INL/RPT-22-68671
Revision 0

Light Water Reactor Sustainability Program

Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation

August 2022

U.S. Department of Energy

Office of Nuclear Energy

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Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation

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August 2022

Prepared for the
U.S. Department of Energy
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Light Water Reactor Sustainability Program

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ABSTRACT

The purpose of this report is to refine and analyze five work reduction opportunities first presented in INL/EXT-21-64134, “Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts.” Researchers selected these five work reduction opportunities from the full Integrated Operations for Nuclear (ION) suite of initiatives. A selected group of utilities verified details of the work reduction opportunities and inputs to the ION Gen 1 model first published in the original report. Categories for verification included capital cost, technology requirements, and operational and maintenance savings among others. Researchers then modeled the data points and data ranges using probabilistic analysis to predict the likelihood of positive or negative net present value outcome.

Research results show the five work reduction opportunities (condition-based maintenance, digital I&C and digital control room, automated planning and scheduling, advanced training technology, and remote assistance and automated troubleshooting) have a high probability of a positive net present value outcome when analyzed individually. Digital I&C was analyzed to reflect the one-time upgrade that these systems would encounter in the remaining extended life of the nuclear plant intended to be licensed beyond sixty years. When the four work reduction opportunities (excluding digital I&C) are unified in one model there is a 99.9% chance that the net present value business case outcome will be positive.

The nuclear industry should interpret these results as encouraging. In line with the ION model, positive financial analysis supports the investment of capital dollars into existing nuclear power plants. Implementation of the five work reduction opportunities in this report is likely to result in substantive long-term savings for the owners and operators of domestic nuclear power plants.

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FIGURES

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ACRONYMS

AI/ML	artificial intelligence/machine learning
AOV	air-operated valve
AR	augmented reality
BCAM	business case analysis method
BPA	business process automation
BWR	boiling water reactor
CAISO	California Independent System Operator
CAPEX	Capital Expenditures
CBP	computer-based procedures
CM	corrective maintenance
CONE	cost of a new entrant
CTA	cognitive task analysis
CWA	cognitive work analysis
CWD	critical work domain
DAM	day-ahead market
DCS	distributed control system
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
FTE	full-time equivalent
HR	human resources
HSI	human-system interface
HSSL	Human System Simulation Laboratory
HTA	Hierarchical Task Analysis
HVAC	heating, ventilation, and air conditioning
I&C	instrumentation and control
ICAP	integrated operations capability analysis platform
IES	Integrated Energy Systems
IFE	Institute for Energy
ILT	instructor-led training
INL	Idaho National Laboratory
INPO	Institution of Nuclear Power Operations
IO	integrated operations

ION	integrated operations for nuclear
IRR	Internal Rate of Return
ISO-NE	Independent System Operator of New England
JIT	just-in-time
LCOE	levelized cost of energy
LMS	Learning Management System
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
M&D	monitoring and diagnostics
MCR	main control rooms
MISO	Midcontinent Independent System Operator
MIT	Massachusetts Institute of Technology
MOV	motor-operated valve
NEI	Nuclear Energy Institute
NLP	natural language processing
NOX	Nitrogen Oxides
NPP	nuclear power plant
NPV	net present value
NRC	Nuclear Regulatory Commission
NYISO	New York Independent System Operator
O&M	operations and maintenance
OCR	optical character recognition
OE	operating experience
OEM	original equipment manufacturer
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PM	preventative maintenance
PTPG	people, technology, process, governance
PWR	Pressurized Water Reactor
QA	quality assurance
QR	quick response
R&D	research and development
RFID	radio frequency identification
ROR	rate-of-return
RP	radiation protection
RPS	reactor protection systems

RTM	real-time market
SPP	Southwest Power Pool
SSC	systems, structures, and components
STPA	system theoretic process analysis
UCD	user-centered design
U.S.	United States
VR/AR	virtual reality/augmented reality
WACC	weighted average cost of capital
WM	work management
WRO	work reduction opportunity

1. INTRODUCTION AND PURPOSE

Commercial nuclear power in the United States (U.S.) has provided safe, low-cost, carbon-free baseload electricity for decades. Today, the industry is at the peak of its historical performance in terms of generation output, reliable operations, and demonstrated nuclear safety. However, it is no longer among the lowest-cost electric generation sources due to a variety of factors including subsidized renewables and natural gas. The original business model developed to address operational and safety requirements—which has been extremely successful—does not support the current economic climate as evidenced by nuclear plants permanently shutting down primarily due to economic considerations. The current business model that has served the operating nuclear fleet so well over its initial lifespan is now a drag on cost performance due to its reliance on a large, highly skilled, and aging labor force, the high level of maintenance required by analog control and safety systems, and the inability to obtain replacement parts for obsolete equipment. In contrast, digital technology and innovation are enabling dramatic efficiencies in production for other large industrial enterprises including manufacturing, mining, and transportation.

This report, along with previous reports describing the Integrated Operations for Nuclear (ION) business model, will document the verification of investment and cost savings for five key work reduction opportunities. This verification will consist of interviews and data collection from leading utilities that have or are in the process of implementing these key innovations. ION Generation I refers to work reduction opportunities (process, technology, people, and governance) that are at a sufficient technology maturity level and would support plant transformation within 3–5 years. As shown in Figure 1, most of the costs that need to be reduced to implement ION Gen 1 fall in the direct labor category which will be this study's focus. This report will confirm at a high level the work reduction opportunities under consideration, the cost to implement, cost to maintain, and operating cost reductions realized through implementation.

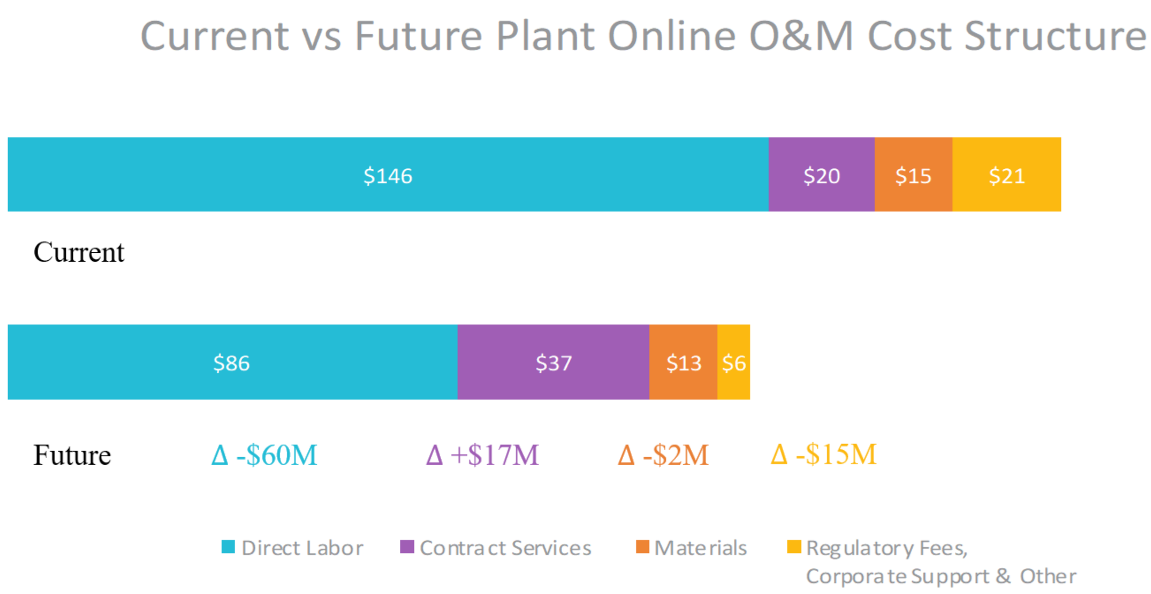

Figure 1. Current and future operations and maintenance (O&M) cost structure.

2. COMPETITIVE POSITION OF U.S. OPERATING NUCLEAR POWER PLANTS

2.1 Introduction

Market forces emanating from the economic environment surrounding the nuclear industry now impose a level of competitive pressure on electricity generators using nuclear power plants (NPP) that threaten the long-term viability of nuclear power (Buongiorno, Parsons, et al. 2018, Potomac 2021). These include, among others, market restructuring, increasing penetration of renewables into electricity markets, and public perception. Restructuring introduced a change in market incentives that drive outcomes today (Blumsack 2007, Joskow 2019). The intermittent nature of renewables creates challenging dispatch issues for baseload generation like nuclear (Joskow 2019, Bistline and Blanford 2020), and the cost declines in renewables have further created challenging economics for nuclear generators (IRENA 2021). In addition to these market forces, public opinion is another factor that has challenged advancement in the nuclear industry. Prior to 2011, a "Nuclear Renaissance" was underway but with the arrival of the earthquake that caused the Fukushima event, the cultural long memory of past nuclear events returned to compound the negative effect of the Fukushima event (Davis 2012, Bisconti 2018) on public opinion.

On the other hand, the competitive position of the nuclear industry is well-poised to meet and take on the challenging economics now present in the industry. Working in coordination, plant owners of nuclear generation are focused on "Delivering America's Nuclear Promise" (NEI 2020), which is a strategic plan aimed at, among other factors, improvements in cost efficiencies to support greater economic competitiveness. Such delivery is an important part of the nation's efforts to decarbonize the U.S. economy because of the nuclear value proposition of clean, firm, fixed energy. So, despite challenging economics, this is an exciting time for the nuclear industry which brings with it the need to better understand the industry's competitive position. To understand that position, this section begins with a discussion of U.S. electricity markets, focusing on the issues that arise from moving from regulated to deregulated markets and on the different types of electricity markets. Then the section shifts to market competition to characterize the industry in the context of market share, profitability, and market rules that bear on the competitive position nuclear generators face. With the context of markets and competition as a guiding framework, the section dives into the nuclear industry's competitive position to consider the industry value proposition, cost savings opportunities, and new market opportunities. Finally, the section wraps up with considerations of the economic environment surrounding the industry to suggest how factors such as 40-yr historic inflation, rising natural gas prices, and uncertain prospects for the cost of capital might affect economic outcomes in the industry.

2.2 Regulated Versus Deregulated Electricity Markets

A logical point of beginning surveying U.S. electricity markets is, to begin with, the differences in a regulated electricity market compared to a deregulated, or sometimes called re-structured, market. Regulated electricity markets emerged not long after electricity became a utility in cities in the United States. Samuel Insull, the first owner of Commonwealth Edison, recognized the inefficiency of individual utilities competing on services because it would require parallel sets of infrastructure, a problem economists refer to as natural monopolies. Insull observed the need to give up market competition in exchange for the certainty of customers, creating a regulatory compact (Blumsack 2020). Insull proposed that his firm be subjected to a state regulator to oversee the number of fees collected from customers in exchange for the right to be the sole purveyor of electric utilities in a prescribed region. Then, part of the regulatory compact, was for the regulator to impose upon utility owners an allowable, fair, rate-of-return (ROR) regulation. In exchange, the utility owner had the exclusive right to a service area. Thus, these early negotiations near the beginning of the 20th Century were the early beginnings of regulated electricity markets.

Beginning with the Shippingport Atomic Power Station in Pennsylvania, the first nuclear power plant for domestic electricity generation, through much of the U.S. nuclear fleet as it is known today, was built under a regulated market regime (Hansen, Dixon, et al. 2020). Because of the market incentives such a regime created, and because of factors in the economic environment during the build-up of the fleet, the business case for nuclear at the time justified taking on financial risk in exchange for stable market returns. For example, one can argue that Westinghouse and General Electric instituted turn-key contracts with utilities because of the expected market returns (Burness, Montgomery, et al. 1980, Hansen, Dixon, et al. 2020).

Early in ROR regulation, researchers observed that a regime with a guaranteed return and a captured market created perverse incentives that were incompatible with economic efficiency (Averch and Johnson 1962). For example, because of how the return is calculated and negotiated, utilities had the incentive to allow costs to overrun because doing so allowed increased profitability. So, the business case governing the deployment of many of U.S. nuclear reactors was one not based on market competition but negotiated agreements with a state regulator. After a series of price shocks in the energy markets of the 1970s, and a series of policy measures through the late 1990s, the start of the 21st Century in U.S. electricity markets entered with an emphasis on market competition. This wave of restructuring resulted in competitive electricity markets in two-thirds of the United States. The market regime wherein the U.S. nuclear fleet built up became vastly different, moving from economic outcomes based on ROR to outcomes based on market competition.

The maps in Figure 2 and Figure 3 show how U.S. electric power markets match up with the location of NPP in the country. There are seven deregulated, wholesale electricity markets: California Independent System Operator (CAISO), Electric Reliability Council of Texas (ERCOT), Southwest Power Pool (SPP), Midcontinent Independent System Operator (MISO), Pennsylvania-New Jersey-Maryland Interconnection (PJM), New York Independent System Operator (NYISO), and Independent System Operator of New England (ISO-NE). Three regions of the country (northwest, southwest, and southeast)– continue to operate regulated electricity markets.

Whereas economic outcomes in regulated markets result from negotiated, ROR regulation, market competition in deregulated markets means competition based on marginal cost, which is to say, incremental cost. In deregulated markets electricity generators submit bids to a market operator. These bids include capacity and the marginal cost to provide that capacity. Nuclear generators, which have very low marginal cost, submit bids to market operators as do power generators using solar, wind, coal, natural gas, and hydropower. Based on-demand, the market operator notifies generators of bid award, resulting in a schedule of that operators provide generation capacity at which times of the day.

One of the problems the deregulated market approach creates for generators of nuclear power is that the award based on the marginal cost covers only the variable costs of operation, not the fixed costs. This leads to what is referred to as the "missing money" problem. That is, under a deregulated market system generators of nuclear power do not receive sufficient revenue to cover fixed costs, hence the missing money. This places nuclear power at a competitive disadvantage because generators with low fixed costs and higher marginal costs can recover the majority share of their cost exposure. A solution to the missing money problem, and discussed in Section 2.3, is capacity markets.

Figure 2. U.S. electric power markets (FERC 2020).

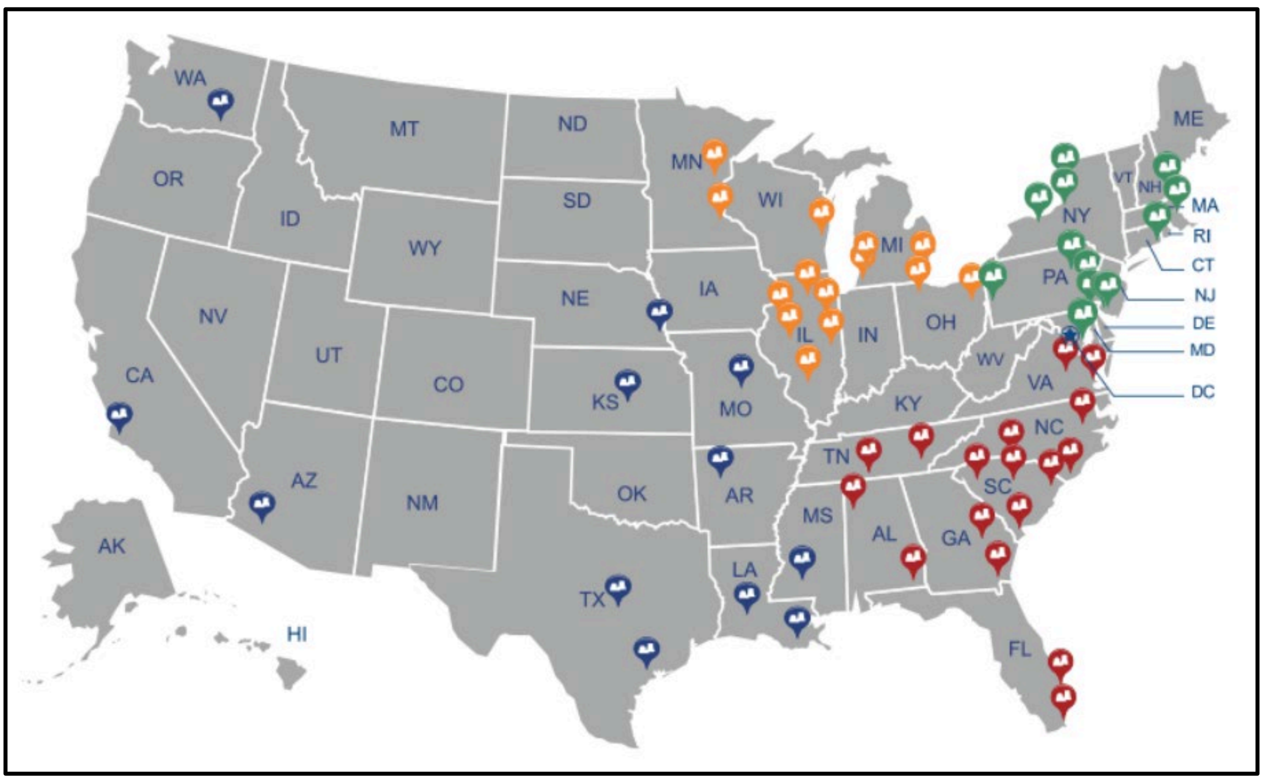

Figure 3. U.S. operating commercial nuclear power reactors (NRC 2022).

Figure 4 plots generation assets according to their marginal costs and fixed costs. In this plot, marginal costs are based on the variable operations and maintenance (O&M) costs plus fuel costs, and fixed costs are the capital expenditures to build the facilities. The plot is illustrative in showing the tradeoff across generation types. Those with the highest marginal costs, natural gas, also have the lowest fixed costs. Those with the lowest marginal costs, nuclear and renewable assets, have the higher fixed costs. And coal, based on the technology type, has both high fixed costs and midrange marginal costs.

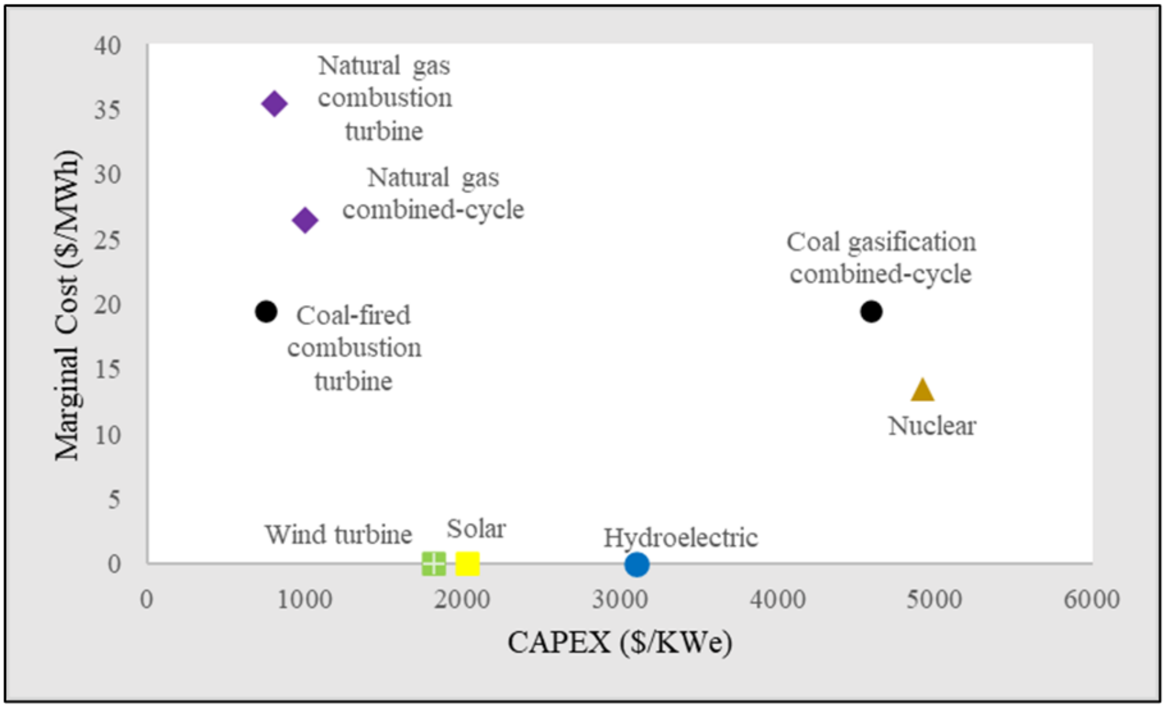

Figure 4. Generation assets by marginal cost and fixed cost (Dixon, Ganda, et al. 2017, Blumsack 2020, Lazard 2021).

2.3 Types of Deregulated Electricity Markets

In a regulated market regime, many of the functions of operating an electrical system are performed under the sole ownership structure of the vertically integrated, regulated utility. In economic terms, this is a natural monopoly. In a deregulated market, markets exist and function to balance the load and maintain reliability on the system that are based on electricity generators' bid to provide services. These markets are the electricity market (encompassing the day-ahead and real-time markets), the capacity market (solves the missing money problem and promotes system reliability), and ancillary services (balancing and regulation reserves). This section briefly discusses how these markets work and then provides data on market size and value in these markets to help clarify the economic environment where NPPs now operate.

The electricity market is often referred to as a "two-settlement system" because there are two market mechanisms used to settle the market. The Day-Ahead Market (DAM) is the market that clears 24 hours in advance of scheduled deliveries. That is, the market operator uses a prediction of demand, 24 hours out, to secure bids from generators to deliver capacity within the specified time frame. The bids the generators submit to the operator are based on the marginal cost of delivering a specified electricity capacity at a specified time. The operator aggregates the bids into a supply curve by the hour. This supply curve is also often called the "bid-stack."

The second settlement is called the Real-Time Market (RTM), and this market occurs at intervals that vary between 5 mins and 15 mins. The need for this settlement arises because of errors in predictions in the DAM. For example, if the forecast for the load (demand) turns out to be different than the prediction 24 hours ago, then the RTM can settle this. Or, if the prediction of capacity from 24 hours ago turns out to be different than what is realized, then the RTM can settle this error, too.

If an error exists, and it often does, in the forecast for the RTM then ancillary services is the mechanism whereby the grid operator can balance the load. Balancing reserves (spinning and non-spinning) is the capacity that a generator has that it can provide to the grid operator within some specified time interval (e.g., 5 min). Regulation reserves is the capacity the grid operator can call upon to maintain the grid operating at 60 Hz. To access these reserves the grid operator adjusts the generators' turbine to maintain the desired frequency.

Each of these services has a market associated with them, wherein electricity generators participate and can be compensated. Table 1 shows the size of these markets across the U.S. wholesale electricity markets.

Table 1. Data (2018) on financial settlements (Hytowitz, Ela, et al. 2020).

ISO/RTO	Energy ($B)	Capacity ($M)	Ancillary Services ($M)
CAISO	10.6	N/A	189
ERCOT	13.4	N/A	603.5
ISO-NE	6.0	3,600	130.9
MISO	21	431	70.5
NYISO	6.38	1,800	491
PJM	29.61	11,000	654
SPP	7.5	N/A	76

Figure 5 shows how each of the electricity markets varies in terms of pricing. The black line in each figure shows the annual average price across 24 hours. The gray shading shows the 95% confidence interval. The chart for CAISO in Figure 5 shows the characteristic "Duck Curve" (CAISO 2016). That is, the average price resembles the shape of a duck. In the middle of the day, non-dispatchable, renewable generation comes online, and a surplus of electricity exists and suppresses prices. Then, in the evening as the sun sets and winds calm down, the price of electricity spikes (the neck of the duck). Then the pattern repeats. The confidence interval for CAISO runs off the graph (prices on the vertical axis run from $0/MWh to $100/MWh) because of the large volatility in the market. ERCOT, although it does not have the same level of volatility in prices, exhibits a similar pattern with an evening ramp. The electricity markets in the Midwest to the eastern part of the U.S. shows much less volatility.

These figures (within Figure 5) are illustrative of the competitive pressure that nuclear generators face in each of these markets, particularly with respect to dispatchable capacity.

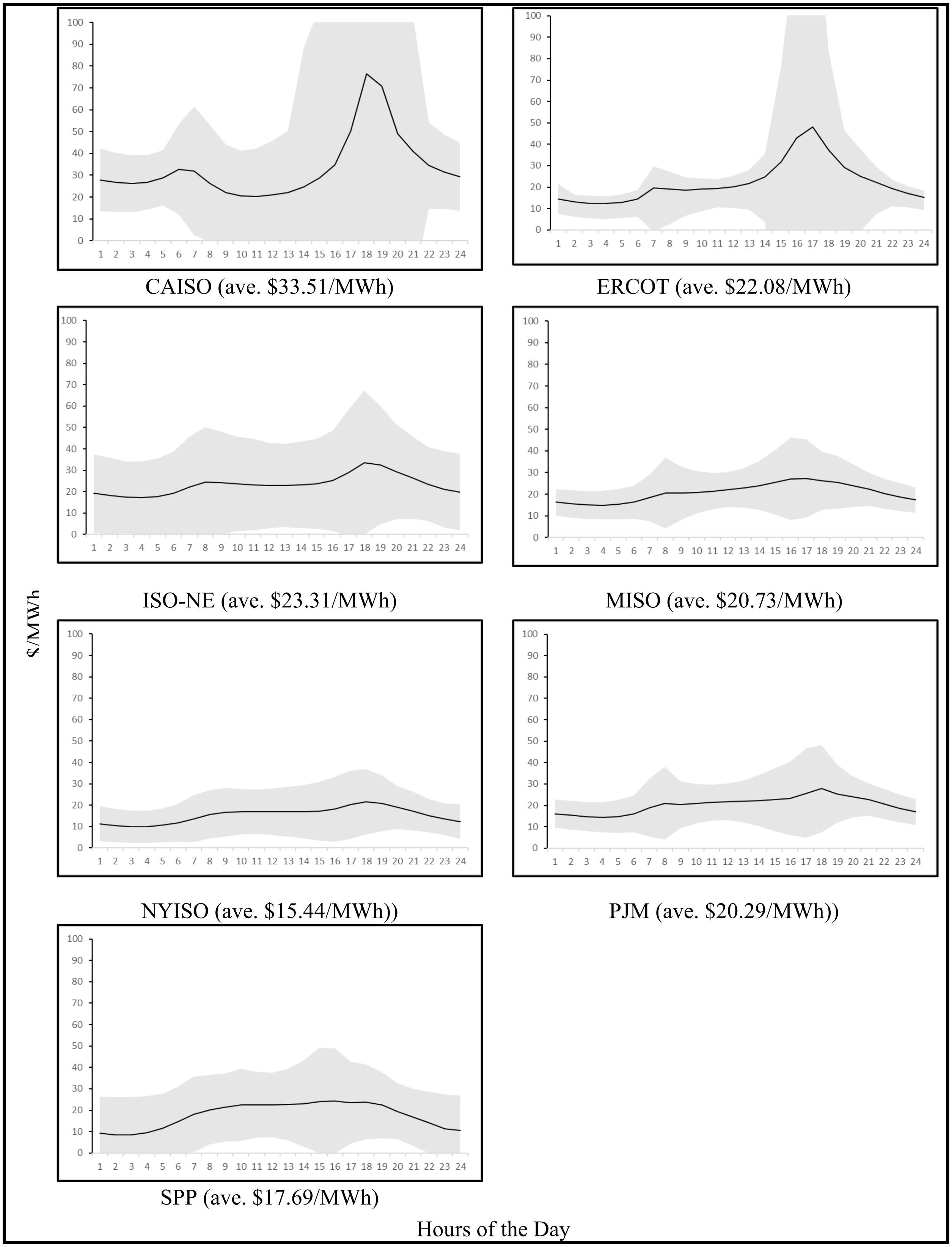

Figure 5. Annual average DAM (2020) prices in U.S. electricity markets (author calculations).

