operators must emphasize this shift as a strategic future priority to meet the challenge posed by a skilled workforce shortage. Key methods of digital upskilling include use of advanced personalized cloud applications that tailor learning to individuals, customized virtual simulations that enable life-like in-situ training with no risk, peer-assisted learning that facilitates the transfer of knowledge between employees, and formalized digital upskilling centers of excellence within fleets.

Next-Gen Inventory Management

Inventory management is a major issue for plant operators. Concern about not being able to secure plant components in a timely manner is a critical pain point for nuclear power plant operators that results in their carrying excess inventory, often for a prolonged period. This means capital gets tied up in warehouses when it could be deployed to generate revenue in other aspects of the business. By 2040, much of this cost burden will be streamlined through a combination of new business models and autonomous inventory management technologies.

Reduce, Reuse, and Remanufacture

By 2040, nuclear power plant operators will completely embrace circularity within inventory management and plant operations. This model includes the deployment of a fully functional physical-plus-digital integrated channel to reduce new equipment purchases by reusing or remanufacturing existing equipment at a lower capital cost; the use of additive manufacturing using circular raw materials to design and manufacture new equipment; and the maximization of collaborations with OEMs or digital solution providers to augment digital solutions that will monitor and track equipment obsolescence. These practices will increase the resiliency of power plant operations and optimize inventory management costs without having any negative impact on workflow procedures.

Nuclear Amazon

At present, plant operators prioritize stocking multiple spares to sustain continuous machine runtime. Even though purchasing costs increase, not all replacement components are used, thus leading to a significant volume of idle inventory. While this approach guarantees equipment availability, the unused components in the operator's inventory are an unwanted cost burden. To alleviate this issue, future plant operators and OEMs will create an Amazon-like joint-inventory system that provides the real-time status of available spares in each plant. To this end, operators will have the flexibility to choose components from the shared online inventory of the OEM spare parts that are readily available for use to replace/refurbish their obsolete equipment ahead of a component failure, thus operating pro-actively while keeping costs lower by avoiding the stockpile of unused inventory.

Complementing the next-gen inventory management shifts, supply chains will transition from a reactive to a predictive model. For example, if an operator's valve system is low on spares, the operator would be notified 30 to 60 days ahead of the actual day the component is required about the availability of spares needed to restock their inventory. Once the operator accepts the restock alert, several what-if scenarios will be calculated to choose the best available spares from other plant operators and OEMs for the physical supply chain personnel to ship and restock. This way, procurement costs get streamlined and savings can be allocated to other critical plant functions.

In this future vision of inventory management, OEMs and plant operators are supported by technology solution providers who will play a major role in integrating the physical and digital aspects of supply chain operations.

Key Conclusions

The energy transition continues to gather momentum. Investment in low-carbon electricity generation—already an established mainstream trend at the start of the 2020s—will be the only viable option by 2040. The twin trends of electrification and the hydrogen economy will mean that significantly higher volumes of electricity will need to be produced in North America, reversing a decade and a half of largely stable demand.

Investment in new generation capacity will certainly be needed. But the most cost-effective way of meeting increased demand is through targeted investment in the existing low-carbon asset base. Investing in the long-term operation of nuclear power plants is the most cost-effective option, given that these assets can now have operational lifetimes of 80 years or more.

But all of these changes cannot be achieved overnight. Decision making in power generation is for the long-term, and its evolution requires a well-planned, targeted investment program. Nuclear service companies already have the solutions available to meet the industry's needs, but industry players must engage to move the process forward so that the cost efficiencies and performance benefits of technologically driven solutions can be realized now.

Access the **Long-Term Planning Maturity Diagnostic** for a first-level diagnosis of your organization's relative strengths and weaknesses regarding core aspects of long-term nuclear power plant planning maturity at https://westinghousenuclear.com/diagnostic.

Endnotes

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