The capacity market is a futures market where the settlements in that market are used to support system reliability. Depending on the specific market, capacity is traded for commitments ranging from 3 months to 3 years. Instead of bids based on marginal cost, these bids are based on what is called the "CONE" or the cost of a new entrant. The CONE reflects the fixed costs of bringing a new generation online. Settlements in this market become a way for generators to recover the revenue needed to solve the missing money problem, noted above, that arises from marginal cost-based bids in the electricity markets.

Table 2 and Table 3 summarize the prices in the ancillary services market and in the capacity market across U.S. wholesale electricity markets.

Table 2. Ancillary Services summary (average $/MW-hour) (Hansen and Rabiti 2021).

ISO/RTO	Spinning	Non-Spinning	Regulation
CAISO	3.61 10-minute response Min run time 2 hours	1.02	7.57 Immediate Response
ERCO	12.12 Response within minutes Min run time 4 hours 2 MW/min, up 3 MW/min, down	4.50 Response within 30 minutes Min run time 1 hour	8.5 Immediate Response 3 MW/min, up 4 MW/min down
ISO-NE	4.66 10-mintue response 1 MW/min up/down	26.63 10 to 30 minute response	18.38 Immediate Response
MISO	1.74 10-minute response	0.23 10-minute response	8.81 Immediate response, full response within 5 minutes
NYISO	3.61 10-minute response	3.08 10 to 30-minute response	6.07 Immediate response, full response within 5 minutes
PJM	3.17 10-minute response	8.11 10-minute response	13.47 Immediate response, 0.1 MW min response
SPP	5.36 10-minute response	0.73 10-minute response	7.28 Immediate

Table 3. Capacity market summary (Hansen and Rabiti 2021).

ISO/RTO	Length of contracting period	Average Capacity Prices and CONE[1/]
CAISO	1-year forward contract	Average Capacity Price: \$100/MW-hour CONE: \$208/MW-day
ISO-NE	3-year forward contract	Average Capacity Price: \$9.63/MW-hour CONE: \$309.59/MW-day
MISO	3-year forward contract	Average Capacity Price: \$1.27/MW-hour CONE: \$257.53/MW-day
NYISO	30-day delivery contract	Average Capacity Price: \$5.04/MW-hour Net CONE: \$366.94/MW-day
PJM	3-year forward contract	Average Capacity Price: \$7.17/MW-hour Net CONE: \$285.5/MW-day
SPP	Incrementally as needed	Average Scarcity Price: \$439/MW-hour[2/] Average Make-whole Payment: \$0.22/MW-hour (DAM), \$18.94/MW-hour (RTM)[2/] CONE: \$234.55/MW-day

2.4 Market Competition

Given the characteristics of the deregulated markets where nuclear generators compete, the next factor leading to the competitive position of nuclear is that of market competition. This section looks at market competition from three perspectives: the fraction of the market that nuclear energy now retains, nuclear costs as they compare to alternative electricity generator technologies, and the role of energy policy on market competition.

Figure 6 shows the distribution of fuel mix in each of the deregulated electricity markets as of the year 2020. In some cases (CAISO and ERCOT) solar is listed in the other category. CAISO and ERCOT have 16% and 6% solar, respectively. For the other ISOs, the share of energy from solar is negligible. It is noteworthy to see which generation types dominate in each region. For example, the largest share of generation from wind is in the SPP at about 54%. The largest generation from coal is in MISO at 42%. Nuclear is the largest generation capacity in the NYISO at 29%. NYISO also has the largest hydro generation at 22%. The largest share of gas generation is in ISO-NE, but gas is the largest generation source in PJM at 47%.

Table 4 shows how total generating costs break down across different dimensions of the U.S. nuclear fleet. The data show that fuel costs are unchanged across plant size but operations of single-unit versus multi-unit plants do induce a difference in fuel costs. Plants in wholesale, deregulated markets have lower fuel costs than those in regulated markets. And boiling water reactors (BWR) tend to have lower fuel costs than PWRs. Single-unit versus multi-unit and wholesale versus regulated drive the largest cost differentials for capital costs. The single-unit versus multi-unit drives a large cost differential for operating costs, but across other dimensions of comparison, operating costs are similar. NEI reports that, over the last 20 years, total generating costs have decreased by nearly 35%, driven primarily by gains in cost efficiency in capital costs, then followed by nearly equal improvements in cost efficiency in fuel and operating costs (NEI 2021).

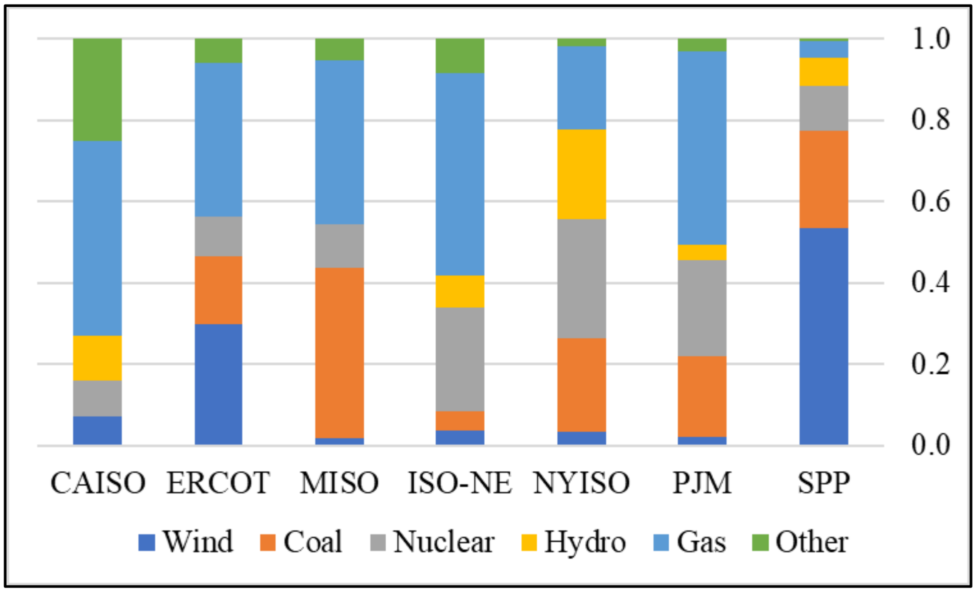

Figure 6. Generation fuel mix as of year 2020 (author calculations).

Table 4. 2020 cost summary ($/MWh)(NEI 2021).

Category	Sites	Fuel	Capital	Operating	Total Generating
All U.S.	56	5.76	5.34	18.27	29.37
Single-Unit Size	20	5.76	7.55	26.33	39.64
Multi-Unit Size	36	5.76	4.84	16.43	27.03
Single-Unit Operator	12	5.89	5.80	20.10	31.78
Multi-Unit Operator	44	5.72	5.21	17.75	28.68
Wholesale	26	5.27	3.63	18.56	27.46
Regulated	30	6.18	6.81	18.02	31.02
BWR	20	5.67	5.29	19.00	29.96
PWR	37	5.80	5.37	17.90	29.07

Figure 7 shows how capital expenditures have changed in the last decade. While costs related to regulatory expenditures and other enhancements have decreased, costs for sustaining the fleet have steadily increased. Figure 8 shows operating costs have changed over the same time frame. The primary categories responsible for cost reductions over the period are support services and operations.

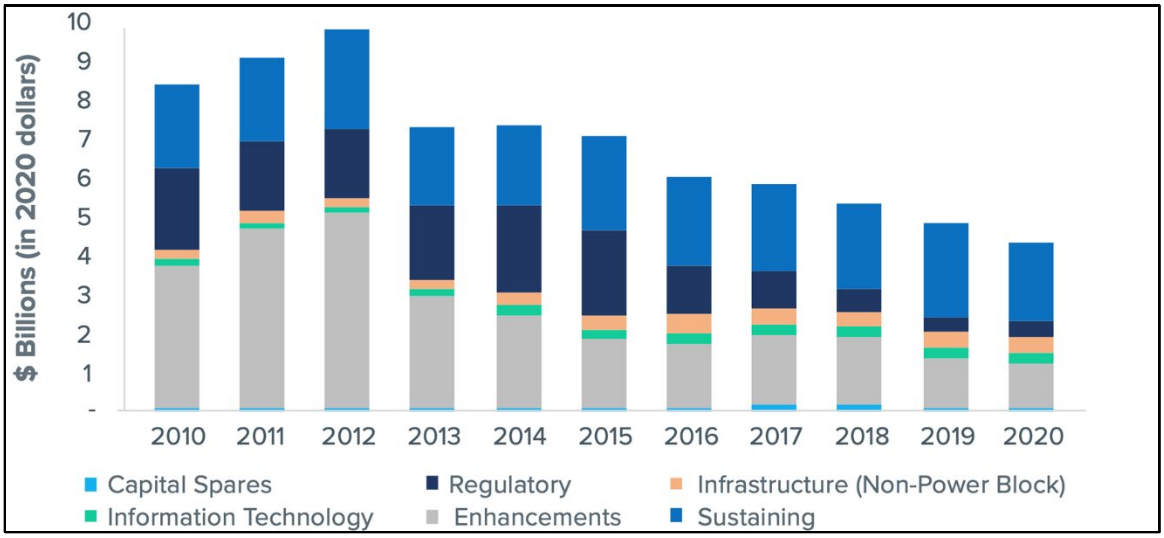

Figure 7. Nuclear industry capital expenditures, 2010 to 2020 (2020 dollars) (NEI 2021).

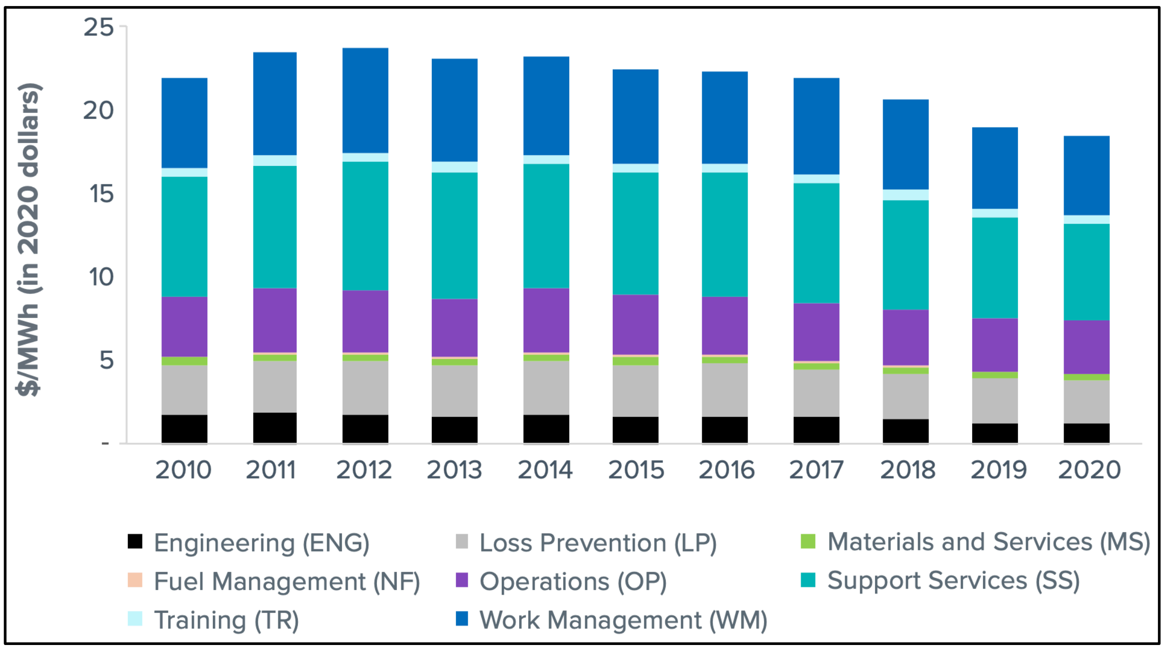

Figure 8. Nuclear industry operations cost, 2010 - 2020 (2020 dollars) (NEI 2021).

The evolution of capital and O&M costs combined with a profile of recent generating costs (Table 4) are particularly relevant in terms of how nuclear technologies compete in the market. As NEI (2021) points out, despite significant gains in efficiency, there are still NPP that shut down ahead of scheduled, planned retirements. NEI notes that most of these early retirements were due to increasing market pressure that came from very low natural gas prices, cost reductions in renewable technologies, and policies that have a distorting effect on market outcomes. Taking the average U.S. generating cost, in Table 4 of about $30/MWh, then comparing that data to the plots in Figure 4, one can see the difficult economic position for nuclear in deregulated markets. The following visuals are informative on how natural gas prices, costs of renewables, and policy have factored into this reality.

Figure 9 shows a time series of natural gas prices over the last 25 years. Natural gas prices are relevant to the competitive position of nuclear generators because natural gas generators are the marginal generator in de-regulated markets. That means, because of the higher marginal cost to produce electricity from gas, natural gas bids are the bids that clear electricity markets. This leads to a tight coupling of wholesale electricity prices and natural gas prices. A recent study found that across five regions and 33 electricity markets in the United States, the average correlation between natural gas prices and electricity prices is 0.88 (Lukes, 2021). A value of 0 means no correlation and 1 means perfect correlation. So, a value of 0.88 implies a tight correlation.

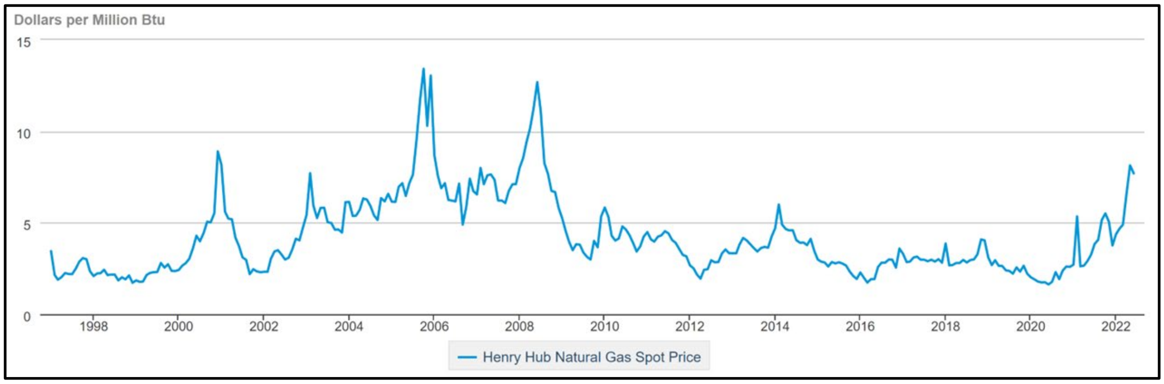

Figure 9. Henry Hub Natural Gas Spot Price (U.S. EIA 2022).

The consultancy, Lazard, performs economic analyses on energy technologies for comparative purposes. In a recent report, Lazard (2021) compares the cost components of energy technology. Figure 10 shows this comparison; levelized cost of electricity (LCOE), and life-cycle cost of electricity.[a] The figure shows total generating costs for nuclear (15 + 4 + 9) that are consistent with the data in Table 4. The figure shows that total operating costs for solar technologies range from \$4/MWh to \$13/MWh. For geothermal technology, operating costs are about \$10/MWh and for wind are about \$5/MWh. Operating costs for gas peaking plants are about \$44/MWh while combined cycle gas operating costs are about \$26/MWh. For coal generators, operating costs are about \$19/MWh. Lazard data later point out that cost reductions for these technologies since 2009 are about 90% for solar and 72% for wind. Over the same time frame, and noted earlier, cost reductions for nuclear are about 35%.

Further leveraging the Lazard study, Figure 11 shows how the combined effect of the Production Tax Credit (U.S. DOE 2022) and the investment tax credit (U.S. CRS 2021) impact the costs at which the subsidized technologies can compete. The data show that tax credits for solar technologies reduce costs by about 10% whereas, for wind, the credits reduce costs by a range of 20% to 65%.

Notwithstanding the competitive pressures stemming from policy and market prices and recognizing the difficult position nuclear generators find themselves in, state and federal policy has been and is in a process to support nuclear generators. Currently, thirty-six states have some type of policy instrument in place that either directly supports or otherwise helps nuclear generators to be more competitive in the marketplace (NEI, 2022). Also, the U.S. Department of Energy has implemented, under direction from the U.S. Congress the Civil Nuclear Credit Program (U.S. DOE, 2022a), which aims to offset differentials in revenue and costs for nuclear generators.

a. Some have argued that LCOE is not a good basis of comparison because of how the metric is often computed, particularly that it does not reflect system costs that a technology imposes on the grid. Loewen, J. (2019). "LCOE is an undiscounted metric that distorts comparative analyses of energy costs." The Electricity Journal **32**(6): 40-42..

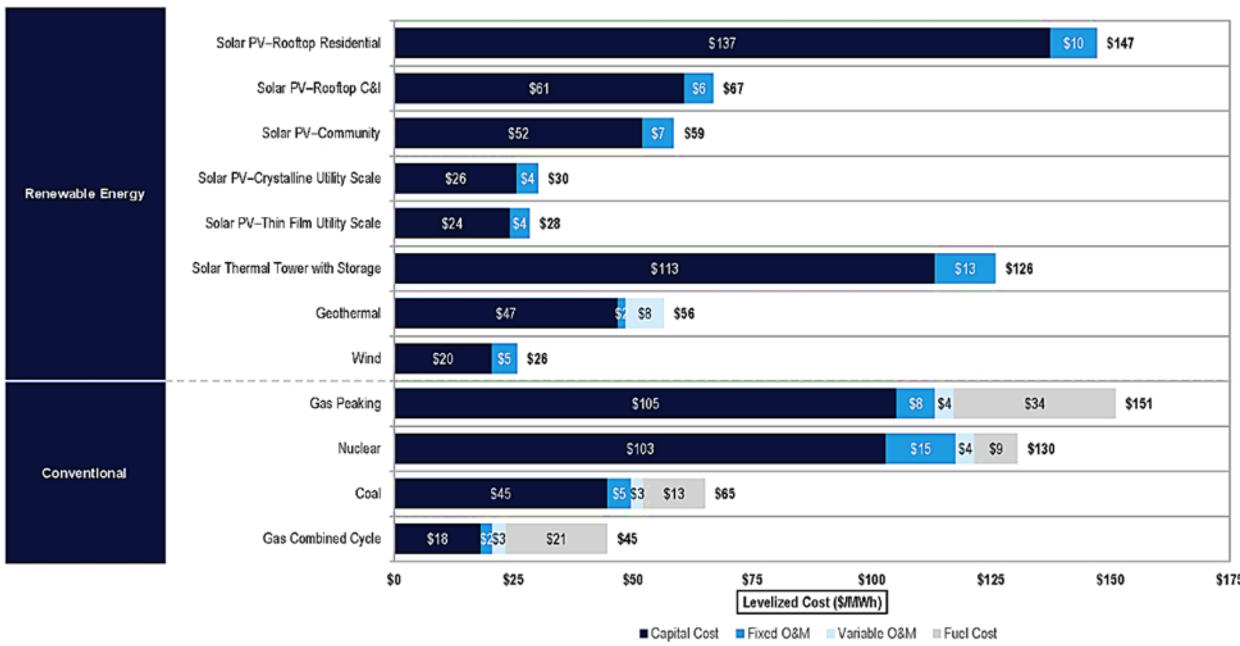

Figure 10. Levelized cost of energy components (Lazard 2021).

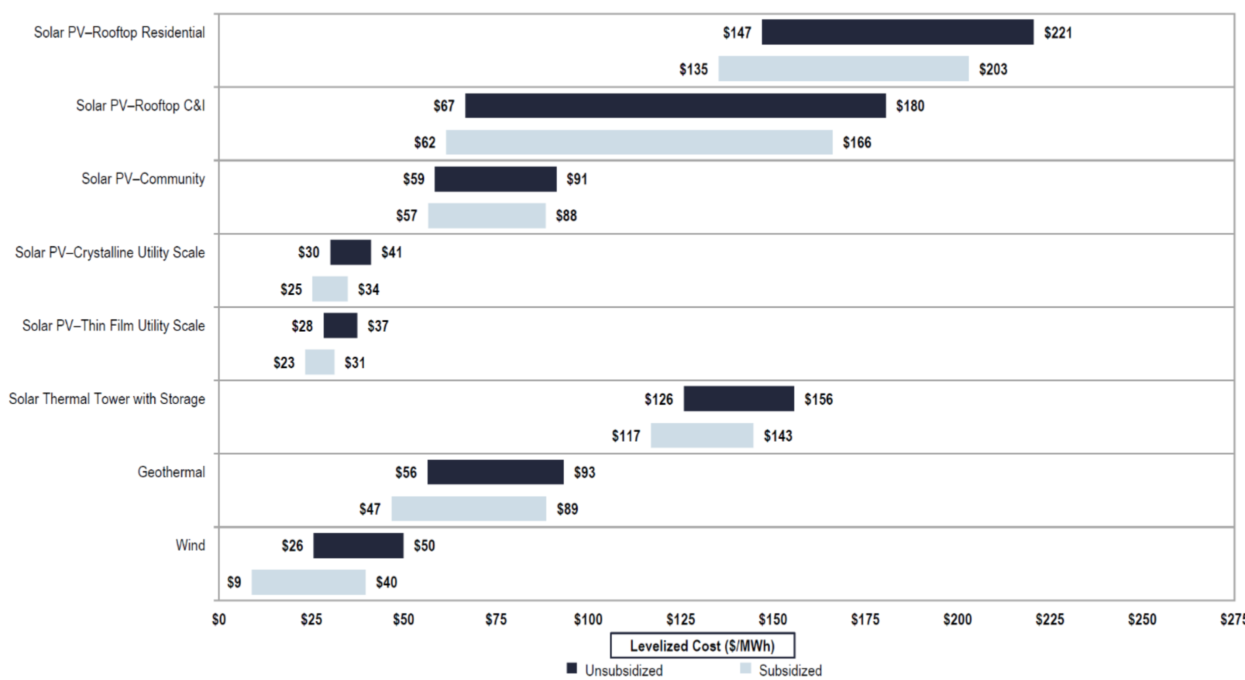

Figure 11. Impact of investment tax credit and production tax credit on renewable generation costs (Lazard 2021).

2.5 Competitive Position

Understanding the competitive position of nuclear generators in the U.S. is aided by the overview of market structure (regulated versus deregulated), electricity markets (different types), and market competition. Given these market forces and the institutions that govern them, the competitive position looks outward to see opportunities for nuclear generators.

Nuclear energy provides clean, firm-fixed power, which means that for decarbonizing the U.S. economy to be successful, nuclear generators must be an active part of it. The presence of nuclear on the U.S. electricity grid avoids up to 506 million metric tons of CO2, it prevents 240 thousand short tons of NOX, and 265 thousand short tons of SO2 (NEI 2020). Others describe how nuclear technology can play an increasing role in the effort to decarbonize the U.S. economy (CleanAir 2018). And yet, nuclear technology can play a role in decarbonizing beyond the electricity sector. Integrated Energy Systems (IES) can facilitate the competitive position of nuclear generators in decarbonizing (Suman 2018).

Ongoing research is underway to investigate how nuclear generators, configured in an IES, can find additional market opportunities through coproducts to electricity. These companion technologies include water purification, hydrogen production, chemical manufacturing, thermal energy storage, electrical energy storage, and heat utilization, to suggest a few (Bragg-Sitton et al., 2020; Bragg-Sitton et al., 2020; NEA, 2022). Growing demand for these coproduct applications increases the competitive position for nuclear generators because of expanding market opportunity.

Current economic conditions factor into the competitive position of nuclear generators. Inflation in the U.S., and globally, is at a 40-year high. This will impact financing costs and access to capital. Sensitivity data in Lazard (2021) can be used to infer what this impact may look like. The Lazard study evaluates LCOE at different discounting rates. Since discounting reflects opportunity cost (i.e., interest rates), these scenarios approximate the impact of inflation on capital costs. These data show that for a 1% change in the weighted average cost of capital, the LCOE increases by 8.4%. This relationship suggests that inflation will drive up the investment costs that nuclear generators face.

As noted earlier, electricity prices and natural gas prices are tightly correlated. Market prices for natural gas will likely continue to impact the competitive position of nuclear generators going forward.

Finally, these factors as outlined here, underscore the importance for nuclear generators to find additional cost savings such as those evaluated in this report.

3. ION BACKGROUND

3.1 Integrated Operations Concept and Application to Nuclear Power

3.1.1 Top-Down Business-Driven Analysis

A key element to ION is its top-down business-driven analysis. ION begins with determining a market-based price point for generating electricity to drive the maximum total O&M budget of an operating plant. The total O&M budget is then iteratively allocated across the organization.

3.1.2 Capability Analysis

Capability analysis refers to the structured development of key resources, or core functions needed to achieve the objectives set across the enterprise after the top-down business-driven analysis. These sections describe the method followed for capability analysis, which follows a generalized way of identifying capabilities and then decomposing these capabilities into specific work functions and their associated work reduction opportunities needed to achieve the business objectives.

Figure 12 illustrates the conceptual process of identifying capabilities, then decomposing these capabilities into sub-capabilities and work functions. The work functions become a basis for identifying work reduction opportunities and enablers that can be used to support the business objectives defined from the top-down business-driven analysis.

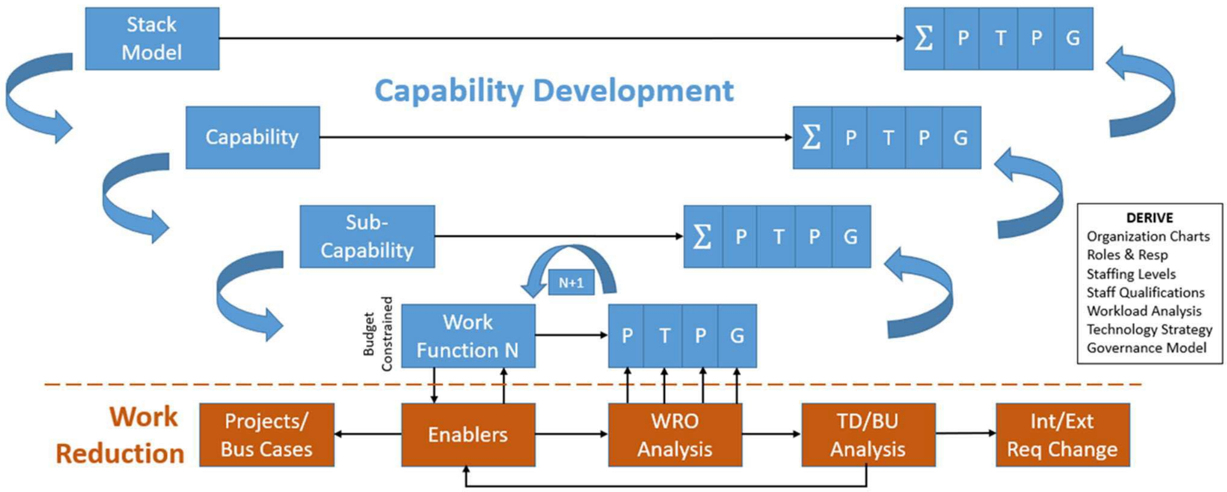

Figure 12. Capability Development

For example, a core capability of a nuclear power plant would entail maintaining the plant. Within this capability, there may be several sub-capabilities with one being external support. Within any one sub-capability, there may be one or more work functions. External support contains a work function defined as work management and execution. At this level, work reduction opportunities can be identified and addressed, such as through innovations like virtual technical support.

In following the Integrated Operations (IO) philosophy, the term "capability" refers to the ability to perform a particular task or activity [ION 2020]. Capabilities comprise interdependent resources pertaining to people, processes, technology, and governance within an organization (See Figure 13).

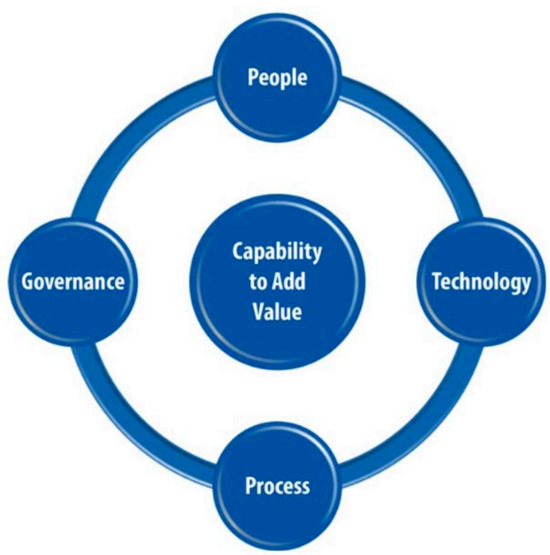

Figure 13. People, processes, technology, and governance—key elements of capability analysis.

Capabilities must add value to an organization by enabling the organization to perform its function and necessary tasks. Figure 14 shows the results of the identified capabilities from Xcel Energy within a common context of nuclear power generation (in orange): Operate, Maintain, and Support.

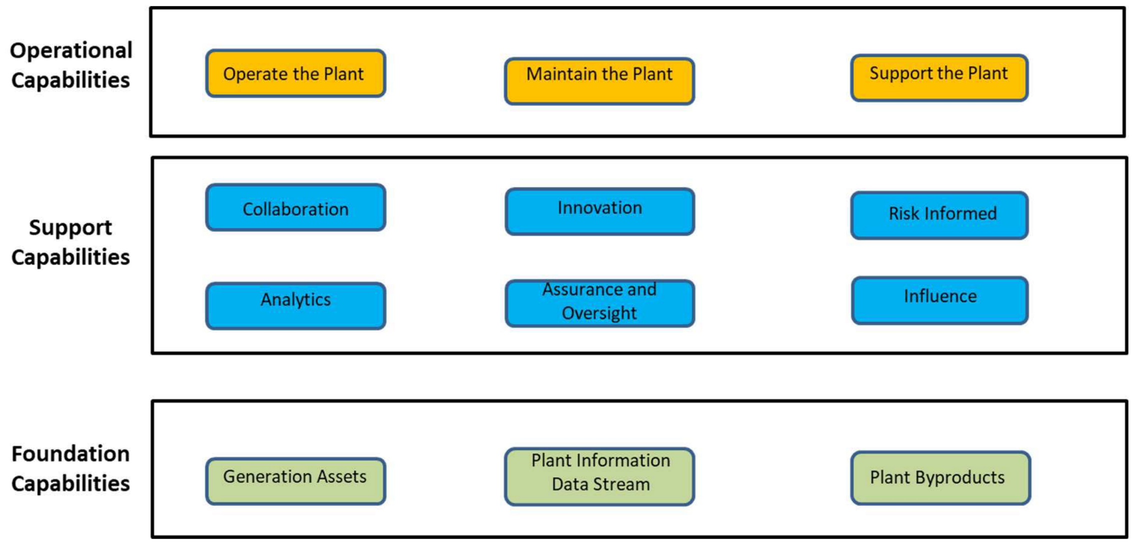

Figure 14. Capabilities identified by Xcel Energy.

Within these operational capabilities, a second level (in blue) identifies capabilities used across the enterprise. The support capabilities link to operational capabilities above and are inter-linked within each support capability. In a simplified example, innovation as a support capability may support all operational capabilities and be inter-linked to other support capabilities like collaboration, analytics, assurance, etc. The purpose of support capabilities is to fill a need for the organization (i.e., as shown in the operational capabilities identified above).

The final grouping of capabilities (in green) is defined as foundation capabilities. These represent the tangible assets of the physical plant. These assets are analogous to the systems, structures, and components (SSCs) of the nuclear power plant at which the operational capabilities function. Put differently, operational capabilities like 'operate the plant' function on the use of these assets (foundation capabilities) like plant systems (generation assets) or sensors (plant information) to support the business objectives. Capabilities are then decomposed into sub-capabilities and work functions. The process of sub-layering is done to make ION-based transformation more manageable. A tool developed to enable capability analysis is the Integrated Operations Capability Analysis Platform (ICAP) described in (Kovesdi 2020), "Report on the Use and Function of the Integrated Operations Capability Analysis Platform and the LWRS Innovation Portal."

The ICAP is a software tool used to perform capability analysis to identify work reduction opportunities and eliminate duplication of work activities. The ICAP was developed to interface with other industry-known tools such as the Electric Power Research Institute (EPRI) business case analysis method (BCAM), which can develop a detailed business case for work reduction opportunities identified by the ICAP. Refer to (Kovesdi 2020) for detailed information about ICAP, its capabilities, and uses.

3.1.3 Former Projects with ION

2020: Application of ION for Xcel Energy XE1 Initiative

Xcel Energy announced in 2018 its goal of achieving 100% carbon-free power generation by 2050. To achieve this goal, Xcel Energy developed a new nuclear business model strategy with the mission of remaining a cost-effective source of carbon-free energy in the future. The foundation of the new business model was informed by related industries faced with similar economic challenges, such as the oil fields in the North Sea.

This approach would fundamentally change how NPPs are operated, maintained, and supported such as by centralizing the organization and minimizing required staffing levels using enabling technology, significant changes to existing processes, utilizing vendor expertise, and utilizing resources on an as-needed basis for emergent issues. In this sense, the assets of Xcel Energy are managed through shared resource distributions, as opposed to providing independent resources per asset. As seen in Figure 15, the way in which the NPP industry performs work is not unlike what is shown to the left where each asset is coupled with its resources. In the transformed business model set out by Xcel Energy, shown on the right of Figure 15, resources are shared between assets to reduce required staffing levels and improve overall work processes.

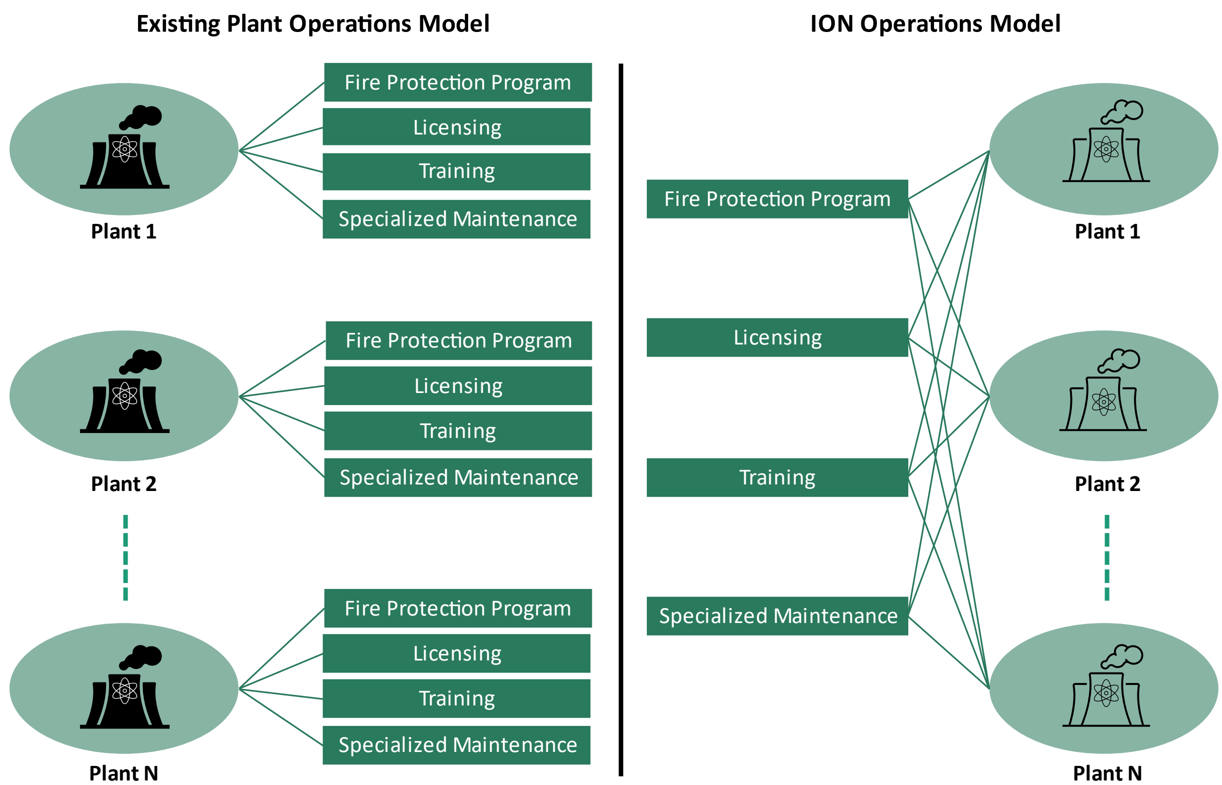

Figure 15. Comparison of existing NPP Operating Model (right) Compared to ION (left), adapted from INL/EXT-20-59537.

In this effort, Xcel Energy initiated the XE1 program, in collaboration with Light Water Reactor Sustainability (LWRS) Program ION researchers, to enable the new nuclear business model. The XE1 program's purpose was to analyze nuclear-generation work functions to permit efficiencies in accomplishing work through work elimination, requirement reduction, process improvement, technology application, and other forms of innovation. Through this collaboration, LWRS researchers developed a framework and accompanying tools (described above) for analyzing and formulating the transformed operating model that Xcel Energy has set out to implement for maintaining excellent nuclear performance in a cost-competitive manner. This work also included support from partners with Scott Madden Management Consultants and Norway's Institute for Energy Technology (IFE). The outcome of this initial work is documented in INL/EXT-20-59537 *Digital Infrastructure Migration Framework Report* and has led to several ongoing initiatives ongoing, described in the upcoming section.

3.1.4 2020: Development of ICAP

To enable capability analysis, LWRS researchers developed the ICAP to capture the results from ION (Kovesdi 2020). The capability stack model was used to develop the ICAP tool to enable identifying capabilities. These capabilities were then decomposed into sub-capabilities and work functions. Next, the ICAP identifies work reduction opportunities for these work functions and allows the assignment of solutions that follow the core philosophy of developing solutions that address people, technology, processes, and governance (PTPG).

There are three important outcomes of ICAP, as described in (Kovesdi 2020):

- **Ties Solutions to the Business Case.** The ICAP ensures that all work/process changes, technology deployments, and organizational changes are traceable to the business case
- **Aligns Solutions with Budget.** It provides a quantitative basis to ensure the cost of performing work functions in the future can be accomplished on a budget
- **Enables Technology Reuse Across Multiple Work Reduction Opportunities.** The ICAP provides a means of aggregating business cases across the work functions (plant-wide) that can benefit from a given work reduction opportunity, such as through technology or process changes (Kovesdi 2020). That is, a given solution that addresses a work reduction opportunity can be translatable to other opportunities to foster inter-linking, as previously described.

The result of this work was the ICAP tool that was a subject of research in XE1 collaboration between Xcel Energy and the LWRS Program. In parallel, a related tool called the Innovation Portal was developed to interface with ICAP. The Innovation Portal serves as a research and development (R&D) information resource of emerging technologies and capabilities that can support work reduction opportunities found in ICAP. Figure 16 and Figure 17 show examples of the Innovation Portal, linking enabling technology to specific work reduction opportunities seen in ION.

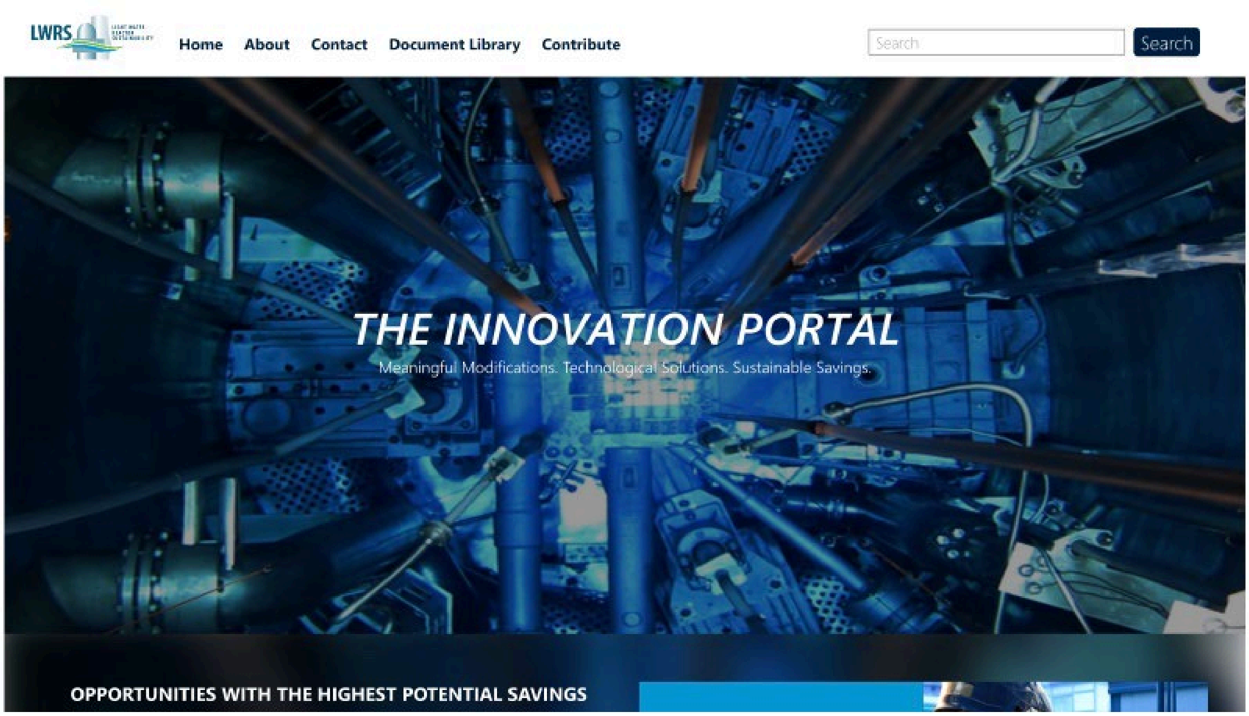

Figure 16. Screenshot of Innovation Portal home page.

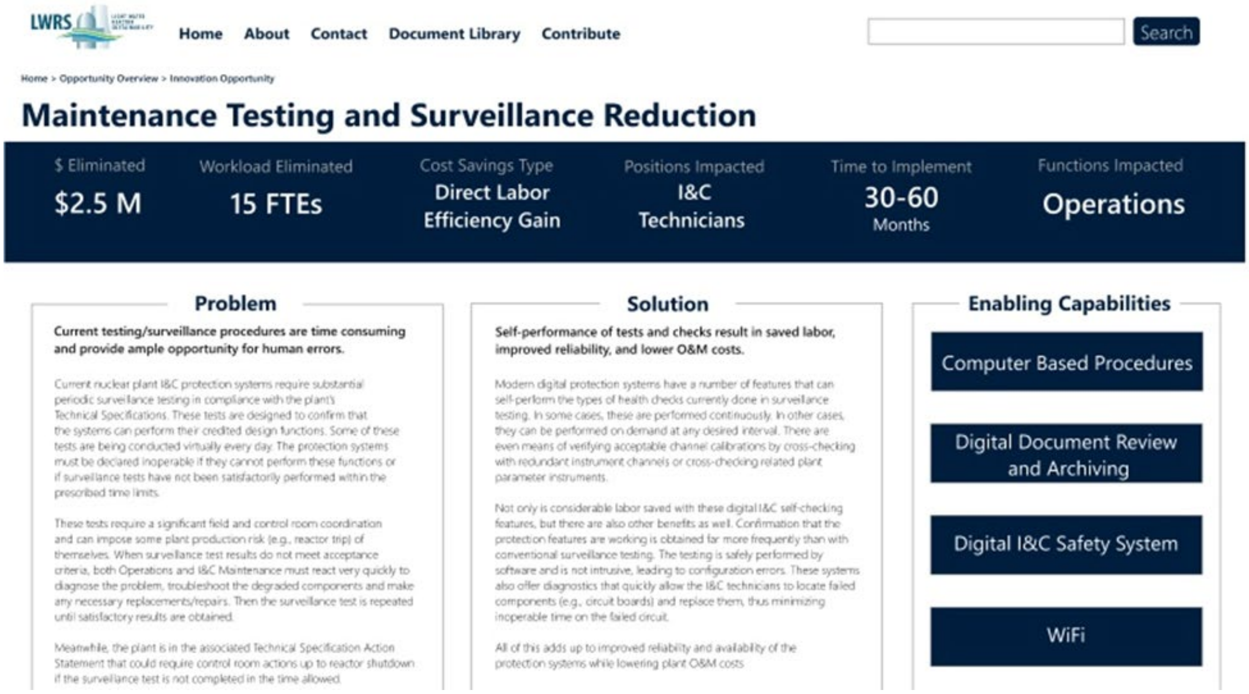

Figure 17. Screenshot of Innovation Portal Work Reduction Opportunity.

3.1.5 2021: Integration with Human-Technology Integration and Sociotechnical Analysis

ION applies innovations to nuclear power plant work functions with an objective to reduce total O&M cost to meet the market-based price point target defined by the top-down business objectives. Depending on the solutions empowered through ION, radical change may be made to the existing work processes. In many cases, the innovations have a human-technology integration component in which human-technology interface requirements must be identified and addressed to avoid safety and efficiency problems associated with human factors issues (Kovesdi, Mohon 2021a). To address the human-technology integration element, recent work by human factors researchers from the LWRS Program developed a toolset to enable effective human systems integration, (Kovesdi, Mohon 2021a). This work documents the application and use of several emerging sociotechnical methods that were demonstrated either in the nuclear industry or related such as in the development of the Zumwalt class of U.S. Navy guided-missile destroyer (Dainoff 2020). The sociotechnical methods supporting ION include system theoretic process analysis (STPA), cognitive work analysis (CWA), hierarchical task analysis (HTA), and cognitive task analysis (CTA) approaches. This developed guidance was demonstrated in two use cases in collaboration with Xcel Energy, primarily in innovating radiological protection functions and tasks through automation, virtual monitoring capabilities, and improving management review meetings using dashboards and collaboration technologies. While each use case applied different methods to address human-technology integration, the underlying approach followed well established user-centered design (UCD) principles, namely in identifying requirements for the new technology (based on understanding the context of use), designing solutions that support these requirements, and evaluating the design solutions to these requirements to ensure safe, efficient, and reliable use.

Complementary to the application of sociotechnical methods above, Kovesdi and colleagues (2021b) developed a generalizable methodology to enable the nuclear industry to address human-technology integration when adopting enabling automation and digital technology. This approach, shown in Figure 18, is based upon several industry-known standards and guidelines including the Nuclear Regulatory Commission (NRC) NUREG-0711 (2012), EPRI 3002004310 (2015), and EPRI's Digital Engineering Guide (DEG; 2018). This approach encompasses five distinct phases that are iterative in nature (shown at the center of Figure 18), beginning with developing a new vision and concept of operations and progressing to implementation and monitoring. The intersection of ION and human-technology integration starts with the understanding of which business objectives drive the realization of a new vision and concept of operation, following ION. Next, a multidisciplinary team of key stakeholders and human factors engineers work collaboratively to enable the vision through UCD approaches as previously described. The advantage of this approach is early buy-in by end users and the application of state-of-the-art human factors design principles at the conception of identified solutions to work reduction opportunities. This allows for improved human readiness levels that ensure success in implementing and executing the new innovations.

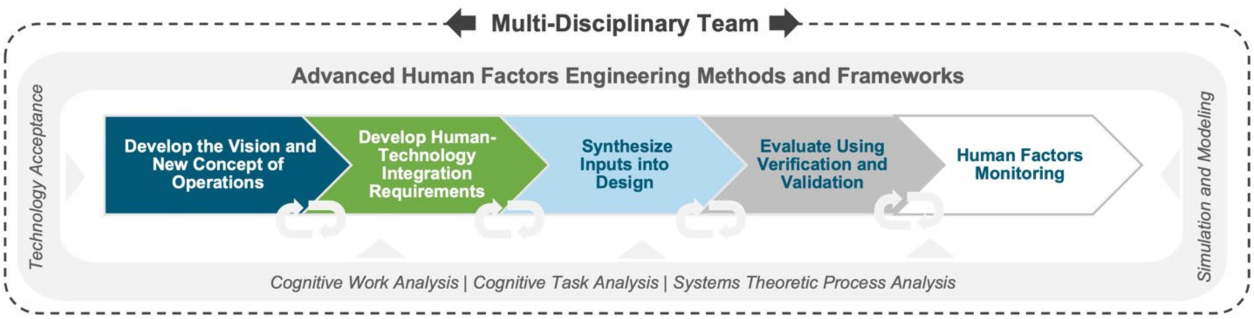

Figure 18. Human-technology integration methodology developed by Kovesdi et al. (2021b)

Put simply, the application of human-technology integration with ION enables success in transforming the operational model of the existing NPP for the future. The application of human-technology integration empowers the workers of the future to utilize technology in a way that promotes safe, efficient, and satisfying work.

3.1.6 2021: ION Generation 1

Massachusetts Institute of Technology (MIT Buongiorno et al. 2018) has indicated that the U.S. NPPs are in danger of being shut down due to being economically challenged. To address these economic challenges, ION researchers and associates from Scott Madden performed detailed economic analyses to develop a strategy in providing the greatest economic impact for the existing nuclear power plant (ION GEN1). This research examined the LCOE (i.e., the levelized cost per unit of electricity generated) that would be required to recover the costs of modernizing a dual-unit pressurized water nuclear power plant. The LCOE accounted for a variety of factors including capital costs, fuel costs, operations costs (fixed and variable), and financing costs. By examining these factors and identifying the most impactful work-reduction opportunities, this research concluded that a key set of foundational domains can be applied to significantly reduce LCOE for NPPs (i.e., comparable to what is seen in a traditional gas combined cycle generation plant).

The O&M process at a nuclear plant is the majority contributor to the high cost of generation. Many processes within this area have remained relatively unchanged since plants first started up. Changes that have been made are often in response to operational errors that arose or large nuclear events like the one at Three Mile Island that influenced the industry as a whole. Plants that expect to continue operations in future decades are faced with the challenge of lowering the costs of doing business to output cost-competitive power. The focus of ION is to review and structure O&M activities that can be potentially transformed by new technology and practices and performed at a reduced cost. O&M activities were categorized into ten critical work domains (CWD) representing areas where most of the work is performed, and where the greatest opportunities for cost reduction are expected to occur.

These key areas defined ION Generation 1 (Remer & Thomas 2021). As described in INL/EXT-21-64134, ION Generation I refers to work reduction opportunities (technology, process, human performance, and governance) that are at a sufficient technology maturity level and would support plant transformation within 3–5 years. The result of this work was a set of identified work reduction opportunities that were grouped into CWDs. Figure 19 presents a mosaic plot of each critical work domain as a function of total savings. The area of each domain is indicative of the total potential savings.

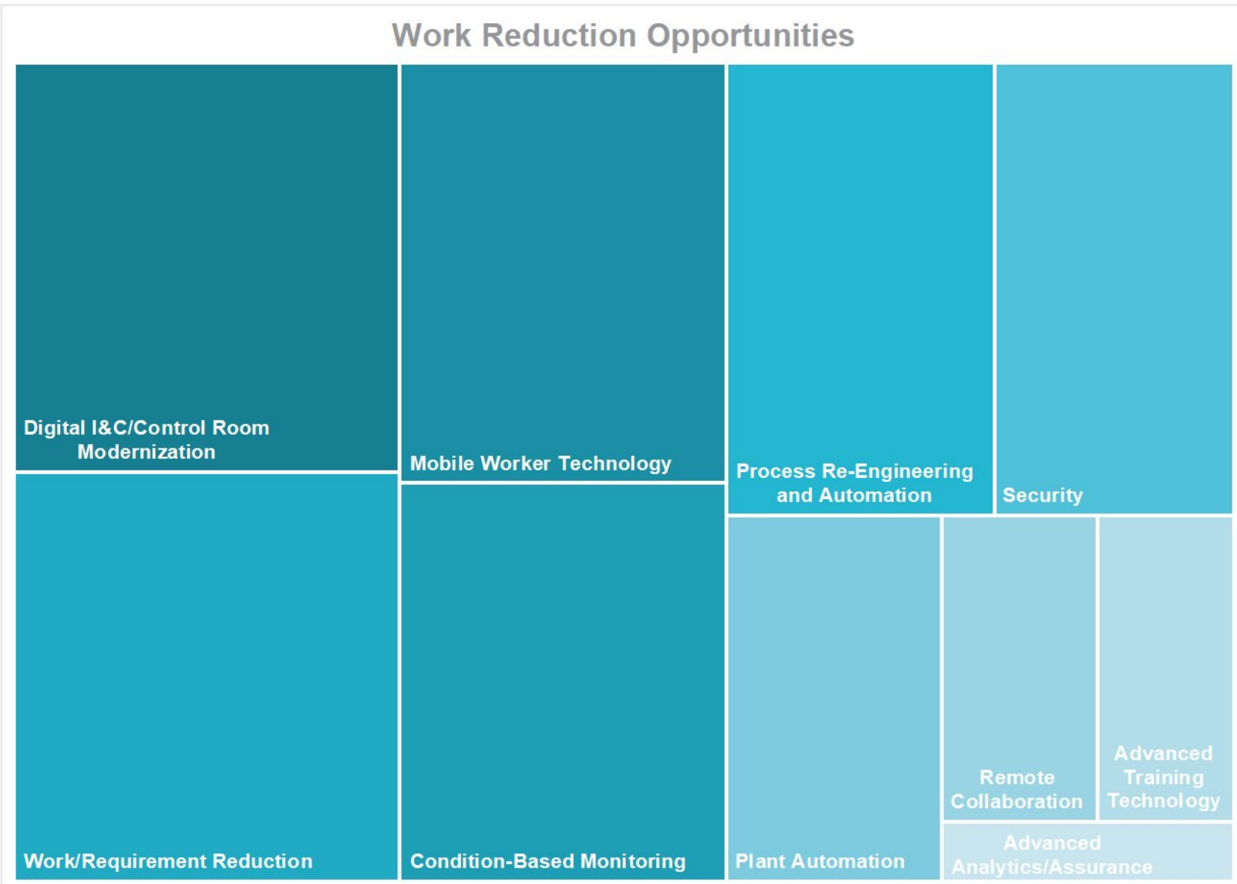

Figure 19. Critical work domains.

The ION GEN-1 research completed in 2021 analyzed the impact of these identified work domains following a four-step process, outlined in Table 5.

Table 5. ION GEN-1 research steps.

Step Goal	Detailed Step Outcomes
Step 1: Established baseline costs for 2026 implementation by estimating	Technology investment cost Ongoing costs Estimated annual cost savings
Step 2: Hosted collaborative workshop to identify constraints and assumptions toward WROs in each CWD	Fundamental technologies required to begin Constraints How technologies and processes will be integrated Work eliminated Cost impacts Time eliminated
Step 3: Summarize details for each WRO to include	Rationalize WRO with top-down cost targets Add CWD as needed
Step 4: Document order of magnitude cost savings and type	Materials Contract services Direct labor

The results captured in the preliminary report estimated cost savings across materials, contract services, and direct labor. The technology requirements for each WRO were established and the following variables were estimated for each WRO:

- Cost savings type
- Functions impacted
- Positions impacted
- Full-time equivalents (FTEs) eliminated
- Time to implement
- Cost eliminated.

The final estimate for the cumulative cost savings based on a normalized two-unit nuclear plant at 1000 MW per unit was that baseline staffing levels could be reduced significantly (approximately 44% reduction) and cumulative savings were estimated at $60 million per year. The largest functional areas realizing these savings included:

- Maintenance (~$15M) – consolidation and elimination of work
- Security (~$10M) – reduction in requirements
- Engineering (~$9M) – consolidation and outsourcing of work
- Training ($5M) – automation and outsourcing of work.

Moreover, the benefits seen from ION GEN-1 reduced levelized cost of energy by one-third, specifically from 30 USD/MWH to 21 USD/MWH. As illustrated in Figure 20, this one-third reduction enables the existing nuclear industry to remain cost-competitive with other electricity generating sources.

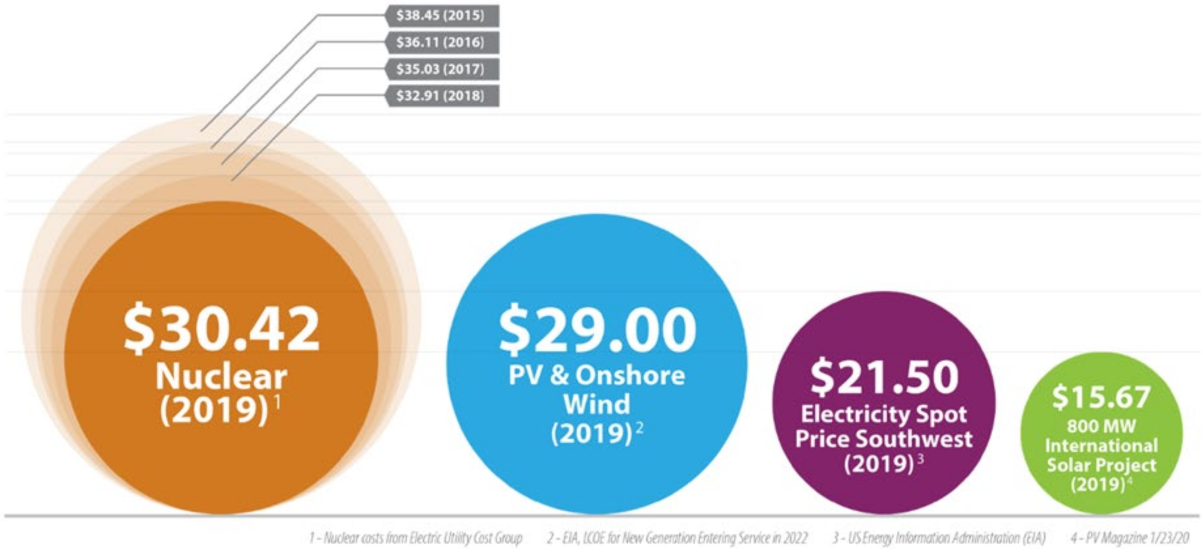

Figure 20. Total average operating costs (adapted from INL/EXT-21-64134).

The cost savings estimated here are built on business models and estimations. ION Gen 1 is focused on validating these numbers by working with utilities experienced in transforming each critical work domain shown in Figure 19.

3.1.7 Transformed Business Operating Model

ION delivers a business-driven approach to transforming the operating model of commercial nuclear plants from labor-centric to technology-centric. Following both a top-down and bottom-up approach, ION transforms the way work is done by synergistically accounting for people, technology, processes, and governance in addressing specific work-reduction opportunities with innovations that have a clear business case. This reduces required staffing levels and O&M costs needed to support the existing nuclear power plant safely and effectively. This is seen in Figure 21 where the worker of the future uses technology identified from ION to perform work safely and more efficiently.

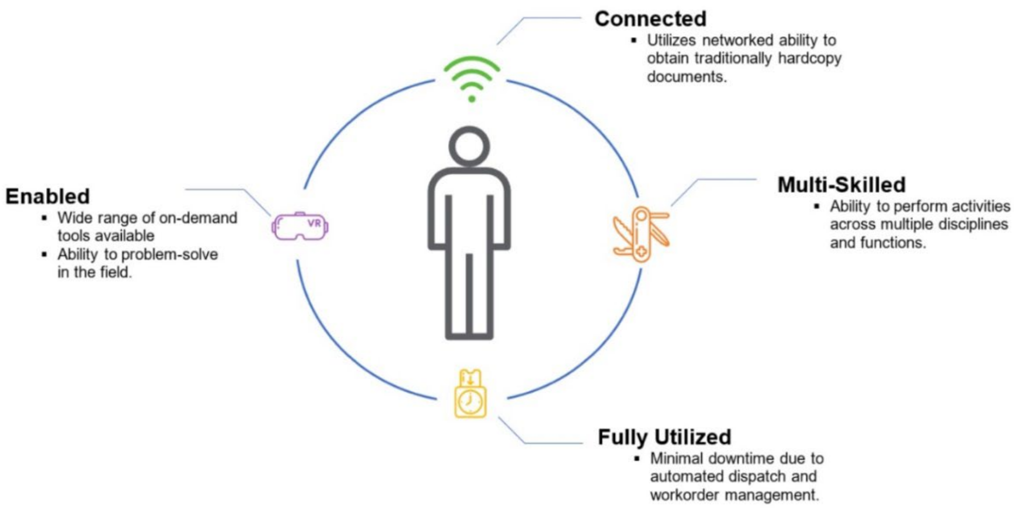

Figure 21. Characteristics of the worker from the future (adapted from INL/EXT-21-64134).

3.2 Levelized Cost of Electricity or Operating Nuclear Power Plants

3.2.1 LCOE Overview

Levelized cost of electricity (LCOE) represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant. Inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations, financial life, and duty cycle. The importance of each factor varies across technologies. For technologies with no fuel costs and small variable O&M costs (solar and wind) the O&M cost, financing costs, and an assumed utilization rate change in proportion to the capital cost.

For technologies that have greater than zero fuel cost, both fuel and capital costs significantly impact their LCOE calculations. For the current nuclear fleet, the initial capital costs of construction have been fully depreciated. The calculations included in this report do not include the capital costs to build the plant, only the costs for the investments required to support each WRO included in this analysis. Since fuel costs for nuclear represent a small percentage of the overall cost, the LCOE tracks closely with O&M costs and becomes a useful metric when comparing nuclear with other energy delivery systems.

When last year's report was written, the current LCOE for a conventional nuclear plant (identified as the Baseline Scenario in Table 6) was uncompetitive with traditional gas combined cycle generation (CCGT). At the time, the LCOE for a conventional nuclear is between \$6 and \$13, more than a traditional gas combined cycle generation when only fuel and O&M are considered. In the previous ION report, the ION Gen 1 plant's LCOE was found to be only eight cents behind the CCGT. This year, market pressures have resulted in natural gas prices increasing significantly, approaching almost \$9/MMBtu. These market pressures have significantly increased the LCOE of CCGT. The LCOE of CCGT has significant vulnerability to market factors, such as gas supply, geopolitical factors, the COVID-19 pandemic, and others. The cost stability of nuclear is a key advantage in this respect.

In this year's analysis, Scenario 2 has been updated using the cost ranges collected from utility participants.

Table 6. Levelized cost of electricity analysis.

	Baseline Nuclear Plant Dual unit NPP (O&M and Fuel Reduction / Lazard)	Nuclear Scenario 1 ION-Gen 1 (O&M and Fuel Reduction)	Nuclear Scenario 2 ION-Gen1 with Sustaining and Innovation Capital (Updated August 2022)	Combined Cycle (J-Frame) (Updated August 2022)
Generation Source	Nuclear			Natural Gas
Plant Size (MW)	2200			1221
Capacity Factor (%)	89 - 97	93		84
Fuel Cost ($/MMBtu)	0.70 - 0.80	0.65		2.95 - $8.14
Heat Rate (Btu/kWh)	10,400	10,300		6744
Fixed O&M ($/kW-year)	82.8 - 103.1	71.36		5.30 – 7.13
Variable O&M ($/MWh)	2.50 - 3.50	3.00		1.84 – 2.48
Overnight Costs ($/kW)	0	0	175 - 218	N/A
Interest Rate (%)	N/A	N/A	9.6	N/A
Production Tax Credit (PTC) ($/MWh)	0	0	0	0
Levelized Cost of Energy ($/MWh)	**$25.00 - $32.00**	**$18.29**	**$20.87 - $21.46**	**$22.46 – $58.35** with $2.95-$8.14 Fuel Cost
				$18.21 with $2.32 2018 Fuel Cost

When you further break down the categories where changes have the biggest impact on the LCOE, these five elements are:

- Capital Investment
- Production Tax Credit
- Fuel Cost
- Fixed O&M
- Variable O&M.

The scenarios described in Table 6 are described below. For each scenario, the plant size, capacity factor, fuel cost, heat rate, and variable O&M were held constant.

- Baseline Scenario: Conventional nuclear plant
- Scenario 1: 13% reduction in Fixed O&M costs and a 7% reduction in fuel costs. Zero capital investment
- Scenario 2: Significant capital investment to modernize plant equipment and processes. This scenario includes the O&M and fuel cost reductions described in Scenario 1. Overnight costs in this scenario are based on total technology and contingency costs ranging between $385M and $479M. These costs include $60M of contingency costs.

4. METHODOLOGY DESCRIPTION FOR ION GENERATION 1 VERIFICATION

4.1 Analysis Method

The first ION (reference) model report studied an array of technological upgrades, modernizations, and innovative approaches to performing work at nuclear power plants. ION represents a new way of doing business at nuclear plants to make and keep nuclear power in the United States competitive with other forms of power production, namely natural gas.

Through the series of more than thirty-five initiatives outlined in ION Generation 1, researchers estimated the costs and savings of each. These estimates were based on utility experience, informal assessments of ongoing projects, and reference to third-party research produced by the Nuclear Energy

Institute, Lazard, and the Electric Power Research Institute. In the end, this method produced a comprehensive view of the changes and upgrades that would contribute to putting NPP on a competitive footing. However, in many cases, the estimates were just that—estimates.

As the ION model matures and the response from the industry grows, more specificity and precision are demanded from the outcomes proposed in the initial iteration. Researchers utilized a deterministic approach when generating model inputs. The values associated with technology costs and savings of FTEs were single value numbers that represented the closest possible value to the accumulated research. This method, while informative and a useful tool for an initial view of the possibilities of ION, has its limitations.

The deterministic model in the first ION report used nominal values for cost and savings for each work reduction opportunity. These values represented one, and only one possibility among the multitude of possibilities of costs and savings available. To arrive at a model that accommodates more than one possibility, the team built a stochastic, or probabilistic, model from the same framework developed in the original.

Including more than one outcome from the ION model requires more than one input for each value of cost and savings. To find these values, the ION team reached out to the United States utility industry for input. But before interactions started with the utility partners, the team needed to pinpoint the five work reduction opportunities that, when analyzed in greater depth, would be most beneficial to our readers and stakeholders.

4.2 Selection of Industry Partners

In order to accomplish a probabilistic version of the ION analysis, researchers required additional inputs from industry partners. Multiple efforts are ongoing in the nuclear industry which are similar to the proposed ION work reduction opportunities. The team identified those utilities and nuclear operators actively implementing projects topically and technologically similar to those included in the ION model. Those utilities were then contacted and asked to participate in a data-gathering conversation.

The goal of the meetings with the selected utility participants was to determine which technological changes were being undertaken associated with one of the ION model categories. The same was done for the anticipated or realized costs as well as the anticipated savings. In many cases, utilities were in the process of implementing these initiatives and some were still in the early planning stages.

The technologies, costs, and anticipated savings received from the utilities were then compared to the estimates in the ION model. This process allowed researchers to confirm the initial numbers and technologies required for implementation. It also provided a data set for each model input of more than one value which opened the avenue for the probabilistic method to be employed.

4.3 Criteria for Selecting Work-Reduction Opportunities to Evaluate

In this next iteration of the model, a selection of ION work reduction opportunities was chosen from the full suite to receive more in-depth treatment. Researchers highlighted the opportunities that were more appealing based on estimated savings. Others were selected as a result of industry feedback in which technological upgrades were deemed to be most essential or necessary for plants in the coming years. Another consideration was knowledge of initiative implementation in industry through which data and updated estimates could be recorded.

4.4 Data Collection Methodology

Once the industry partners were selected and representatives agreed to participate, the ION team prepared a series of interviews and interactions. The interactions between the utilities and the researchers were designed to gain a better picture of the initiatives being considered or implemented by the corporation.

An initial meeting took place to introduce utility participants to the ION concept and the goals of the coming interactions. The next set of interactions included interviews concerning the scope of the various projects being undertaken. Utilities were asked if each of the proposed technologies included in the work reduction opportunity were a part of the initiative and if not, was there any reason for the technology to be excluded. If there were technologies included in the scope that the ION model had not considered, further conversations helped determine the reasons and justifications.

Once the scope was well understood, the researchers turned their attention to cost and savings. Each technology in the model has an associated cost of implementation including hardware, software, labor, engineering, project management, and other items. In some cases, the costs were well known. In others, the costs were estimated. If there was no knowledge of the cost of the technology, utility personnel were asked to review the ION values to provide reactions to their magnitude.

A similar approach was employed when requesting savings information that was not available. Researchers simply asked the utilities, as experts in their nuclear organizations, if the savings estimates could be considered reasonable or achievable.

4.4.1 Data Analysis and Model Building

Once the data from utilities had been collected and recorded, researchers had a minimum of two values for each ION model input. These inputs now constituted a range of possibilities for each technology cost and full-time equivalent savings. Instead of just one possibility, the model could now be built to consider a multitude of possibilities.

A given range of values was analyzed statistically and used to find the net present value of a simulated project. To make the model more realistic, researchers used a range of values for the cost of capital and included ongoing costs for each technology. Prices rise over time and the O&M costs of full-time equivalents also increase year-over-year, as do costs to maintain the equipment. These increases were factored into the calculation.

The model employed a Monte Carlo simulation to arrive at a standard distribution of expected outcomes. Probabilistic analysis admits that exact values for cost and savings are not known precisely, and the analysis should therefore represent many outcomes. Through the statistical analysis, conclusions about the model can be made based on the many possibilities generated. Instead of a single outcome that may or may not be accurate for a multitude of parties, the Monte Carlo method generates probabilities associated with positive and negative outcomes, giving the reader a better sense of risk and reward.

4.5 Schedule

Utility partner selection, introductions, interviews, data collection, data analysis, and reporting took place over a period of 4 months in the first half of 2022. See Figure 22 for an illustration of the schedule.

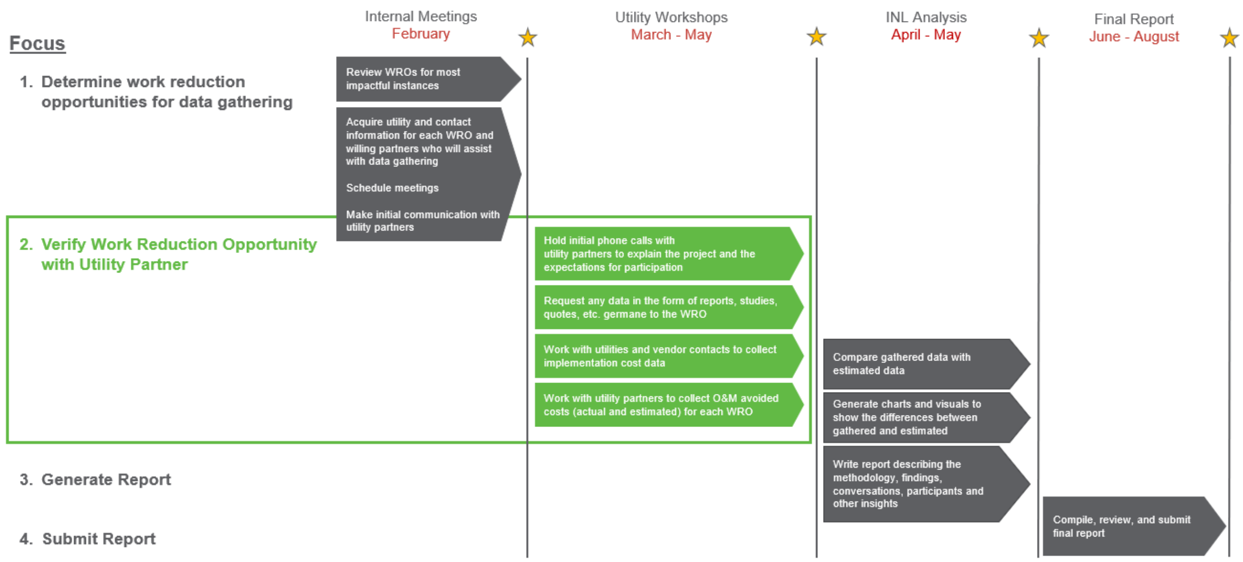

Figure 22. ION Generation 1 - verification schedule.

5. UNDERSTANDING THE BUSINESS CASE

5.1 Scope of Work-reduction Opportunities Analyzed

The following work reduction opportunities were included in a unified net present value calculation: condition-based monitoring, automated planning and scheduling, advanced training, and remote and automated troubleshooting. Using probabilistic statistical methods and Monte Carlo analysis techniques, researchers were able to generate a probability of a positive net present value resulting from the implementation of all four work reduction opportunities. The result is found in Figure 23.

The digital I&C work reduction opportunity is fundamentally different in scope and expected product life than the previously mentioned work reduction opportunities. Digital I&C represents a large investment that occurs once in the subject nuclear plant's future upgrade plans. The digital I&C work reduction opportunity implementation is foundational to the long-term viability of nuclear plants considering license extension beyond sixty years. Many parts and components associated with digital I&C systems are already difficult to procure. Obsolescence has become a significant challenge and burden. Replacement components will only become scarcer and more expensive over time eventually becoming a limiting factor to safe and reliable nuclear operation. For these reasons, the digital I&C work reduction opportunity was treated differently. The digital I&C work reduction opportunity's net present value model was extended to thirty years versus twenty for the other work reduction opportunities to reflect the one-time and final upgrade to these plant systems. Detailed analysis and description of the digital I&C work reduction opportunity can be found in Section 6.2

This model captures financial impacts beginning from the first year after implementation. In this approach, all one-time and ongoing technology costs are captured together.

5.2 ION Model: Unified Net Present Value

Based on INL's research as described in the ION model, taken together, the four work-reduction opportunities (condition-based monitoring, automated planning and scheduling, advanced training, and Remote and Automated Troubleshooting) have a 99.9% chance of producing a positive net present value, as indicated in Figure 23. This analysis does not include the many additional work-reduction opportunities within the ION model that have not been modelled in this report and are included in previous LWRS research contained in INL/EXT-21-64134.

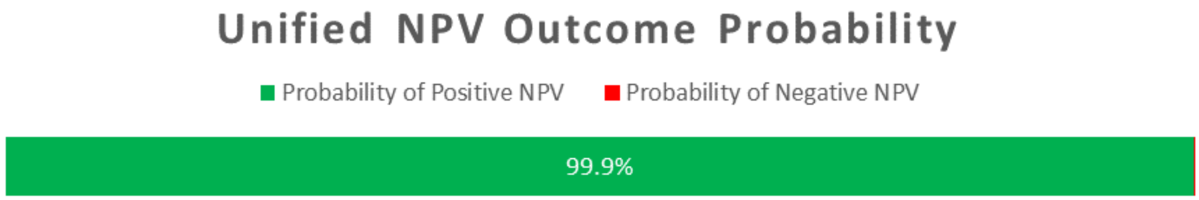

Figure 23. The probability of a positive or negative new present value outcome for implementing four work-reduction opportunities: condition-based monitoring, automated planning and scheduling, advanced training, and remote and automated troubleshooting.

5.3 Capital Investment Required

One-time investment for each work-reduction opportunity included in this analysis is summarized in Table 9. Total one-time investment ranges between approximately $52.2M and $79.1M. For specific technologies that makeup each opportunity, please refer to Section 6.

Table 7. One-time investment.

Model Input	Minimum	Maximum	Standard Deviation
One-Time WRO Cost			
Digital Training	$22,600,000	$33,700,000	$5,550,000
Automated Planning	$9,000,000	$16,650,000	$3,825,000
CBM	$8,000,001	$12,000,002	$2,000,001
Remote Troubleshooting	$12,600,000	$16,700,000	$2,050,000
Total:	***$52,200,001***	***$79,050,002***	***$13,425,001***

5.4 Projected Savings

Minimum and maximum input values to the ION model as shown Table 7 were used to find a population of net present values for the combination of four work-reduction opportunities. Employing a Monte Carlo simulation, the model arrived at a standard distribution of five thousand expected outcomes. Each outcome was plotted along a normal distribution curve.

A positive NPV indicates a favorable business case for the project investment, indicating the project is expected to return more free cash to the utility. A negative NPV indicates that the business case is not favorable and that the project will return less free cash to the utility.

For this analysis, the NPV varied between -$25M and $207M, with a 99.9% chance of achieving a positive NPV outcome, (Figure 24). The NPV has a standard deviation of $30.1M, (Figure 25).

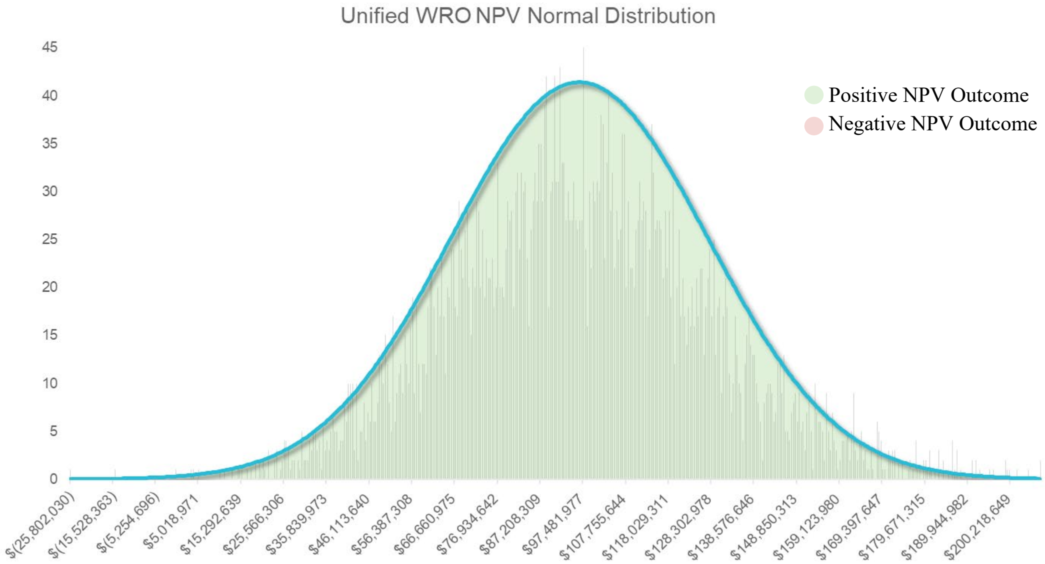

Figure 24. NPV distribution of implementation of report WROs.

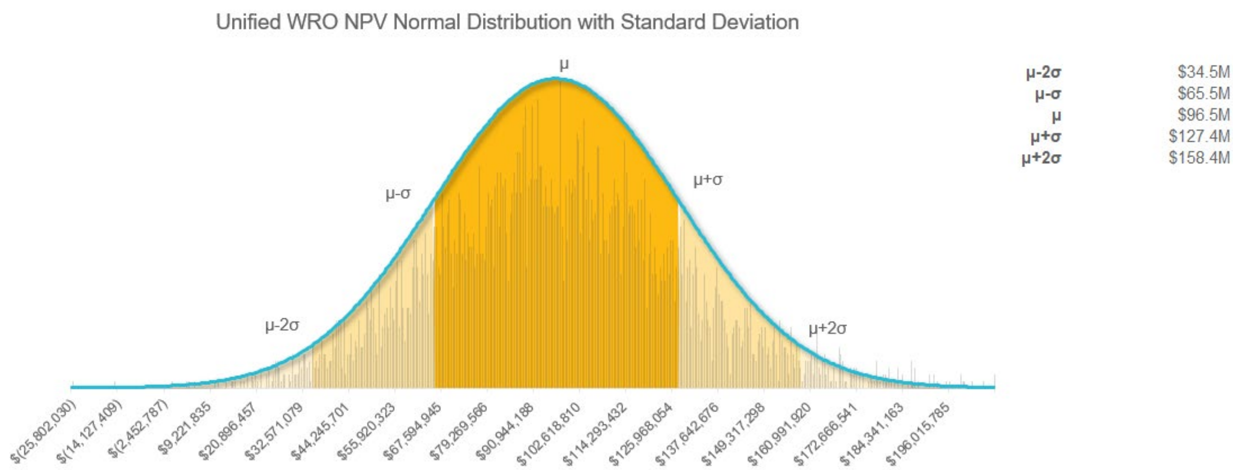

Figure 25. Normal distribution of report WROs.

To provide more detail into the NPV outcome, Table 8 indicates the percent chance of achieving certain NPV values or greater. For example, investment in these opportunities has a 50% chance of resulting in an NPV of $95.6M or more, and a 30% chance of resulting in an NPV of $112.0M or higher, etc.

Table 8. NPV per percentile.

Chance of Achieving NPV	NPV Value or Greater
50%	$95.6M
40%	$103.5M
30%	$112.0M
20%	$121.6M
10%	$136.3M

5.5 Payback Period

Figure 26 models the cumulative savings and costs over a 20-year period. As seen below, the payback period for the four work reduction opportunities is approximately 4.5 years. As previously stated, this model assumes year one is the first year after completion of implementation for all four work reduction opportunities. Utilities implementing these opportunities may have varied payback periods, as savings can begin to accumulate earlier in the implementation process if they are implemented over multiple years. For example, if a utility analyzes and implements condition-based monitoring at their plant, savings can begin to accumulate earlier and support the financial justification of subsequent work-reduction opportunities.

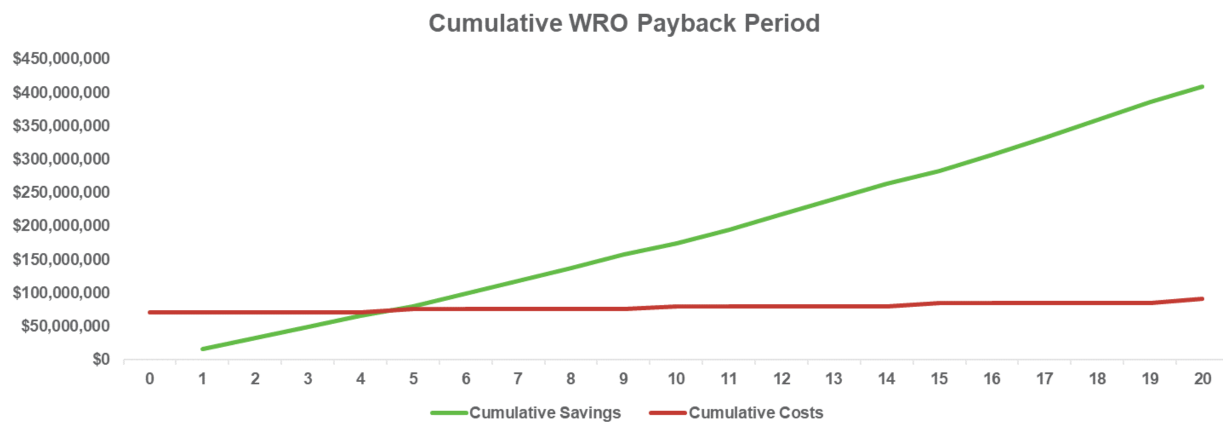

Figure 26. Cumulative WRO payback period.

5.6 Ongoing Technology Costs

In future sections of the report, the details of the ongoing costs pertaining to each work-reduction opportunity are covered in detail. In summary, all technologies required for this modernization have associated ongoing costs. These costs represent ongoing maintenance and service contracts held with the original installer, OEM, or component supplier for each technology. It also represents periodic internal maintenance upgrades. These service contracts or self-performed upgrades are required to ensure support for ongoing hardware and software functionality. It is estimated that once every five years the software systems will require maintenance and upgrades. Table 9 summarizes the ongoing costs for each opportunity.

Table 9. Unified model ongoing costs.

Model Input	Minimum	Maximum	Standard Deviation
On-Going Cumulative Costs			
Digital Training	$850,000	$1,800,000	$475,000
Automated Planning	$400,000	$2,000,000	$800,000
CBM	$130,000	$540,000	$205,000
Remote Troubleshooting	$195,000	$610,000	$207,500
Total:	***$1,575,000***	***$4,950,000***	***$1,687,500***

5.7 Full-Time Equivalent Savings and Other Model Inputs

Table 10 below highlights the inputs pertaining to the FTE savings, and other assumptions or the Monte Carlo analysis.

Table 10. Unified model WRO model business case inputs.

Model Input	Minimum	Maximum	Standard Deviation
FTE Savings			
Digital Training	16	31	8
Automated Planning	7	16	5
CBM	14	39	13
DI&C	46	52	3
Remote Troubleshooting	29	33	2

Cost of Capital	8.75%	10.50%	.88%
Obsolescence and Spare Parts Savings	$800,000	$1,000,000	$100,000
FTE Cost Increase	3%		

6. ION GENERATION 1 – SELECTED TRANSFORMATION DOMAINS

6.1 Condition-Based Monitoring

6.1.1 Scope of Work Reduction Opportunity Analyzed

The preventative maintenance program at a typical nuclear plant is executed by the maintenance staff and administered by engineering. Maintenance workers perform preventative maintenance and record the as-found state of the component in the work order notes. Engineers read those notes and collect operating experience (OE), then look to product manuals, industry research, and the opinions of experts when adjusting the frequency of preventative maintenance tasks. Less maintenance performed saves the plant O&M spending on maintenance time and parts.

The manufacturer does not know in advance the exact working conditions or duty cycle of each component they sell. Most operator's manuals tilt their prescribed preventative maintenance suggestions in the conservative direction (i.e., toward more frequent, and more extensive maintenance). Manufacturers design preventative maintenance programs for the most extreme applications of their products. The manufacturer's bias for more maintenance has an impact on the nuclear plant's preventative maintenance program.

Another force driving the size of the preventative maintenance program is the nature of equipment performance itself. In many cases, it is impossible to know with precision when a component is near failure. Many technologies and methods are employed to assess and predict failure, but most are noncontinuous, nonintrusive, or non-precise. In other words, it is easy to know how close a pump is to failure by taking it apart and measuring its internal components; however, this necessitates removing the component from production, defeating its function.

Some examples of predictive activities are vibration analysis, oil analysis, thermal imaging, and ultrasonic readings. Data from these technologies may be gathered frequently from the most sensitive equipment like switchyard components or feedwater pumps. Less frequent readings are taken from those systems, not in continuous use or not significant to safety or production. Readings are analyzed by experts in an attempt to predict when components will need preventative maintenance.

Due to the conservative nature of the vendors' preventative maintenance suggestions, the limitations of predictive technologies, and the overall strategy for outstanding equipment reliability, preventative maintenance at a nuclear plant can be frequent and expensive.

6.1.2 Current Methods

The correct frequency of preventative maintenance relies on the collection, analysis, and dissemination of signs of degradation given by components themselves. Much effort at the nuclear plant is exerted to collect various indicators that a component may need maintenance.

There are common ways nuclear plant maintenance workers and engineers monitor components to assess their health and functionality. Among them are vibration monitoring, oil analysis, ultrasonic inspection, visual inspection, metallurgical testing, periodic test result analysis, and trending, motor current monitoring, infrared thermal imagery, motor-operated valve (MOV) and air-operated valve (AOV) diagnostics, and heating, ventilation, and air conditioning (HVAC) filter pressure differential monitoring, and others.

Technicians and engineers manually collect data from components using handheld sensors. The data are then typed into software used for analysis or samples are sent to a lab. Preventative maintenance determinations are then made from these results. The data collection frequency is important, as is the trending methodology. Conservative decision-making bias will typically lead a person to err on the side of over-maintenance rather than under-maintenance.

6.1.3 ION Methods

The ION business model utilizes a similar approach to managing preventative (and corrective) maintenance. It builds from the current model of component monitoring, data collection using sensors, data analysis for trends and forecasting, and historical precedent.

In the ION model, components are fitted with fixed sensors capable of continuously collecting data. Much like pressure and temperature gauges, these sensors collect vibration amplitudes and frequencies, motor current properties, oil properties, thermal heat signatures, and other parameters meaningful to the component's health. The sensors can be wired or transmit signals via a wireless communication network. Data are collected and housed in a database typically on company servers that are part of the business network. Data are then shared with software capable of diagnostic or prognostic analysis. Software may interface with an attendant or engineer or may be programmed to automatically trigger a preventative maintenance work order in the nuclear unit's asset suite under the right network circumstances.

6.1.4 Technology and Investments Required for Condition-Based Monitoring

6.1.4.1 Communication Network (Wi-Fi or Equivalent)

High-bandwidth wireless systems or communication networks are capable of supporting several gigabits of upstream and downstream data transmission. This network is necessary to support the substantial amounts of data that are being uploaded and downloaded by digital components installed throughout the plant. These components are capable of transmitting continuous information pertinent to their functions.

Additionally, by transitioning to online components, a larger amount of plant personnel will be accessing plant information through mobile devices (e.g., smartphones and tablets).

This technology is also used in:

- Digital I&C systems
- Advanced analytics and assurance
- Plant automation
- Process re-engineering and automation
- Mobile worker technology
- Advanced training technology
- Remote collaboration
- Work and requirement reduction
- Security.

6.1.4.2 Component Sensors for Detecting Failure Modes

Transitioning from preventative to Condition-Based Maintenance involves fitting wireless sensors onto various plant assets, such as motors, transformers, valves, etc. These sensors can perform tasks such as oil analysis, dissolved gas analysis, analysis of actuator/valve conditions, thrust wear monitoring, vibration (see Figure 27), etc.

Once plant assets are retrofitted with sensors or replaced with components containing original equipment manufacturer (OEM) sensors, data can be wirelessly transmitted to a monitoring and diagnostic (M&D) center where asset conditions are continuously monitored. As conditions are monitored by software and subject matter experts, either or both will be able to detect degrading asset conditions and plan preventative or corrective maintenance to avoid triggering a failure mode.

Additionally, collected data can be used to diagnose assets more effectively and efficiently in the event of an actual failure.

This technology is also used in automated troubleshooting.

Figure 27. Magnetically attached wireless vibration sensor (EPRI).

6.1.4.3 Diagnostic and Prognostic Analytics

Diagnostic and prognostic analytics is software used to analyze and trend data collected from wireless sensors fitted to plant assets. Data collected indicate actual performance. The software analyzes the data with respect to an acceptance criterion, reviewing and reporting the component's performance through a set of management controls, initiating preventative maintenance for deficient performance, and then monitoring for improved and acceptable performance.

This technology is also used in digital I&C for maintenance testing and surveillance reduction, and automated troubleshooting. Table 11 indicates the deployment readiness of each of the technologies discussed above.

Table 11. Technology deployment readiness.

Technology	Widely Deployed	Narrowly Deployed	Not Deployed
Communication Network	X		
Component Sensors for Detecting Failure Modes		X	
Diagnostics and Prognosis Analytics		X	

6.1.5 ION Model: Net Present Value Analysis

Based on INL's research of condition-based monitoring as described in the ION model, this work reduction opportunity has a 95% chance of achieving a positive net present value outcome as indicated in Figure 28.

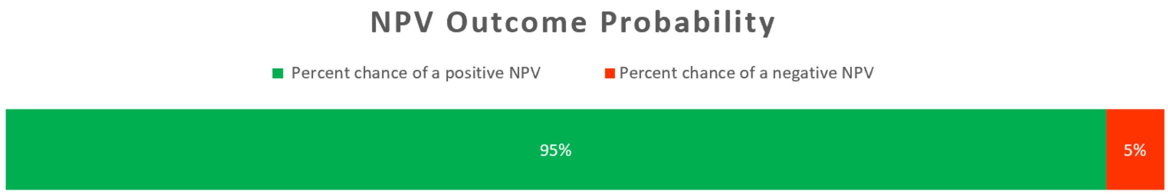

Figure 28. The probability of a positive or negative net present value outcome for the condition-based monitoring work reduction opportunity.

6.1.6 Validation Methodology

In the previous report, the ION model used single value estimates for each input to the model. This resulted in a deterministic estimate of the overall cost and savings associated with each work reduction opportunity.

Inputs to the condition-based monitoring section of the model included:

One-time and ongoing cost of the following technological upgrades

a. Communication network

b. Component sensors detecting all failure modes

c. Diagnostic and prognosis analytics

Number of full-time equivalent hours saved in the following areas

a. Condition-Based Maintenance FTEs.

This next phase of ION model preparation involved collecting a range of data points for each input. Additional data points were found by reaching out to nuclear utilities and gathering input. Other data points were mined from complementary research. These actions achieved a range for each input to the model, representing the range of actual values and the uncertainty found in estimating large multiyear projects. This analysis assumed a cost of $163K per FTE with a yearly increase of 3%. Increases in overall cost to maintain the new systems and components were also considered to be approximately 2% per year.

Sensors detecting component failure modes are necessary investments for this WRO. However, for the ION model, technologies are shared and utilized within multiple work reduction opportunities. The sensors collecting component data are installed as a part of Remote and Automated Troubleshooting WROs. Therefore, Figure 29 and Figure 30 do not include costs for these sensors.

Figure 29, Figure 30, and Figure 31 represent ranges captured for each model input in graphical form.

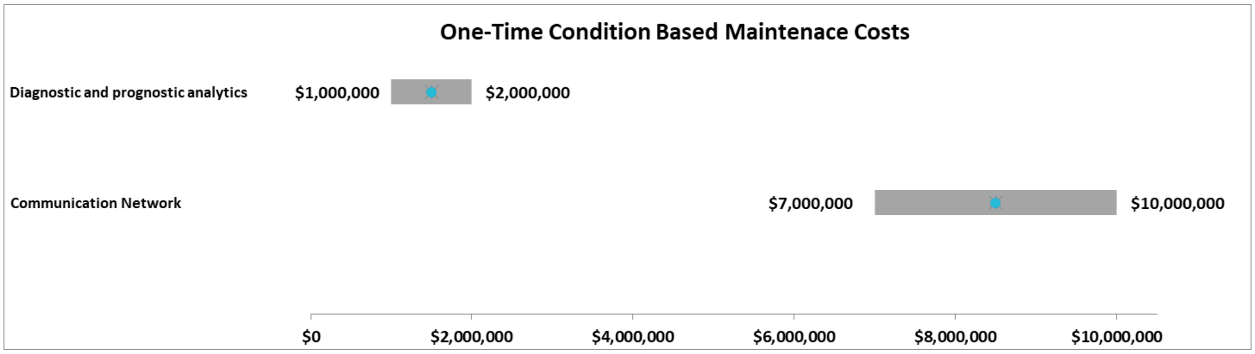

Figure 29. One-time condition-based monitoring hardware and software costs.

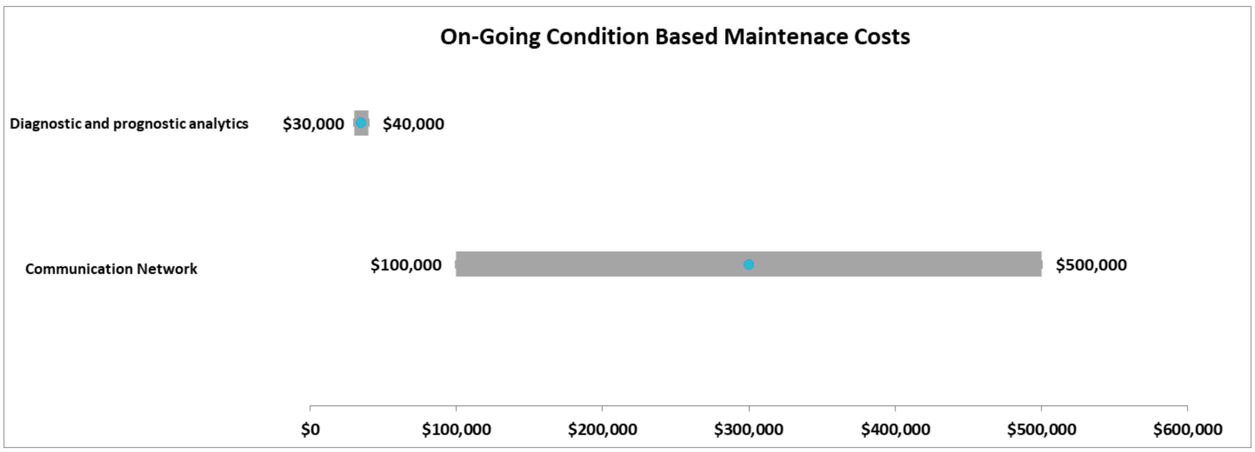

Figure 30. Ongoing condition-based monitoring hardware and software costs.

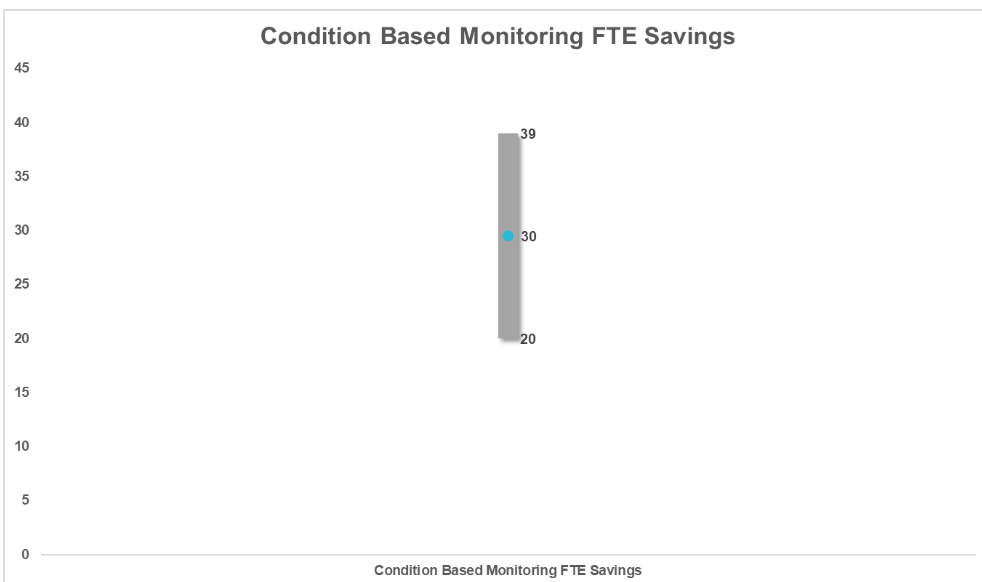

Figure 31. Condition-based monitoring FTE savings.

6.1.7 Areas of Uncertainty (Investment, Ongoing Costs, Savings)

As a result of obtaining data ranges for each input, the ION model calculation can now utilize a stochastic method. Areas of uncertainty can be determined by calculating the standard deviation of each range of costs and savings associated with a technological upgrade. The one-time costs of the communication network have the greatest uncertainty in this work reduction opportunity. Participants of this study reported one-time costs ranging between $7M and $10M, with a standard deviation of $1.5M.

The cost range of this technology is due in part to network needs. Specifically, network costs range due to the number of active users, the number of sensors or retrofitted plant assets, and the required bandwidth to support real-time monitoring of assets. Plant size also drives cost as additional hardware will be needed to ensure connectivity in all areas of the plant. Vendor choice and internal vs. external implementation partnerships contribute to variability as well.

The one-time cost of component sensors also has significant uncertainty in this analysis. Participants of this study reported costs ranging between $4M and $7M, with a standard deviation of $1.5M. The costs of component sensors range significantly primarily due to the number of assets determined to be viable candidates for continuous online monitoring. The greater number of assets included in the participant's scope, the greater the costs. Additionally, costs of the sensors can range significantly based on asset design, and sensor function (vibration, dissolved gas analysis, etc.). Retrofitting assets with OEM vs. third-party sensors can also drive cost variation.

6.1.8 Ongoing Costs

All technologies required for this modernization have associated ongoing costs. These costs represent maintenance, service, and licensing fees held with original service or component suppliers. Ongoing component sensor costs depend on maintenance and services required to keep them operational.

6.1.9 Model One-Time Costs, Ongoing Costs, and FTE Saving Input Values

Minimum and maximum input values to the ION model as shown in Table 12 were used to find a population of net present values. Employing a Monte Carlo simulation, the model arrived at a standard distribution of 5,000 expected outcomes. Each outcome was plotted along a normal distribution curve.

Table 12. Condition-based monitoring business case inputs.

Model Input	**Minimum**	**Maximum**	**Standard Deviation**
One-Time Hardware and Software Costs			
Communication network	$7,000,000	$10,000,000	$1,500,000
Diagnostic and prognostic analytics	$1,000,000	$2,000,000	$500,000
Total:	*$8,000,000*	*$12,000,000*	*$2,000,000*
Ongoing Hardware and Software Costs			
Communication network	$100,000	$500,000	$200,000
Diagnostic and prognostic analytics	$30,000	$40,000	$5,000
Total:	*$130,000*	*$540,000*	*$205,000*
FTE Savings			
Condition-based monitoring FTE savings	20	39	10

Model Input	Minimum	Maximum	Standard Deviation
Cost of capital	8.75%	10.50%	0.88%
FTE cost increase	3%		
Yearly salary blended rate per FTE	$163,000		

For this analysis, the NPV ranged between –$49.7M and $137.2M, with a 95% chance of achieving a positive NPV outcome (see Figure 32). The NPV has a standard deviation of $23.1M (see Figure 33).

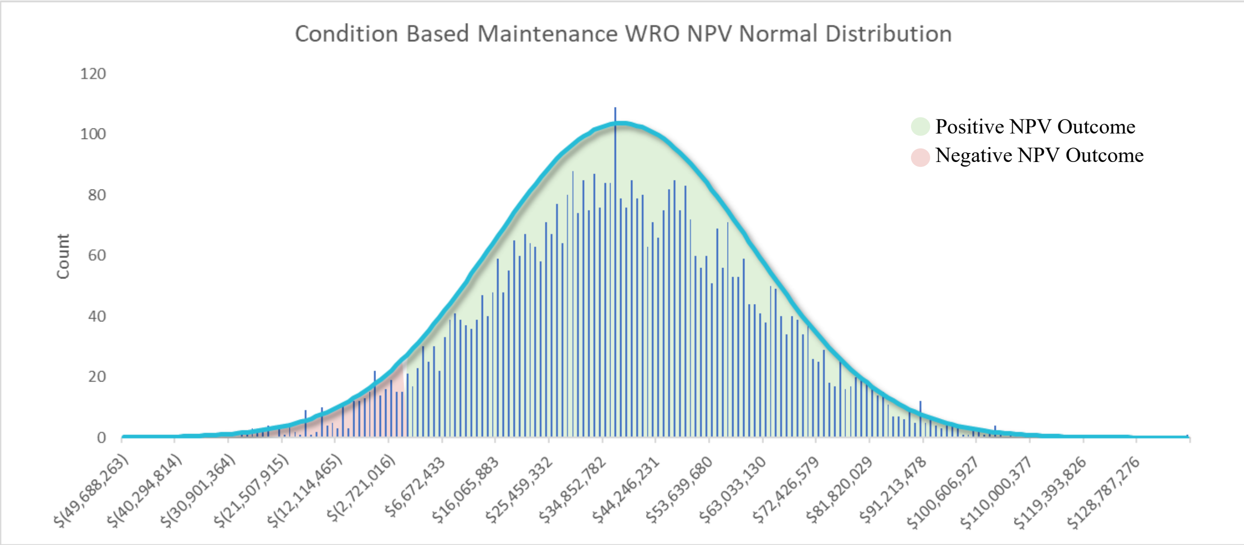

Figure 32. NPV distribution of condition-based monitoring.

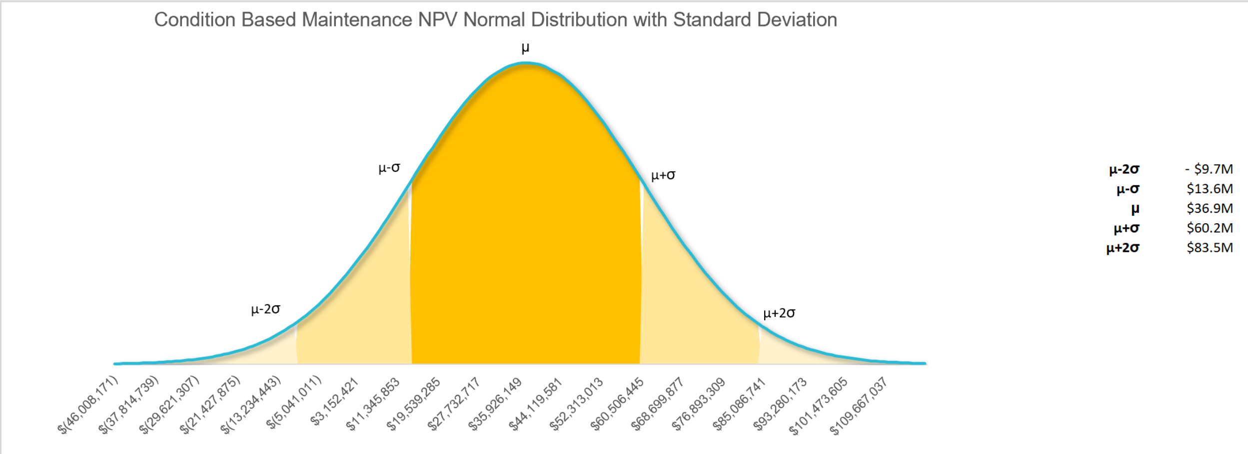

Figure 33. NPV distribution bell curve of condition-based monitoring.

Providing more detail on the possibility of achieving a positive NPV outcome, Table 13 indicates the percent chance of achieving NPVs above the breakeven point. For example, investing in Condition-Based Maintenance has a 20% chance of resulting in an NPV of $57.3M or more and a 10% chance of resulting in an NPV of $67.7M or higher.

Table 13. NPV per percentile.

Chance of Achieving NPV	NPV Value or Greater
80%	$18.5M
60%	$31.7M
40%	$43.4M
20%	$57.3M
10%	$67.7M

6.1.10 Lessons Learned from Early Implementations

Sensors that were installed in the plant feed data to the M&D center where it is analyzed by technicians, who are aided by software. Data collected can be valuable to the plant site as it allows much more resolution and detail than traditional methods. However, users of the data have discovered that M&D data cannot be used for operational decisions or other technical quality assurance programs like operability assessments.

Another effect of installing sensors and maintaining staff to interpret the incoming data is that these technicians and engineers become the de facto experts on equipment performance. Due to the high amount of data entering the system around the clock, the resolution and ability to see perturbations is unique to those who are monitoring these new sensors. Other plant employees are seeking advice and interpretation from those who are most familiar with the data delivered by the newest sensors.

6.2 Digital I&C/Control Room Modernization

Existing plants rely to a large extent upon obsolete I&C equipment. Safety systems are almost exclusively first-generation analog systems that are of original plant vintage. While non-safety I&C systems have leveraged digital technology, these have been installed in a piecewise manner and, in many cases, have operated significantly beyond their design lifetimes. Operators rely on these systems along with paper-based procedures and processes to perform primarily manual tasks from the main control room and in the field.

Technology designed and installed many decades ago is becoming more difficult to troubleshoot, maintain, replace, and service. This section of the ION model report identifies current cost drivers in this area and presents a way forward for nuclear I&C components and computer systems to enable reductions in plant total cost of ownership while maintaining or enhancing plant reliability and availability. Digitalization can provide capabilities beyond like-for-like functional replacements. Digitization of systems and components can have multiplicative effects where the resultant capabilities can be much more than the sum of the constituent parts. The aggregate result can have a significant, beneficial effect on the day-to-day operation of the plant. Replacements and upgrades can contribute positively to equipment reliability and can reduce workload, generating FTE savings through years of continuous operation.

6.2.1 Current State of Industry I&C and Control Room Design

6.2.1.1 Tests and Surveillances

Current nuclear plant I&C protection systems require substantial periodic surveillance testing in compliance with the plant's technical specifications. These tests are designed to confirm that systems can perform their credited design functions. There are numerous such tests, and a number of them are being conducted virtually every day. Protection systems must be declared inoperable if they cannot perform these functions or if surveillance tests have not been satisfactorily performed within the prescribed time limits.

When surveillance test results do not meet acceptance criteria, both operations and I&C maintenance personnel must react quickly to diagnose the problem, troubleshoot the degraded or inoperable components, and make any necessary replacements/repairs. The surveillance test is repeated until satisfactory results are obtained. Meanwhile, the plant is in the associated technical specification action statement that could require control room actions up to reactor shutdown if the surveillance test is not successfully completed in the time allowed.

Legacy nuclear plant operations tests and surveillances rely heavily on paper procedures and forms. Operations staff will review the procedures and print the necessary sections, attachments, and forms from the procedure. As the test is conducted, steps are marked manually on the paper procedures. Any attachments or test results are written in pen directly on the printed forms.

When the test is complete, the procedure is scanned and sent to document services for processing as a quality assurance (QA) record. The completed forms are accessed by other personnel through a document management system that displays the scanned pages. Any data mined from the test procedure must be manually transferred to another program, spreadsheet, or report.

6.2.1.2 I&C Safety Systems

Existing nuclear plant safety systems have a proven track record of high reliability and availability. These legacy systems, however, are increasingly obsolete and more difficult to diagnose, troubleshoot, maintain, and reverse engineer. Talented maintenance technicians and engineers have been working on these systems for many decades. Many have or are reaching the end of their careers. Newer employees will not be able to access that wealth of experience as time goes by. Many new employees may not have even learned the protocols, computer languages, or components included in the design of these systems in their formal training. A situation where only one or two people in the company have intimate knowledge needed to fix and maintain these systems is a reality in many plants across the United States fleet.

It can be difficult to recruit new hires who have scholarly knowledge and/or practical experience in modern digital technology to work on obsolete analog or digital systems and components. The nuclear industry must compete in a technically innovative marketplace for talent. Many see working on obsolete nuclear I&C systems as a potential career dead end.

6.2.1.3 Digital I&C Components

The existing safety related I&C and protection systems at nuclear plants are composed of thousands of discrete logic and control devices, interlocks, and permissive relay contacts spread through a large number of electrical cabinets, interconnected by thousands of cables. While digital I&C systems have been employed in non-safety I&C systems, many of these implementations have been point solutions which have been operated far beyond their design lifetimes. Support of such legacy I&C systems, including the control room human-system interface (HSI), requires substantial maintenance and engineering efforts, which are becoming both more difficult and costly. These challenges are compounded when the failure of these items must be addressed expeditiously to address the resultant degraded condition impacting plant operational control. Such failures can also result in technical specification-required functions to be inoperable, forcing the plant into prescribed action statements to address the degraded conditions, up to potentially a forced reactor shutdown.

6.2.1.4 Component Identification

Much of the work of the operations staff, and especially those who perform the hands-on work of manipulating components, rely upon selecting the correct component in the field. Currently, most legacy methodologies require reading a component tag visually and checking it against the procedure, test, or work order being performed. At times, and for critical tasks, a peer check is available. While the incident rate for mis-position events is low, the consequences of an error can be high.

6.2.1.5 Communication and Information

Operations staff are trained and equipped to use multiple methods of communication while in the plant performing work. Telephones are installed throughout the plant at convenient high-traffic locations. Many operators carry plant phones or radios that allow communication from a work location or while moving around the plant.

When an issue is encountered in the field there is currently little in the way of image or video sharing capability. Calls between personnel to discuss a situation are limited to conference calling or speaker phone. The ability to witness the performance of work activity in the field from the control room or outage control center is limited. Having the ability to observe operations from remote locations would add to the accuracy, training, and corrective capability as well as allow management observations to take place from outside radiation areas.

6.2.2 Future State of I&C and Control Room Design

6.2.2.1 Digital Infrastructure and Generic Framework for Nuclear Plants

A wide body of research has been conducted on the digital architecture and systems at a typical nuclear power plant. The Digital Infrastructure Migration Framework (Hunton, England 2021), part of the LWRS Program at INL, outlines a generic framework for a future state nuclear digital infrastructure that would apply to any facility.

In the two columns on the left side of the simplified digital infrastructure architecture model shown in Figure 34, Purdue Model network levels, which are commonly leveraged in the industrial control system industry, are related to corresponding cyber security levels as defined by the NRC in Regulatory Guide 5.71, “Cyber Security Programs for Nuclear Power Reactors.”

Components and software described in this report will be installed within the multiple levels of the architecture shown in Figure 34. For instance:

- Digital I&C field devices will exist in Purdue Model network level 0.
- Digital I&C controllers that implement software to affect plant system control will exist at Purdue Model network level 1.
- Supervisory I&C capabilities such as data aggregation, data presentation to operators on video-driven digital HSIs, and the ability to initiate control actions from those same HSIs are provided at Purdue Model network level 2.
- Advanced applications directly support operator control, such as computerized procedures functionally coupled to the I&C systems to allow for “smart” capabilities within those procedures. These are hosted at Purdue Model network level 3.
- Transmission of increasingly digitized I&C plant data through a one-way data diode to emergency preparedness facilities to improve their capability to support the plant during significant plant events and allow for better communication to the public of plant status in such an event. These features are hosted at Purdue Model network level 3.5.
- Aggregation of increasingly digitized I&C plant data with other data (e.g., wireless sensor data collected from plant equipment) at Purdue Model network level 4. This enables more advanced diagnostics and prognostics to optimize plant maintenance. Other plant processes that are increasingly being digitized on the corporate network such as equipment stores management, requisitioning, and work package development can also directly receive data from I&C to enable automation of these processes when I&C equipment failures are detected.

Each “domain” (shown in different colors to the right of Figure 34) and Purdue Model Level has particular functionality and associated requirements tied to that functionality. This must be recognized and incorporated into the design and the operational use of the capabilities enabled by this comprehensive view of digitalization. At the same time, it is imperative that the aggregate solution represented by the digital infrastructure be considered holistically to obtain the maximum benefit at an enterprise (e.g., a nuclear unit, a multi-unit facility, or at a utility fleet level).

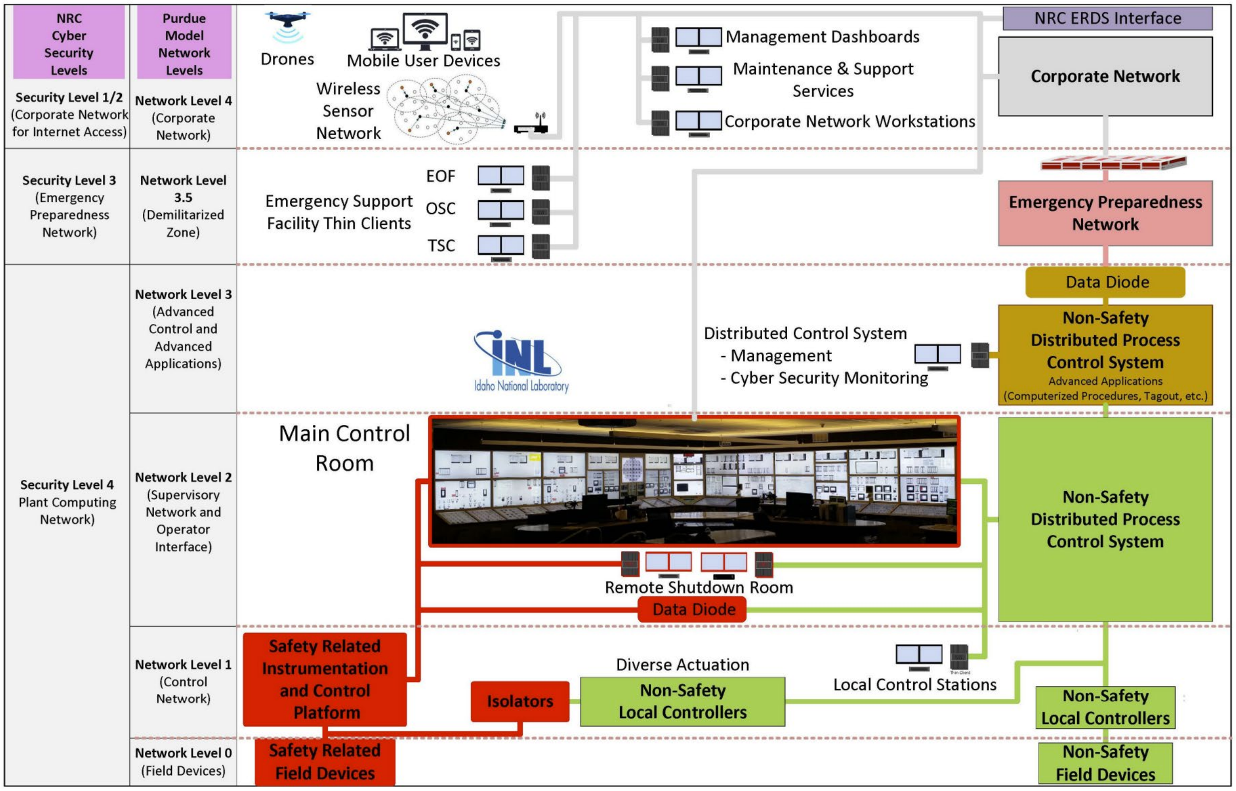

Figure 34. Simplified I&C framework.

A more detailed presentation of the digital infrastructure concept, its design philosophy, and its envisioned utilization is provided in (Hunton, England 2021), "Digital Infrastructure Migration Framework Report." It has been briefly summarized here to point the reader to this research as an enabler of the ION model, and to provide context for the digital I&C work reduction opportunities discussed below.

6.2.3 Maintenance Testing and Surveillance Reduction

Modern digital protection systems are designed with components that can self-perform diagnostics and execute the types of health checks currently accomplished during surveillance testing. In some cases, these automatic diagnostic tests are performed continuously as an inherent design feature that eliminates the existing surveillance completely, including recording and storing of results. In other cases, they can be performed on-demand at a pre-determined interval. Results of these activities can be automatically recorded and stored in a digital format. There are means of verifying acceptable channel calibrations by automatically cross-checking with redundant instrument channels or cross-checking related plant parameter instruments.

Not only is considerable labor saved with digital I&C self-checking features, but other benefits are gained as well. Confirmation that the protection features are working is obtained far more frequently than with conventional surveillance testing. The testing is safely performed by software and is not intrusive, leading to the elimination of potential configuration errors. These systems also offer diagnostics that quickly allow the I&C technicians to locate failed components (e.g., circuit boards) and replace them, thus minimizing inoperable time on the failed circuit. All of this adds up to improved reliability and availability of protection systems while lowering plant O&M costs.

6.2.4 Digital Control Room and Operational Efficiency

Access to corporate network resources has been provided in most nuclear plant main control rooms (MCR) to improve administrative efficiency. Additionally, a number of digital upgrades to non-safety I&C systems have been performed by nuclear utilities. However, most non-safety digital I&C upgrades have been point solutions that have provided like-for-like replacement of functionality in the field. Even when limited additional functionality has been provided (e.g., automating a main turbine startup), nuclear utilities have been reluctant to undertake significant I&C related upgrades of the MCR HSIs. Concerns with regard to cost, regulatory risk, and impact on the large investment in procedures, training programs, and other support functions have impeded large MCR I&C HSI upgrades. Additionally, there is a degree of organizational inertia where current operators familiar with existing control room arrangements and functionality are reticent to change.

Such thinking does not address the significant obsolescence problem in maintaining the existing MCR HSIs. It also does not account for the operational benefits of leveraging and integrating digital HSIs in the MCR. Finally, it does not address the negative reaction of a sizable portion of the current workforce when they come into the existing MCRs. Younger workers expect nuclear plant MCRs to use modern technology with which they are familiar so that they can apply their skills. Instead, they see MCRs designed with technologies used in the 1940s through the 1980s.

Introducing digital systems into the MCR creates opportunities for reducing workload and enhancing human performance while at the same time reducing human errors. This is especially true of a digital safety I&C platform connected (via a one-way data diode) to non-safety distributed control system (DCSs) platform. Such a configuration (as shown at Purdue Model network level 2 in Figure 34) presents plant data and affords for plant control using video display units in a way that can meet individual I&C platform requirements while, at the same time, optimizing its presentation to improve human performance. This is opposed to existing MCR HSIs where antiquated individual parameter indications (e.g., paper strip chart recorders or meters) and control switches are available in just one visual location on the control board.

State-of-the-art human performance engineering techniques are able to leverage these digital capabilities to support more effective operator performance. This results in a more human-centered main control room. These techniques can be applied on a proportional basis for a hybrid control room (a mixture of analog and digital I&C technologies), eliminating the need for a full-scope approach to control room modernization. Improvements can be accomplished through gradual change and stepwise projects.

Modern digital I&C systems combined with other digital capabilities provided by applications throughout the digital infrastructure can enable significant efficiencies in completing operational and control room tasks, tests, and evolutions. This includes reducing auxiliary operator and maintenance technician field time. The result is labor savings for control room operators, field support, and oversight, including:

- More efficient control room and related field operations and reduced time to execute plant evolutions. Higher levels of automation allow operators to initiate commands while remaining in a state of monitoring and oversight.
- The reduced administrative burden for the operations staff due to logging and archive features of the digital technologies.
- The inherent reliability of the digital systems and the elimination of discrete devices and alarms prevent inattention to component failures that may result in operator workarounds and other operational burdens.

- The HSI of digital systems standardizes and simplifies operations as opposed to the current or legacy array of devices inside and outside the control room.
- Task-based displays bring the plant data and controls for a given plant evolution to a single or cluster of nearby displays that eliminates the need for operators to move around the control room accessing discrete devices.
- Properly controlled access to other applications/information at the corporate network level can also reduce MCR workload and improve overall plant situational awareness. Digital work packages can be reviewed from the business network. Capabilities for MCR operators to track the performance of work in the field can be supported. Prognostic and diagnostic information concerning plant equipment performance at the corporate network level could also be made available to plant operators to alert them of potential operational issues with plant equipment. While these data could not be used directly by MCR operators to manipulate plant equipment, they could help direct operator attention to their I&C systems to establish whether those indications confirm an operational issue that they may have otherwise not observed.

The cost avoidance of this work reduction opportunity reflects reduced staffing in operations, engineering, maintenance, and regulatory compliance by eliminating a number of different tasks involved with plant operations and support of control room functions. Operators, if needed for ancillary purposes such as emergency response, can be redeployed to other support tasks when not needed in normal control room operations. Other support tasks related to degraded control room functions, whether they are engineering or regulatory compliance issues, are avoided by the reliability and operator self-service features of a digital control room. These reductions have a significant leveraged effect given they are performed around the clock for multiple units.

6.2.5 Analog I&C Work Elimination

Modern digital I&C systems for control, protection, and control room features eliminate these discrete devices and the significant workload they represent for maintenance and engineering. When going from an analog system to a digital replacement, the number of piece parts that make up the existing system can be reduced dramatically (about 70%). There is simply less equipment to fail and repair in digital systems.

Also, in properly designed digital systems, control and protection features are never “lost” because of a digital hardware failure if they are implemented in standard I&C equipment and software. In redundant implementations, automatic failover to the backup occurs with no loss of function. In redundant and nonredundant applications, failures are typically detected automatically down to the field replaceable unit. Failed hardware can be quickly replaced, and software reloaded (if necessary to restore functionality in most digital failure scenarios). In the event of failure of HSI equipment, such as displays, keyboards, etc., these functions can temporarily be assigned to other functioning HSI equipment in the control room while the degraded component is quickly replaced. None of this involves intrusive component troubleshooting and repair and can typically be done with the systems online. The expense of the replacement parts is also minimized, with replacements typically being standard circuit boards, displays, power supplies, etc., compared to the large volume of expensive discrete logic devices.

6.2.6 Obsolescence, Spare Part Reduction, and Obsolescence Management

Obsolescence of discrete I&C parts is a large issue facing the maintenance of legacy analog control and protection systems in nuclear plants. This includes the thousands of devices on the control boards of a conventional control room. These devices are subject to declining support from their suppliers due to non-nuclear industry transition to modern digital systems. In many cases, components are no longer commercially available and nuclear plants are internally repairing components or having third parties re-engineer and fabricate replacement parts. This technique is expensive and risky, especially when it entails qualification for safety-related use.

When effectively managed through careful vendor selection and a continuous lifecycle management program, digital infrastructure obsolescence issues can be economically and technically addressed. This is best achieved by carefully selecting and "decoupling" digital infrastructure hardware and enabling foundational software and firmware (e.g., operating systems, cyber security capabilities) from the applications that it hosts at each Purdue Model network level. In this way, the intellectual property investments made on these enabling applications can be harvested with minimal (or no) revalidation testing as the digital infrastructure is periodically refreshed as required to account for advancing technology.

6.2.7 Technology and Investments Required for Digital I&C

6.2.7.1 Computer-based Procedures

Computer-Based Procedures (CBP) involve the digitalization of detailed approved procedures with embedded process workflow. CBPs show the same information as paper-based procedures, but via computers and other mobile devices. CBPs can also show real or near-time plant status, and deliver just-in-time training, output diagrams, and other photographs. Compared to paper-based procedures, CBPs require fewer resources for the creation, updates, revisions, distribution, etc. In addition, to reduce workload for creation and maintenance, CBPs can positively impact personnel performance by allowing for the seamless transition between procedures and presenting situation-based instructions based on plant data and previous logs. Figure 35 shows an example of a CBP presented on a mobile device. This image indicates how completed, active, and future steps can be presented to the user.

This technology is also used in Process Re-Engineering and Automation.

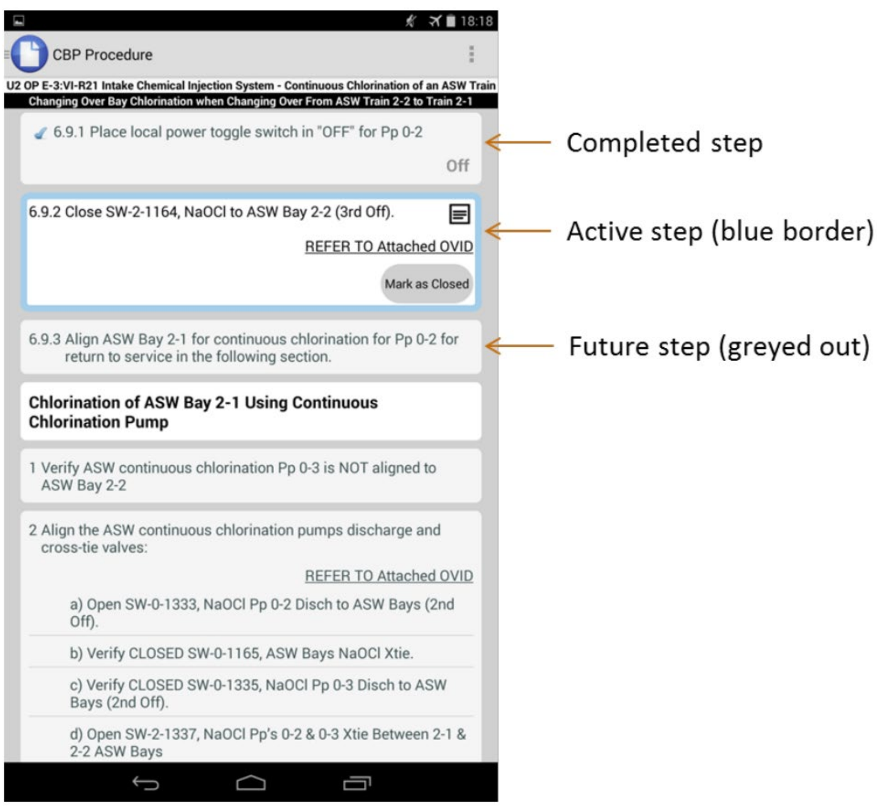

Figure 35. Computer-based procedures can indicate completed, active, and future steps to users.

6.2.7.2 Digital I&C Systems

Digital I&C safety systems at Purdue Model levels 0, 1, 2, and 3 (as appropriate) include systems to support plant operations in the event of an incident or power outage. Elements of an I&C safety system include safety-related HVAC controls, accident sequencers, reactor protection systems (RPS), etc. The RPS, for example, prevents the operation of the reactor in an unsafe condition by shutting down the reactor whenever limits of safe operating conditions are reached. Like other I&C safety systems, the RPS will continue to survey variables for tracking purposes.

Modern digital protection systems have a number of features that can self-perform the types of health checks currently done in surveillance testing. In some cases, these are performed continuously. In other cases, they can be performed on-demand at any desired interval. There are even means of verifying acceptable channel calibrations by cross-checking with redundant instrument channels or cross-checking related plant parameter instruments.

Digital I&C non-safety systems available in the industry offer the capability to host all non-safety I&C functionality in a nuclear plant (as business analyses would dictate). These systems are typically developed by non-nuclear vendors with deep, worldwide market penetration. If properly leveraged, (Hunton 2019) this technology can be economically employed and supported through a well-defined, vendor-managed obsolescence management program (Hunton, et al. 2019).

Transitioning to a two-platform (one safety platform and one non-safety platform) provides a multiplying factor when digitizing I&C systems in these two areas. This allows for cost savings through:

- Standardization of equipment/software (reducing parts stores)
- Standardization of implementation (across multiple legacy functions migrated to a platform)
- Standardization of Human Factors Engineering implementation and HSI development
- Lifecycle management consolidation to a minimum number of vendors/technologies.

6.2.7.3 Digital Document Review and Archiving

Document digitization software automatically converts all printed files, office documents, procedures, etc., into sortable and searchable files. Digital files have low storage requirements and are accessible by computers, mobile, and other electronic devices. By digitizing documents, they can be easily managed in digital libraries. Additionally, digitization software saves time by converting documents into editable text for reuse. This is primarily done at Purdue Model network level 4.

This technology is also used in:

- Advanced Training Technology
- Process Re-Engineering and Automation – Campaign Maintenance ION Generation 1 transformation domains.

6.2.7.4 Communication Network (Wi-Fi or Equivalent)

High-bandwidth wireless systems hosted at the Purdue Model network level 4 are capable of supporting several gigabits of upstream and downstream data transmission. This network is necessary to support substantial amounts of data being uploaded and downloaded by digital components throughout the plant. Additionally, by transitioning to wireless communication, plant personnel will be accessing plant information through mobile devices (e.g., smartphones and tablets).

This technology is also used in:

- Condition-based Monitoring and Maintenance
- Advanced Analytics and Assurance

- Plant Automation
- Process Re-Engineering and Automation
- Mobile Worker Technology
- Advanced Training Technology
- Remote Collaboration
- Work and Requirement Reduction
- Security.

6.2.7.5 Mobile Devices and Mobile Video

Mobile devices and mobile video include smartphones, tablets, and wireless video cameras. These are hosted at Purdue Model k level 4. Plant personnel can use these mobile devices to monitor, track, and trend component information that is captured by digital components. Mobile devices can also be used to deliver high-priority notifications to plant personnel. Additionally, these devices can be used to access digitized/CBP, work orders, training, and drawings. Workers are also able to join a video call with other colleagues throughout the plant site and in other remote locations.

This technology is also used in:

- Mobile Worker Technology – Fieldwork Task Consolidation
- Mobile Worker Technology - Fieldwork Preparation and Coordination.

6.2.7.6 Large Overhead Displays

Large overhead displays include large computer monitors used to broadcast plant status and control information to personnel. For I&C systems, these are primarily hosed on the non-safety DCS at Purdue Model level 2 in the MCR. These can also be used in emergency response facilities (Purdue Network level 3) and to support enterprise-level functions such as at a corporate maintenance and diagnostic center (at Purdue Network level 4). In addition to displaying plant status, these large overhead displays can be used to show alarms and information for other emergency or accident conditions. Information presented on these displays can also be configurable by crew members to ensure efficient and effective interaction and coordination. Overhead displays can also temporarily be assigned to other functioning equipment in the control room if another display or control room component needs to be replaced. This process does not involve intrusive component troubleshooting and repair and can typically be done with the systems online.

6.2.7.7 Component Identification Technology

Component identification technology includes quick response (QR) codes, optical character recognition (OCR) technology, and radio frequency identification (RFID). The use of this technology would be at Purdue Network level 4.

QR, or quick response codes, are a type of matrix barcode. QR codes are machine-readable optical labels that contain information about the item to which it is attached. QR codes can be read by an imaging device, such as a smartphone, and processed until the image is interpreted. QR codes can be used for item identification, time-tracking, document management, etc.

OCR, or optical character recognition technology is software that recognizes and converts handwritten or printed text into machine-encoded text. This technology is typically used in data entry tasks when digitizing documents. OCR technology allows for documents to be electronically edited, sorted, and stored more efficiently.

RFID uses electromagnetic fields to automatically identify and track tags that are attached to objects. This technology requires the use of small radio transponders, a radio receiver, and a transmitter. Tags that are attached to objects transmit data when triggered by an electromagnetic pulse from a nearby RFID reader.

This technology is also used in:

- Plant Automation – Workflow-enabled clearance tagging, lock out tag out
- Plant Automation – M&TE controls – Tool tracking.

6.2.7.8 Technology Deployment Readiness

Table 14 indicates the deployment readiness of each of the technologies discussed above.

Table 14. Technology deployment readiness.

Technology	Widely Deployed	Narrowly Deployed	Not Deployed
Computer-Based Procedures		X	
Digital I&C Safety Systems		X	
Digital Document Review and Archiving			X
Communication Network	X		
Mobile Devices and Mobile Video	X		
Large Overhead Displays	X		
Component Identification Technology		X	

6.2.8 Necessary Research and Development Needed to Achieve ION Gen 1 Business Model Cost Reductions Within 5 Years

Further research is needed to identify nuclear I&C safety and non-safety systems, in both pressurized water reactors (PWRs) and BWRs, that are most necessary to replace. As the cost to sustain legacy I&C systems and loop components continues to climb, determining which systems and components are better suited for replacement in the near future versus years from now will be helpful. Also, narrowing the cost range for the systems will help make the NPV model more accurate and applicable. This can be done by surveying additional utilities and engaging the vendor community and OEMs for budgetary pricing.

There is a significant amount of upgrading and replacement that can take place with technology already commercially available in the marketplace. Advancements made in other industries are applicable to the nuclear industry with minimal changes. This is encouraging for any utilities planning on a significant upgrade cycle to their I&C systems. Finding products from other industries and researching their suitability for nuclear can open new avenues for OEM participation in a digital I&C plant upgrade.

Other research could focus on a fully digital infrastructure business case that includes the I&C framework presented in Figure 34. This would aid nuclear plant operators in considering large scope upgrades for the future reliability and availability of their plants.

6.2.9 ION Model: Net Present Value Analysis

Based on INL's research of Digital I&C upgrades as described in the ION model, this work reduction opportunity has a 66% chance of achieving a positive net present value outcome as indicated in Figure 36.

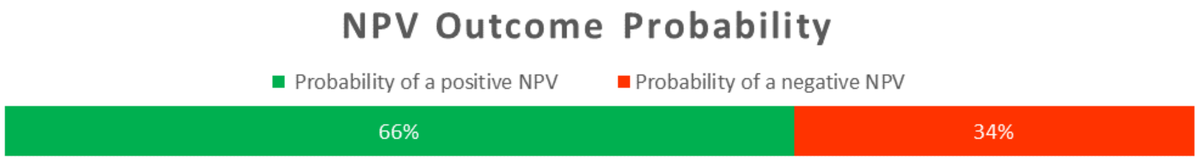

Figure 36. The probability of a positive or negative NPV outcome for the digital I&C work reduction opportunity.

Note that the digital I&C upgrades included in the scope of this report are fundamental and essential to any operating nuclear facility which expects to be in operation for decades to come. Utilities that have already begun the analog to digital transition used similar logic to justify the expense. Replacing analog components with digital equivalents is necessary for the continued long-term operation of the nuclear plant. The risk of relying on existing analog systems and components will continue to rise in the coming years threatening safe and efficient operation. Additionally, the cost of spare parts and rate of obsolescence of existing analog components will significantly increase in the coming years.

6.2.10 Validation Methodology

In the previous report, the ION model used single value estimates for each input to the model. This achieved a deterministic estimate of the overall cost and savings associated with each work reduction opportunity.

Inputs to the Digital I&C section of the model included the following:

1. One-time and ongoing cost of the following technological upgrades
    a. Computer-Based Procedures
    b. Digital I&C Systems
    c. Digital Document Review and Archiving
    d. Mobile Devices and Mobile Video
    e. Large Overhead Displays
    f. Component Identification Technology

Number of full-time equivalent hours saved in the following areas
- a. Surveillance Reduction
- b. Digital Control Room
- c. Analog I&C Work

Additional savings
- a. Obsolescence and Spare Parts.

This next phase of ION model preparation involved collecting a range of data points for each input. Additional data points were found by reaching out to nuclear utilities and gathering input. Other data points were mined from complementary research. These actions achieved a range for each input to the model representing the range of actual values and the uncertainty found in estimating large multiyear projects. For this analysis, a cost of $163K per FTE with a yearly salary increase of 3%, was assumed. Last, an 8% cost of ownership was applied.

A communication network and digital components are necessary investments for this WRO. However, for this analysis, the communication network is incorporated into the NPV model for Condition-Based Maintenance, also analyzed in this report. Digital components are included in this analysis, but participant utilities combined those components within the digital I&C systems category. Therefore, Figure 37 and Figure 38 do not include separate costs for digital components or the communication network. Additionally, not all participant utilities are including component identification technology within the I&C work scope. As a result, the range of costs included in this analysis is from $1, representing no installation, to $50K indicating incorporation of the category.

As a result of obtaining data ranges for each input, the ION model calculation can now utilize a stochastic methodology. The following charts represent ranges captured for each model input in graphical form.

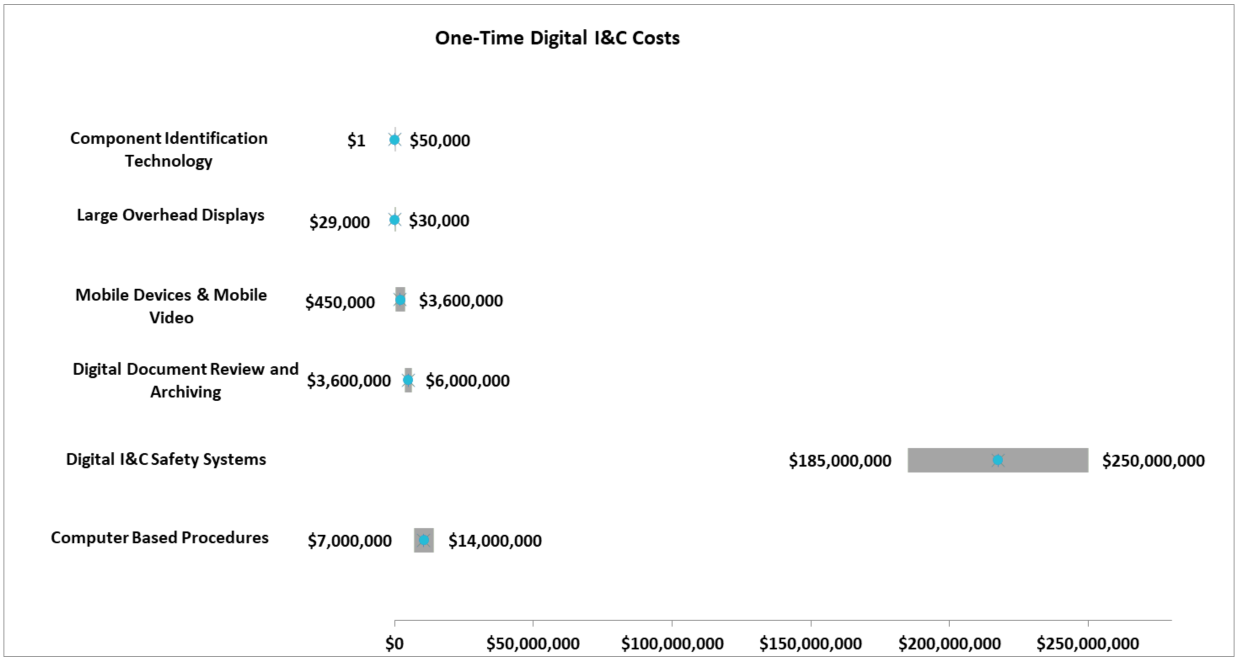

Figure 37. One-time digital I&C hardware and software costs

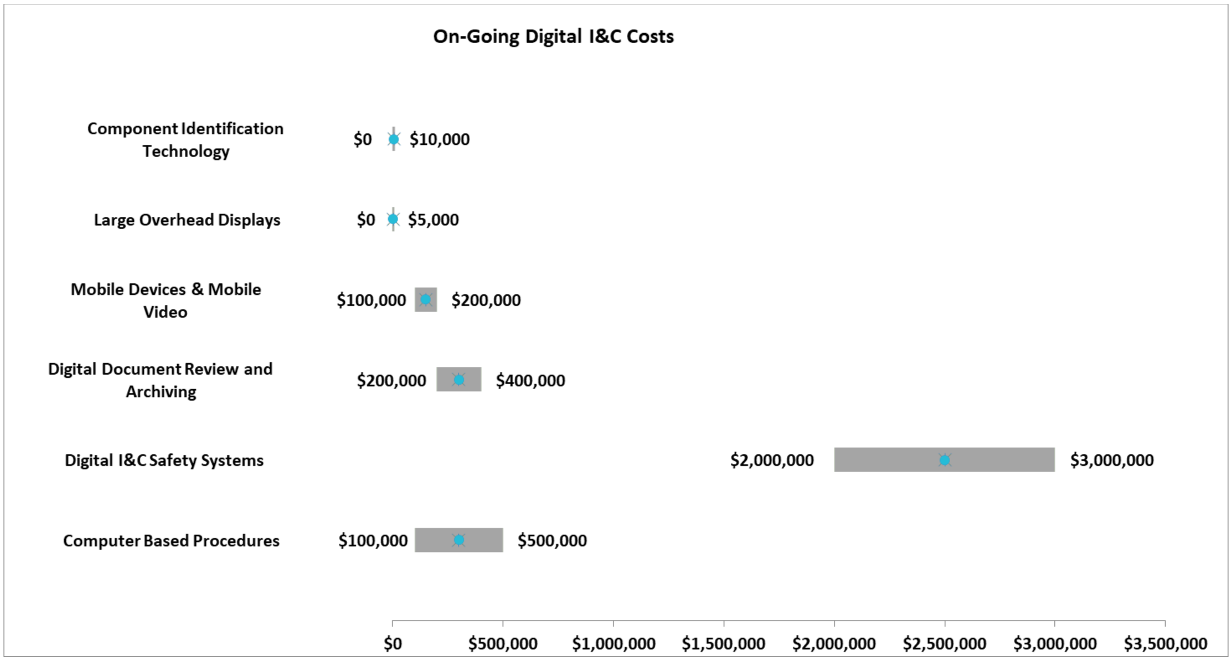

Figure 38. Ongoing digital I&C hardware and software costs

6.2.11 Areas of Uncertainty (Investment, Ongoing, Savings)

Areas of uncertainty are found by calculating the standard deviation of each technological upgrade range. The one-time purchase and implementation of digital I&C systems represent an input with high model uncertainty. The model used a range between $185M and $250M. The minimum and maximum cost range has a standard deviation of $32.5M.

The cost of this technology ranges significantly due to differing I&C systems and plant designs, as well as the varying functional needs of the plant site. Additionally, the number of components and points included in the scope of this work reduction opportunity can have a significant impact on the one-time and ongoing implementation costs.

The one-time purchase and implementation of CBP also represent an input with high model uncertainty. Due to the cost uncertainty associated with CBP, the model used a cost between $7M and $14M. The minimum and maximum value range has a standard deviation of $3.5M.

The cost of this technology ranges significantly due to the functional needs of the software, and the quantity of procedures to be included. The number of procedures to be digitized and transitioned to CBP has the most significant impact on the cost of this technology. The greater the number of procedures to be digitized, the greater the one-time and ongoing costs.

6.2.12 Ongoing Costs

All technologies required for this modernization have associated ongoing costs. These costs represent ongoing maintenance and service contracts held with the original installer, OEM, or component supplier for each technology. It also represents periodic internal maintenance upgrades. These service contracts or self-performed upgrades are required to ensure support for ongoing hardware and software functionality. It is estimated that once every five years the software systems will require maintenance and upgrades.

6.2.13 Model One-Time Costs, Ongoing Costs, and FTE Saving Input Values

6.2.14 Projected Savings

Minimum and maximum input values to the ION model as shown in Table 15 were used to find a population of net present values. Employing a Monte Carlo simulation, the model arrived at a standard distribution of 5,000 expected outcomes. Each outcome was plotted along a normal distribution curve. A positive NPV indicates a favorable business case for the project investment, indicating the project is expected to return more free cash to the utility. A negative NPV indicates that the business case is not favorable and that the project will return less free cash to the utility.

Nuclear plants in the United States are contemplating license extension to sixty, eighty, and even one-hundred years. Any plant considering operation beyond sixty years, a project to upgrade digital and I&C systems is being considered. Naturally, the digital I&C work reduction opportunity requires significant capital expenditure, planning, engineering, and installation over multiple years. Due to the size and scope of the digital I&C work reduction opportunity, it is expected that the upgrades will only occur once in remaining plant life. It is for these reasons the digital I&C work reduction opportunity is modelled differently. Calculation of the net present value of this work reduction opportunity was done using a thirty-year period, rather than the twenty used in the other four work reduction opportunities included here. Researchers also included an obsolescence cost to this work reduction opportunity. The increase in replacement component costs becomes a limiting factor in later years of the model. High component costs in later years of the model represent the coming time when replacement parts are so scarce and expensive as to be unprocurable.

The cost of acquiring obsolete components for digital I&C systems, many of which are obsolete and out of production, is significantly increasing year-over-year. By replacing legacy and obsolete components with digital equivalents, the cost of obsolescence can be avoided. In the ION model, a range of expected annual component replacement cost increases was used to account for the savings. The model used a range between 18% and 24% using input from research found in (England 2020), "Business Case Analysis for Digital Safety-Related Instrumentation and Control System Modernizations. Over a 30-year period, the cost of obsolescence has a significant impact on the financial outcomes observed through this opportunity. At 19% increase in digital I&C parts costs per year, the value of this model input approaches $100M spending per year twenty or more years into the future.

For this analysis, the NPV can range between -$201.6 and $1.7B, with a 66% chance of achieving a positive NPV outcome, see Figure 39. The NPV has a standard deviation of $141.3M, see Figure 40.

Due to the rapidly rising cost of obsolescence and spare parts, and the wide range of costs collected from utility participants represented by the large standard deviations, scenarios that approach a positive net present value of $2B exist in the model. They should be considered outliers. The outliers present a right-skewed normal distribution with a large tail on the positive net present value side of the curve in Figure 39 and Figure 40.

Table 15. Digital I&C business case inputs.

Model Input	Minimum	Maximum	Standard Deviation
One-Time Hardware and Software Costs			
Computer-Based Procedures	$7,000,000	$14,000,000	$3,500,000
Digital I&C Safety Systems	$185,000,000	$250,000,000	$35,000,000
Digital Document Review and Archiving	$3,600,000	$6,000,000	$1,200,000
Mobile Devices and Mobile Video	$450,000	$3,600,000	$1,575,000
Large Overhead Displays	$29,000	$30,000	$500
Component Identification Technology	$1	$50,000	$25,000
Total:	*$196,079,001*	*$273,680,000*	*$38,800,500*
Ongoing Hardware and Software Costs			
Computer-Based Procedures	$100,000	$500,000	$200,000
Digital I&C Safety Systems	$2,000,000	$3,000,000	$500,000
Digital Document Review and Archiving	$200,000	$400,000	$100,000
Mobile Devices and Mobile Video	$100,000	$200,000	$50,000
Large Overhead Displays	$0	$5,000	$2,500
Component Identification Technology	$0	$10,000	$5,000
Total:	*$2,400,000*	*$4,115,000*	*$3,257,500*
FTE Savings			
Surveillance Reduction FTE Savings	14	16	1
Digital Control Room FTE Savings	24	26	1
Analog I&C Work FTE Savings	8	10	1
Cost of Capital	8.75%	10.50%	0.88%
Obsolescence and Spare Parts Savings	$800,000	$1,000,000	$100,000
FTE Cost Increase	3%		
Yearly Salary Blended Rate per FTE	$163,000		

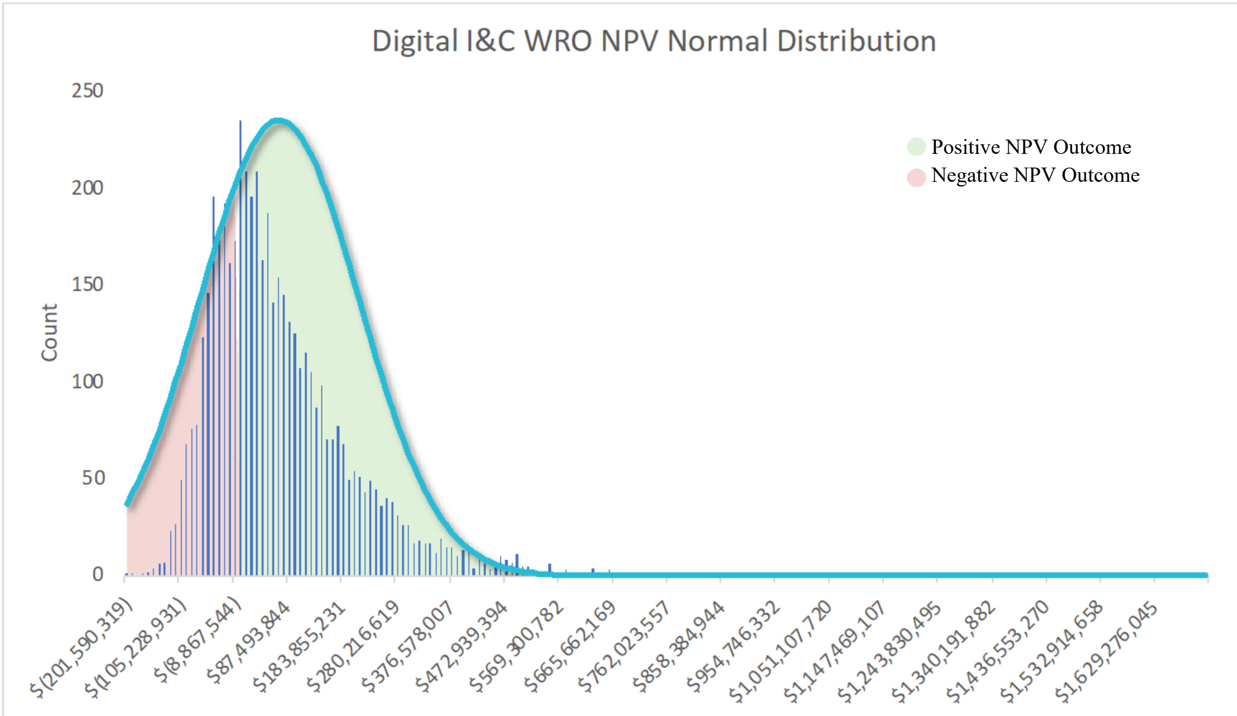

Figure 39. NPV distribution of digital I&C technology.

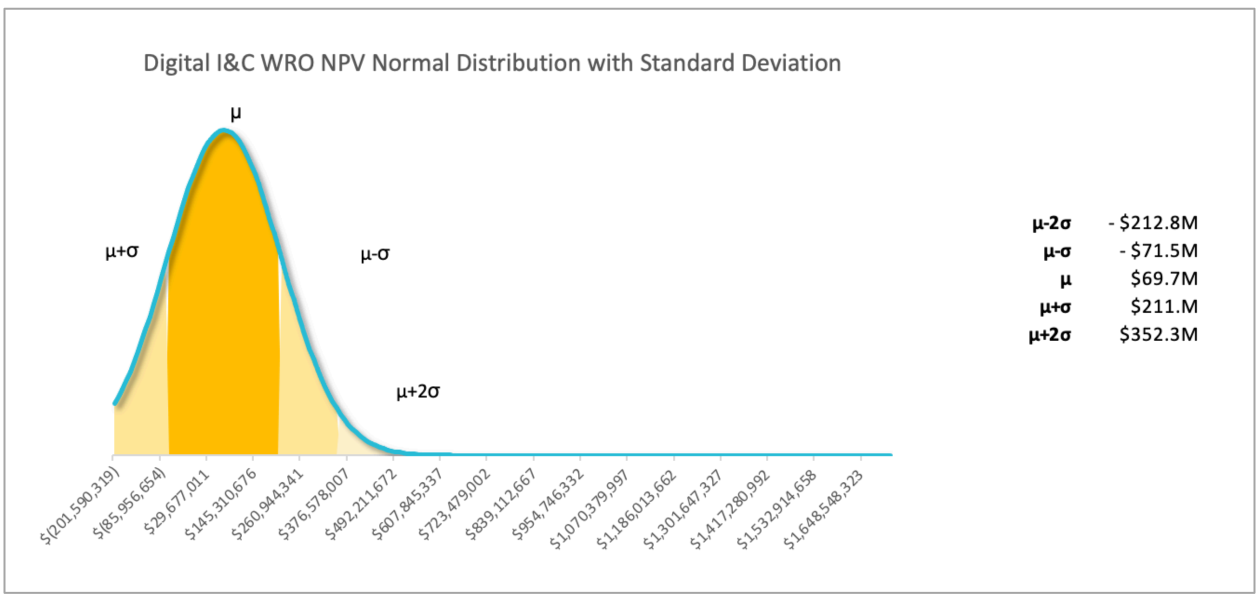

Figure 40. Normal distribution of I&C technology.

To provide more detail into the NPV outcome, Table 16 indicates the percent chance of achieving certain NPV values or greater. For example, investing in Digital I&C has a 20% chance of resulting in an NPV of or more and a 10% chance of resulting in an NPV of $241.5M or higher.

Table 16. NPV per percentile.

Chance of Achieving NPV	NPV Value or Greater
50%	$37.5M
40%	$67.9M
30%	$105.1M
20%	$155.9M
10%	$241.5M

6.2.15 Lessons Learned from Early Implementations

While surveying U.S. utilities it was found that the substantial investment required to upgrade the digital I&C plant systems was viewed through the lens of continued reliable plant operation. These investments were required to continue that operation for the coming decades. In this way, the main priority was slightly different from the ION approach, but the scope and scale of the project was exact.

6.3 Automated Planning and Scheduling

6.3.1 Scope of Work for Reduction Opportunity Analyzed

Traditional nuclear work management activities require multiple skills and efforts by individuals in the planning and scheduling departments. There are two main categories of nuclear plant maintenance work orders: preventative maintenance and corrective maintenance work orders.

Preventative maintenance work orders are, by definition, repetitive. They are generated from model work orders with little to no additional treatment from maintenance planners. Preventative maintenance work orders follow performance frequencies dictated by the PM model. They are required to be completed in a defined time window, making scheduling these work orders repetitive.

Much of the novel work management process is initiated when a discovery is made of conditions in the plant that necessitate a maintenance activity. Work requests are written and entered into the work management system by plant employees who witness component conditions or other indications of a maintenance need. The benefits of implementing automated planning and scheduling at a plant site will be prominent within the corrective maintenance workstream.

After a work request is initiated, it is screened by work control to determine its merit and priority. Priority is influenced by how the issue may impact plant events, generation, and safety. The scope of the work request is based on the pre-written comments and other outstanding related work orders or work requests open in the system.

If the work request passes screening, it is prioritized and sent to a maintenance planning department. Maintenance planners then place it in the queue of work orders to be planned. The work order's position in the queue and its assigned department is based on priority, topic, complexity, and component category (i.e., mechanical, electrical, civil, etc.).

Once the maintenance planner starts planning, the research and assembly of the work order begins. The Planner may conduct a walkdown of the component in question, speak to the originator, and/or open and read previous work orders for the same component or failure mode. The Planner may also read the operation and maintenance manual of the component to gain insight into methods of repair, review drawings, and assemblies, and determine appropriate parts for replacement.

As the planner moves through the process of planning the work order, it is simultaneously scheduled in the appropriate work week. This satisfies the urgency indicated by the work order priority. It is also necessary to find a location in the schedule when the component itself and the necessary craft are available to execute the work. Schedulers balance many inputs to accommodate safe operation of the plant and the system, timely and effective maintenance, craft workload, and parts availability.

6.3.2 ION Model for Automated Planning and Scheduling

The ION model suggests an automated process by which simple and repetitive work orders are processed, planned, and scheduled.

A majority of maintenance work orders are not topically unique in nature. In other words, components can fail in only so many ways. Methods for fixing typical component failures are well understood by the plant, the industry, the manufacturer, and the research community. Many corrective techniques have been previously performed at the site or elsewhere in the fleet. As such, this repository of previously performed work in the form of electronic data should be considered an asset that can add value in an automated way to the planning and scheduling workflows.

Assembling and organizing the repository of past work orders into a database will allow the software to draw upon previous instances of completed maintenance for work orders currently being planned. As new work requests are generated manually, the software can read text descriptions and search previously planned and completed work orders in the database for matches. Additionally, sensors placed in the plant can monitor components or processes that can be programmed to send alarms or error signals indicating a parameter out of specification. These signals can then be tracked and picked up by software tools. The software then initiates the work order process by generating a work request. A planning algorithm can draw out previously completed work order instructions as well as accompanying tasks on the same work order such as a painting task or insulation work.

Parts from the catalog that were required and consumed by similarly completed work orders can be pre-populated for review by the Planner. Collection of references like drawings, vendor manuals, photos, and other work order inputs needed to plan the new tasks can be assembled automatically.

Based on the component tag number and all the parameters associated with that tag like safety or production significance, maintenance classification, passive or active function, and even upcoming tests or plant maneuvers that will require the part’s full functionality, a suggested work order schedule placement can be automatically generated. The scheduling decision engine can also incorporate current maintenance crew workload and parts availability or supply chain lead times to assure the work is performed at the optimal occasion. An intelligent Work Management tool can also group multiple work orders together thereby scheduling maintenance for multiple components that reside within the same clearance boundary and minimizing system outages and operator clearance activities.

As a result of these and other features of automated planning and scheduling, significant savings can be achieved.

6.3.3 Technology and Investments Required for Automated Planning and Scheduling

6.3.3.1 Business Process Automation (BPA) Tools

Business process automation is a software tool that automates or assists portions of the work management process. This software tool can be used to address tasks such as initiating a work request from component sensors to archiving work order completion information and QA records. These tools work by analyzing historical plant data, plant OE, and changing plant conditions to pre-plan work orders, and schedule online or outage work. Some BPA tools can also be used to optimize scheduling by bundling similar work opportunities, determining the need for operator walk-downs, and tracking task progress. Additionally, BPA tools can also be used to forecast parts and materials, analyze warehouse inventory, and optimize storage costs.

The goal of utilizing BPA tools is to streamline time-consuming and highly manual processes, such as searching and compiling plant data, validating work skills and qualifications, and creating work orders and work packages. This technology is also used in campaign maintenance.

6.3.3.2 Common Failure Mode Tracking

Common failure mode tracking is a module or functionality to be included in common enterprise asset management tools. Common failure mode tracking analyzes historical work orders and failure mode history across plant assets and uses artificial intelligence and machine learning to automate planning. Once a failure mode is identified from a work request, the software analyzes the failure mode history of that tag number or other similar components and then delivers an optimized maintenance plan based on past equivalent failure modes.

6.3.3.3 Artificial Intelligence/Machine Learning Using Natural Language Processing

Artificial intelligence (AI) solves problems and completes tasks using computer science and complex datasets. AI often encompasses machine learning (ML), which enables software to predict outcomes more accurately without explicit programming. This is accomplished by analyzing historical datasets.

Natural language processing (NLP) is the ability of a computer to understand human language. Like machine learning, NLP is also a component of AI. NLP requires preprocessing data by preparing and cleaning text data for machines to analyze. This can be done by breaking down the text into smaller units, removing common words such that only unique words remain, or tagging specific parts of the text, such as adjectives and verbs. Algorithm development then creates linguistic rules using statistical methods to determine the context of a text group. Automated planning and scheduling combine both AI and ML techniques.

This technology is also used in:

- Plant Automation – Crew Scheduling
- Plant Automation – Auto-assist Condition Reporting Analysis
- Plant Automation – ALARA Planning
- Plant Automation – Decontamination Robotics.

6.3.3.4 Technology Deployment Readiness

Table 17 indicates the deployment readiness for each of the technologies described above.

Table 17. Technology deployment readiness.

Technology	Widely Deployed	Narrowly Deployed	Not Deployed
BPA Tools		X	
Common Failure Mode Tracking			X
Artificial Intelligence and Machine Learning (AI/ML) using NLP			X

6.3.4 Research and Development Needed to Achieve ION Gen 1 Business Model Cost Reductions Within 5 Years

The industry can benefit from additional research into the scope and cost of common failure mode tracking and AI. These technologies are not yet widely deployed in the industry. Standardization of methods, software, vendors, and features of these technologies may bring costs down and allow for a standard approach to dominate. NLP should be a priority effort in this additional research.

6.3.5 ION Model: Net Present Value Analysis

Based on INL's research of automated planning and scheduling as described in the ION model, this work reduction opportunity has a 75% chance of achieving a positive NPV outcome as indicated in Figure 41.

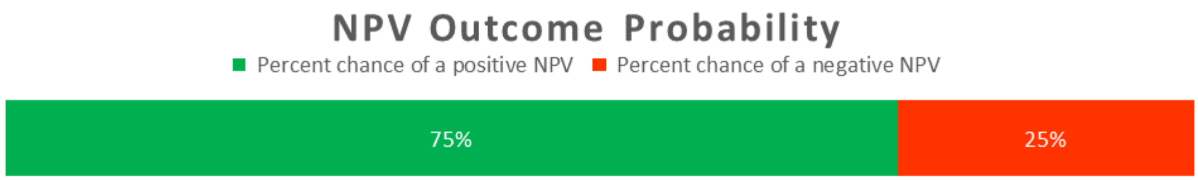

Figure 41. The probability of a positive or negative NPV outcome for the automated planning and scheduling work reduction opportunity.

6.3.6 Validation Methodology

In previous research (INL/EXT-21-64134) the ION model used single value estimates for each cost and savings input to the model. This achieved a deterministic result of the overall cost and savings associated with each work reduction opportunity.

The next phase of ION model preparation involved collecting a range of data for each input. Additional data points were found by surveying nuclear utilities and gathering their input from first-hand knowledge and experience. Additional data points were mined from complementary industry research. This achieved a range of values for each input to the model representing the uncertainty found in estimating large multiyear projects. As a result of obtaining data ranges for each input, the ION model calculation can now utilize a stochastic methodology.

Inputs to the automated planning and scheduling section of the model included the following:

1. One-time and ongoing cost of the following technological upgrades
    a. Automatic Work Release/BPA Software
    b. Corrective Planning and Scheduling Software
    c. Common Failure Mode Software
    d. Natural Language Processing Software

Number of full-time equivalent hours saved in the following areas

    a. Automated Planning and Scheduling.

Figure 42 and Figure 43 represent ranges captured for each model input in graphical form.

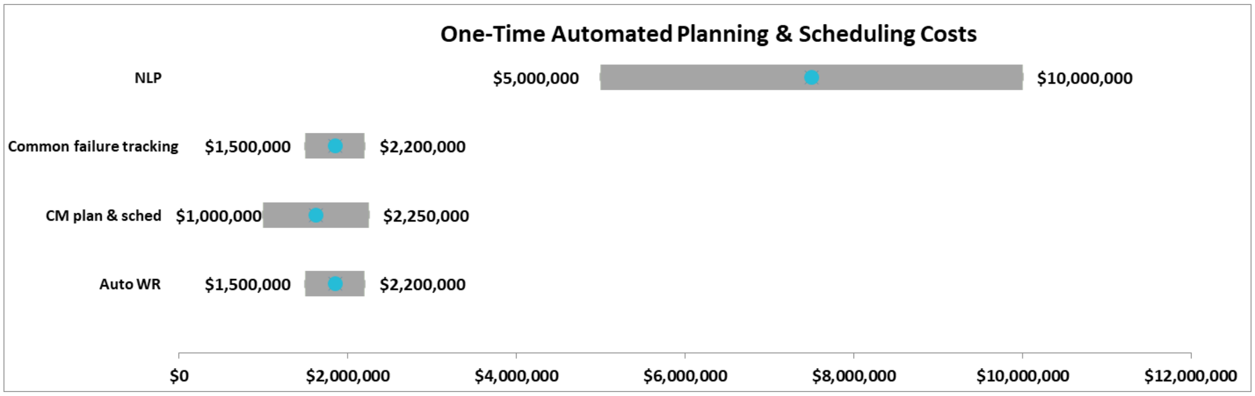

Figure 42. One-time automated planning and scheduling costs.

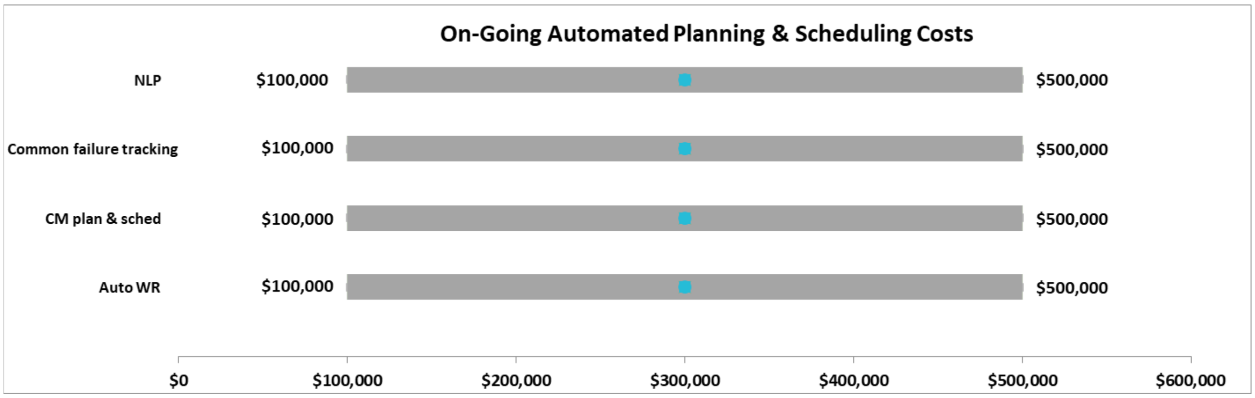

Figure 43. Ongoing automated planning and scheduling costs.

6.3.7 Areas of Uncertainty (Investment, Ongoing Costs, Savings)

Determining areas of uncertainty is represented by the standard deviation of each technological upgrade CAPEX investment. The one-time purchase and implementation of NLP software represent an input with higher model uncertainty. NLP is not a widely used technology and therefore investment costs are not well known. Due to the uncertainty associated with NLP, the investment range used in the model is between $5M and $10M with a standard deviation of $2.5M.

The cost of this technology ranges significantly due to differing module needs. NLP software can range depending on the functional needs of the software. NLP software can come in different packages with features to identify entities and labels by types (person, organization, location), the ability to understand the overall meaning expressed in text, the ability to extract sentences, identify parts of speech, etc.

6.3.8 Ongoing Costs

All technologies required for this modernization have associated ongoing costs. These costs represent maintenance, service, and licensing fees held with the original service/software supplier for each technology upgrade. These service contracts or internal upgrades are required to ensure support for ongoing software functionality. It is estimated once every five years software systems will require maintenance and upgrades. An 8% increase in the cost of upgrades and maintenance was applied every 5 years.

6.3.9 Model One-Time Costs, Ongoing Costs, and FTE Saving Input Values

6.3.10 Projected Savings

Minimum and maximum input values for the ION model, as shown in Table 18 were used to find the NPV of one project. Employing a Monte Carlo simulation, the model arrived at a standard distribution of five thousand expected outcomes. Each outcome was plotted along a normal distribution curve shown in Figure 44.

Table 18. Automated planning and scheduling business case inputs.

Model Input	Minimum	Maximum	Standard Deviation
One-Time Hardware and Software Costs			
Automatic Work Release Software	$1,500,000	$2,200,000	$350,000
Corrective Maintenance Planning and Scheduling Software	$1,000,000	$2,250,000	$625,000
Common Failure Mode Tracking	$1,500,000	$2,200,000	$350,000
Natural Language Processing	$5,000,000	$10,000,000	$2,500,000
Total:	*$9,000,000*	*$16,650,000*	*$3,825,000*
Ongoing Hardware and Software Costs			
Automatic Work Release Software	$100,000	$500,000	$200,000
Corrective Maintenance Planning and Scheduling Software	$100,000	$500,000	$200,000
Common Failure Mode Tracking	$100,000	$500,000	$200,000
Natural Language Processing	$100,000	$500,000	$200,000
Total:	*$400,000*	*$2,000,000*	*$800,000*
FTE Savings			
Automated Planning and Scheduling FTE Savings	7	16	4.5
Cost of Capital	8.75%	10.50%	0.88%
FTE Yearly Salary Rise	3%		
Yearly Salary Blended Rate per FTE	$163,000		

A positive NPV indicates a favorable business case for the project investment, suggesting the project will return more free cash to the utility. A negative NPV indicates that the business case is not favorable and that the project will return less free cash to the utility. For this analysis, the NPV can range between an NPV of -$27.4M and a positive NPV of $42.6M. The project has a 75% chance of achieving a positive NPV outcome, see Figure 44. The NPV has a standard deviation of $8.6M, see Figure 45.

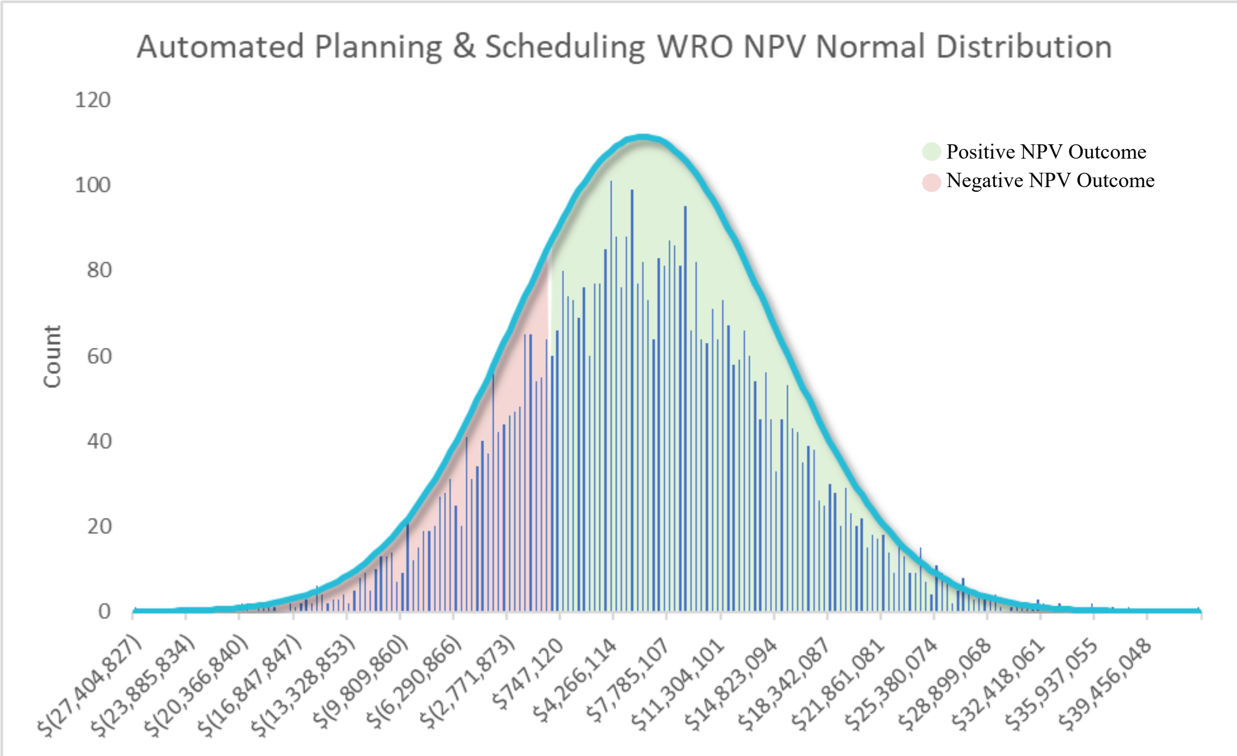

Figure 44. NPV distribution of automated planning and scheduling technology.

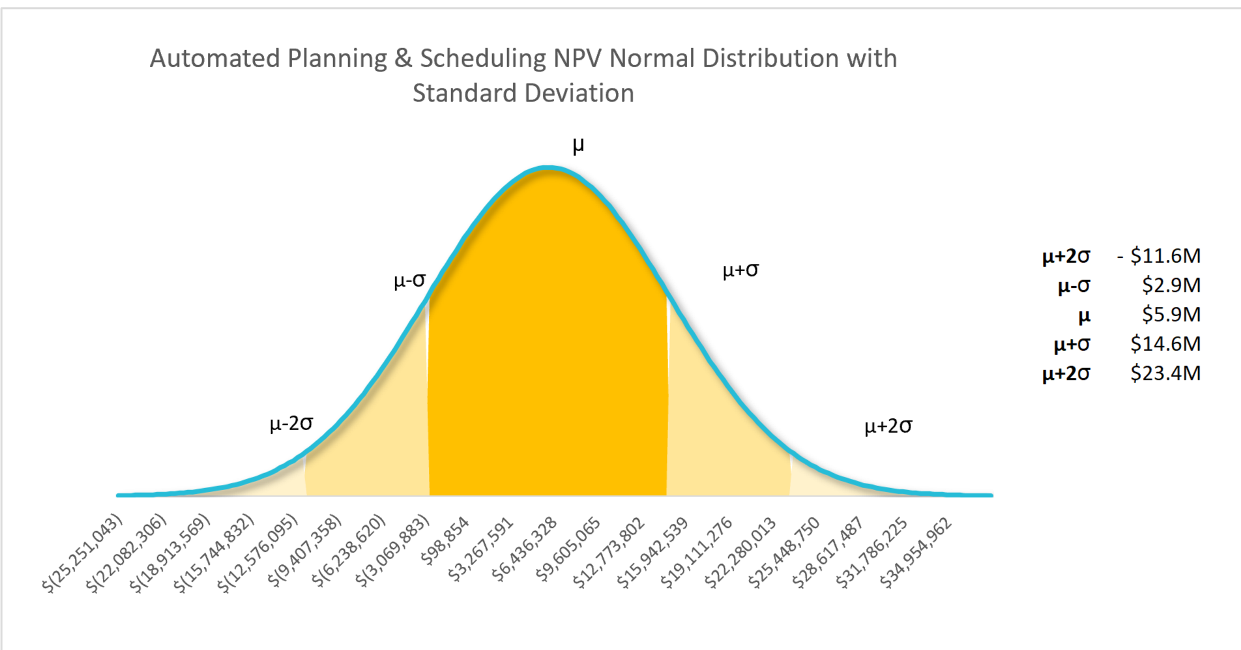

Figure 45. Automated planning and scheduling normal distribution.

To provide more detail on the possibility of achieving a positive NPV outcome, Table 19 indicates the percent chance of achieving a NPV above the breakeven point. For example, investing in automated planning and scheduling has a 20% chance of resulting in an NPV of $13.1M or higher and a 10% chance of resulting in an NPV of $17.0 or higher.

Table 19. NPV per percentile.

Chance of Achieving NPV	NPV Value or Greater
50%	$5.7M
40%	$8.0M
30%	$10.3M
20%	$13.1M
10%	$17.0M

6.3.11 Lessons Learned from Early Implementations

There were no significant lessons learned from the study of this work reduction opportunity.

6.4 Advanced Training Technology

6.4.1 Background/Current Situation

Employee training through classroom instruction, procedural reviews, and the use of hands-on mockups has been in practice for nuclear plants since early construction and remains the staple of the nuclear industry today.

6.4.1.1 Instruction and Delivery Methods

Nuclear operating companies and utilities manage training programs for their workforce and maintain industry accreditation for their programs. Companies employ dedicated, full-time training instructors and deliver training often organized in three sections: operations training, technical training, and general training. Centralized industry produced training that applies to all nuclear professionals is also available for selected topics, often initial introductory courses, or basic academic content (e.g., EPRI – U). Training departments are accredited by INPO and utilize the systematic approach to training.

Full-time training instructors develop and deliver topical material through instructor-led training. Instructors commonly deliver content in a classroom setting however COVID has moved some instructor training to a virtual environment. Instructors deliver training to learners typically in a one-time group setting or class. Classes typically are not recorded. Supplemental resources and links to additional information on the same topic require research to find and access after classroom instruction is complete.

The line organization (operations, chemistry, radiation protection (RP), maintenance, engineering) may also develop material to maintain qualifications or to simply keep the workforce up to date on topics of interest.

Presentation slides are the typical means of presenting information to learners. Information on the slides is in written and bulleted form with a few photos or illustrations. Improved through additional video or enhanced images are rare but helpful. Some programs offer self-paced, on-demand training courses through computer-based training. Computer-based training content is similar in style to classroom presentations but uses additional features that make the experience more engaging. Some nuclear operators are focused on adding computerized just-in-time training and learning resources, but the content is currently limited to a few topics.

6.4.1.2 Learner Experience

Students attend the training in groups or classes and attendance is required during a set time of the day and week. Commonly this requires travel and schedule workarounds to attend classes at a dedicated training center or facility. Many smaller nuclear operators struggle with assembling a cohort with critical mass that will fill a technical training course.

Students who wish to refresh their knowledge on a topic often rely on the original presentation material. This material usually lacks the verbal instructions one would receive from the classroom setting.

Students take tests while sitting in the classroom. Instructors deliver tests on a set time and schedule making attendance for the test period mandatory. Makeup tests are available but require the same level of security as the original test. Makeup tests require the presence of an instructor or testing authority.

6.4.1.3 Records and Qualifications

Training completion and qualification tracking often require input or verification from a training administrator or clerk to update a Learning Management System or Qualification database which can take days to weeks. Nuclear workers maintain formal qualifications that align with specific specialized skills. Qualification renewal training is available only a few times per year. Individual and site consequences of lapsed worker qualification are high. Personnel enter qualifications manually using forms and, in some cases, procedural attachments and paperwork. Some companies have deployed automated notifications of qualification expiration, but this practice has not been widely adopted.

With advances in dynamic learning methods through video instruction, computer-based training, and mixed reality technologies, many industries have moved away from traditional classroom instructor-led training to online learning and virtual methods. New workers and learners expect digital content as part of their training program which is a significant shift from how the industry has trained the workforce to date.

ION Gen 1 includes work reduction opportunities through advanced training technology using commercially available solutions which offer several benefits to nuclear power workers and operators. The benefits include improved training effectiveness, greater flexibility in learning delivery, improved knowledge transfer, reduced travel, and reduced training program costs.

6.4.2 Scope of Work Reduction Opportunity Analyzed

6.4.2.1 Operations Training Modernization

Operations training is one of the most critical areas within a nuclear utilities training department (See Figure 46) since proficiency must be demonstrated on an ongoing basis and poor operator exam outcomes are not tolerated. Operations personnel attend classroom-style classes where they are taught nuclear systems, procedures, emergency protocols, and more. The operator moves through the program in preparation for a license examination. In addition to classroom training, the operator learns to manipulate the plant in a replica control room or simulator. Basic operations and emergency scenarios are practiced and tested internally by the utility and then once for licensure.

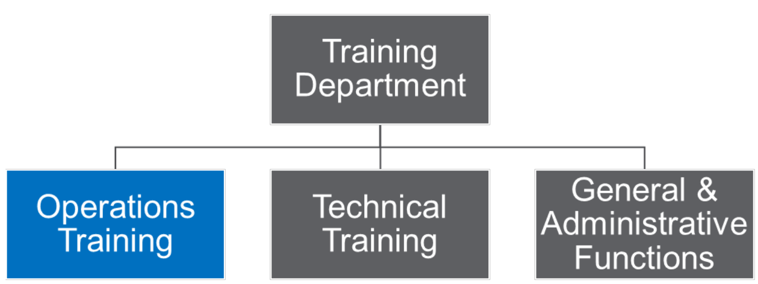

Figure 46. Operations training modernization functional training areas.

Modern training delivery systems provide the opportunity to not only meet training objectives but to do so while also reducing costs. It is proposed that nuclear plants use modern simulations to enhance operational realism and improve operations training effectiveness. Digitizing and automating training as well as digital and programmable control room scenarios will accelerate time to proficiency and reduce failures.

Students sitting in the classroom environment will benefit from multimedia presentations and modules that are available after class is complete. The impact of absences due to travel, illness, or other life events can be minimized since the material will be, at a minimum, recorded and modules will be available anytime for any student who wishes to re-hear the material or experience it in a different setting.

The Human System Simulation Laboratory (HSSL) developed a full-scope, full-scale digital control room simulator. A full-scope simulator might be a tabletop simulator running on a desktop personal computer or a paneled simulator used for training purposes. A full-scale control room simulator mimics the physical layout of the plant's control room. Virtual reality control rooms have also been employed at NPP overseas like the one in use at the Finnish Utility Fortum (Rice 2019).

The prototyped system is implemented in a fully functional variant in the full-scope control room simulator. The glass-top simulator using the underlying plant model from the training simulator may serve as a surrogate for the actual plant training simulator. This process can avoid the need to physically modify the training simulator (e.g., change hard panels to introduce displays) until the implementation phase.

Digital simulators make it possible for the same hardware to run different models and simulate the control rooms of multiple plants, an advantage for utilities with nuclear fleets. Simulator exercises can be digitized, so they can auto-update due to changing plant conditions and modifications. In addition, simulations can be simplified to be self-service where trainees can select which simulations to run and be tested with the results compiled by a computer-based analysis system.

This self-testing feature will ensure license candidates are ready to stand for the NRC operator qualification exams. Eye tracking software and other technologies can be used to evaluate operating procedures and suggest procedure improvements.

6.4.2.2 Technical and General Training Modernization

Technical training includes maintenance, RP, chemistry, and engineering instruction represented by Figure 47 and is part of the site's training department.

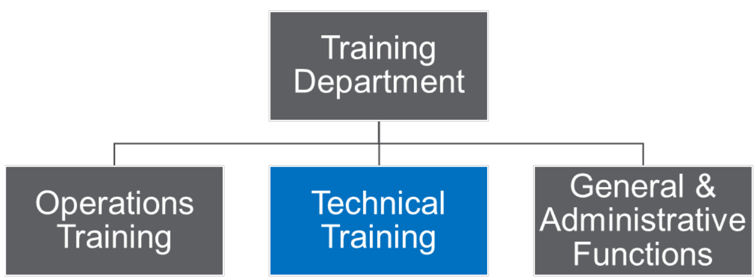

Figure 47. Technical training modernization functional training area.

6.4.2.3 Observations of the Current State of Technical Training

Technical training typically delivers its content in the classroom. Students attend one of several provided training sessions. Instructors schedule training to accommodate and avoid large sitewide plant events like outages as well as busy holiday seasons. This leaves longer classes like basic systems in the summer, and shorter single-day classes for other periods of the year.

Traditional training schedules do not take into consideration the best time for individual workers to receive training. New hires may find themselves with ten or more months of work before being able to learn plant systems in a formal setting. Delayed qualifications can result from classroom training unavailability.

The amount of novel content developed in any particular cycle is based on the training plan and the maintenance of qualifications in any particular group. New training content is important to maintain critical skills, but instructors currently deliver modules to students in a classroom that could be delivered electronically outside the classroom, especially repetitive backbone content. Instructors deliver backbone content to personnel in the classroom every cycle. This takes instructor and student time in the classroom setting. Replacing repetitive backbone content with pre-recorded sessions eliminates a significant amount of classroom time for the instructor and learner.

6.4.2.4 Just-In-Time and Practical Training

Beyond backbone and qualification classroom training are the topic of just-in-time (JIT) and practical training. The concept of JIT training is well established but can also benefit from a digital upgrade. JIT training instruction can be converted to digital, and delivery could take place through a handheld device while the craft worker is standing in front of the component or in the workshop.

Linked or embedded instruction within an electronic work package can ensure the right resources receive the training at the right time. 360 video and clickable links throughout the training presentation will also enhance the experience and lead to more successful completion of the task as the trainee can pause, explore, re-play, and rewatch the training. Watching someone else perform a task is very instructive and can be easier to follow for some learners over slide-style presentations or bulleted steps.

6.4.2.5 Training New Employees

New employees must typically wait for the next session needed for orientation or qualification to be offered by the training department. The wait time can take months and up to a year in some cases. Orientation training does not change significantly from year to year and therefore is a viable candidate for digital delivery.

Recruiting early career and qualified employees will be a top priority in the coming years as current generations choose retirement. Nuclear managers recognize the fact that classical classroom delivery of training and skill development is quite different today than it has been in the past. A new employee who recently graduated from a technical school or university is likely to be more acquainted and comfortable with electronic training delivery.

Qualification training is likewise similar from year to year and therefore can be made digital as well. Using advanced training technology can get new employees orientated faster, qualified sooner, and reduce O&M training overhead and classroom resources.

6.4.3 Training Records Automation

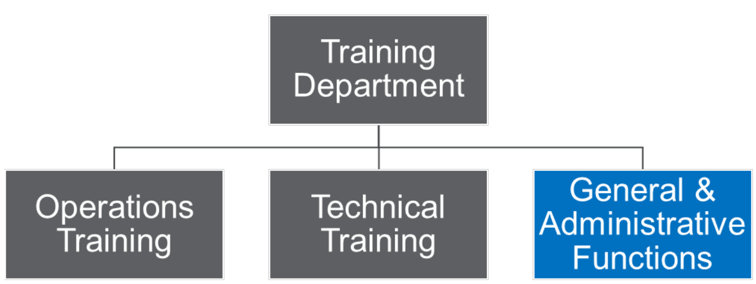

Figure 48. Training general and administrative functional area.

In legacy systems, the volume of paperwork and digitized forms that training personnel handle requires time and effort by an attendant or clerk connected to the training department as represented in Figure 48. Class rosters, qualification cards, reading assignments, and other training records are all managed carefully to avoid Institution of Nuclear Power Operations (INPO) accreditation issues or loss of qualification.

When qualification is due to expire, it is not always clear which training modules to take or when the training department will make them available in the classroom.

Automating and digitizing these systems will provide students and managers near-instant credit recognition of classes completed, qualification status, minimal to no paperwork, and the transparent progress of new employee orientation training.

The advantages of a digital training recordkeeping system are:

- Handles all training attendance
- Records test taking and test results
- Displays qualification progress and status
- Houses and secures quality assurance records
- Makes qualification and training status available to any manager or supervisor
- Houses the entire records process, procedures, forms, and records in one application.

6.4.4 Technology and Investments Required for Advanced Training Technology

6.4.4.1 Necessary Technology Needed for Advanced Training Success

Digital Simulator with Auto-Update Software

A full-scope plant simulator comprises several layers of systems. At the heart are system models that interact to create a realistic model of plant behavior, including thermal-hydraulic software modeling using RELAP, a vendor-specific simulator platform (e.g., simulator software development packages by GSE, WSC, and L-3), and a plant-specific model executed on the simulator platform.

These models combine to form the back end called the engineering simulator. The engineering simulator interfaces with the front-end simulator, which consists of the control room HSI that the operator uses to understand plant states and control plant functions.

The front-end simulator may take many forms such as an analog hard panel system found in typical U.S. training simulators, or a digital soft control system found in some foreign plants and research simulators. Digital soft control systems may take the form of mimics to analog plant I&C or may represent advanced I&C that incorporates features such as overview displays and information-rich trending displays. The human-machine interface may be a workstation or a multi-panel stand-up system such as the simulator in Figure 49.

Figure 49. Reconfigurable, full-scale glass-top simulator.

Training Modules

As previously described, the typical training module delivered in a nuclear power plant training environment is a slide presentation shown overhead with students physically attending the lecture in a classroom.

The ION model envisions training delivery utilizing a mix of digital and classroom training methods. Videos are recorded and assembled that reflect required backbone, elective, supplemental, JIT, safety, and other content relevant to nuclear workers. The complexity and technology used in the new training modules should be considered when creating the content.

Advanced training modules, especially those including skill-based content, can consist of videos of workers performing a task in the field with accompanying procedural guidance. Links within the video can connect the learner to other resources like procedures and drawings that are relevant to the task.

Modern Learning Management System

A learning management system (LMS) is software that manages training and educational content. The system is built on a software platform that can create and distribute training sessions to employees through a company server or hosted in the cloud. The system selected should also handle the administration, documentation, tracking, reporting, and automation of training in the organization.

When the system is housed on the cloud, it is usually managed by a vendor in a software as a service model. Users access the content on the vendor’s server. This model requires less technical expertise than a similar system housed on local servers.

New training content is uploaded to the system by administrators. Those lessons are then delivered to students through the platform. The instructor will be able to track progress and create tests for each class. Learning sessions are delivered straight to employees and test scores are automated.

Virtual Reality or Augmented Reality Headsets

A Virtual Reality (VR) headset is a head-worn tool with a display that covers the eyes, presenting an immersive three-dimensional (3D) experience to users. VR headsets can either be self-contained, with built-in computers to handle videos and animation, or connected to a computer powering content. VR headsets contain various combinations of sensors, such as accelerometers, proximity sensors, gyroscopes, etc. to detect the user's motion. VR headsets can be used to allow personnel to interact with virtual environments that simulate scenarios (See Figure 50). This allows for scenario-based training to be delivered safely.

An augmented reality (AR) headset is a head-worn tool that allows users to view images and content that is overlaid onto the real environment. Like the VR-Headset, AR headsets can either be self-contained or powered by a computer. Some headsets can serve as both AR and VR headsets.

VR/AR technology can be used to create realizing scenarios within NPP to train personnel on performing tasks safely, efficiently, and effectively. Scenarios can be created on performing maintenance tasks on plant components (turbines, motors, heat exchanges, etc.), as well as performing critical functions within plant control rooms.

This technology is also used in:

- Mobile Worker Technology – Remote Plant Support
- Mobile Worker Technology – Fieldwork Task Consolidation.

Figure 50. Virtual reality headset.

Mobile Worker Software

Software that will deliver training content to the worker in the field will be needed for JIT training. It will also be needed to deliver training to workers who spend time outside the plant environment. outdoors, in switchyards, in a truck, or located in a remote shop.

Mobile worker software delivers the suite of forms, procedures, and reference materials to the worker in the field using a handheld device like a tablet or phone. The software will also interface with the LMS and deliver JIT training based on work orders and procedures in use by the worker.

This technology is also used in:

- Mobile Worker Technology – Field Work Preparation and Coordination
- Process Re-Engineering and Automation – Computer-Based Procedures.

Digital Documents Management Software

Training records are QA documents. They must be searchable and retrievable in electronic format and be able to be secured against corruption or loss. A software package that can efficiently produce the training QA record for review is necessary for the work reduction opportunity to be effective.

This technology is also used in:

- Digital I&C- Maintenance Testing and Surveillance Reduction
- Process Re-Engineering and Automation – Campaign Maintenance ION Generation 1 transformation domains.

6.4.4.2 Technology Deployment Readiness

Table 20 indicates the deployment readiness of each of the technologies discussed above.

Table 20. Technology deployment readiness.

Technology	Widely Deployed	Narrowly Deployed	Not Deployed
Digital Simulator with Auto-Update Software			X
Dynamic (Digital/Video/XR) Training Modules		X	
Modern Learning Management System	X		
Virtual Reality or Augmented Reality Headsets		X	
Mobile Worker Software		X	
Digital Documents Handling Software		X	

6.4.4.3 ION Model: Net Present Value Analysis

Based on INL's research of advanced training technology as described in the ION model, this work reduction opportunity has an 87% chance of achieving a positive NPV outcome as indicated in Figure 51.

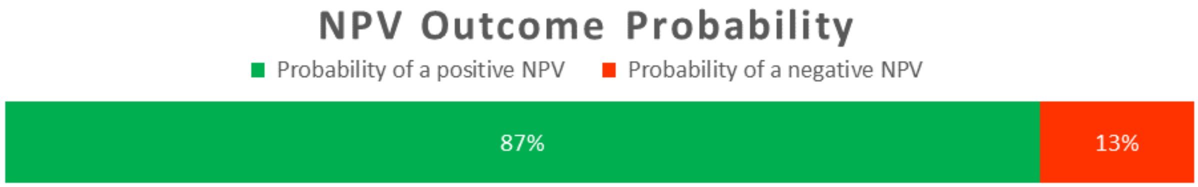

Figure 51. The probability of a positive or negative new present value outcome for the advanced training technology work reduction opportunity.

6.4.5 Validation Methodology

The ION model used single value estimates for each input to the model. This achieved a deterministic estimate of the overall cost and savings associated with each work reduction opportunity.

Inputs to the advanced training section of the model included the following:

1. One-time and ongoing cost of the following technological upgrades
    a. Digital simulator with auto-update software
    b. Training modules
    c. Modern Learning Management System
    d. Virtual reality or augmented reality headsets
    e. Mobile worker software
    f. Digital documents management software.

Number of full-time equivalent hours saved in the following areas

a. Operations training
b. Technical training
c. General training
d. Training records.

This next phase of ION model preparation involved collecting a range of data points for each input. Additional data points were found by reaching out to nuclear utilities and gathering input. Other data points were mined from complementary research. These actions achieved a range for each input to the model representing the range of actual values and the uncertainty found in estimating large multiyear projects.

As a result of obtaining data ranges for each input, the ION model calculation can now utilize a stochastic methodology. Figure 52 and Figure 53 represent ranges captured for each model input in graphical form.

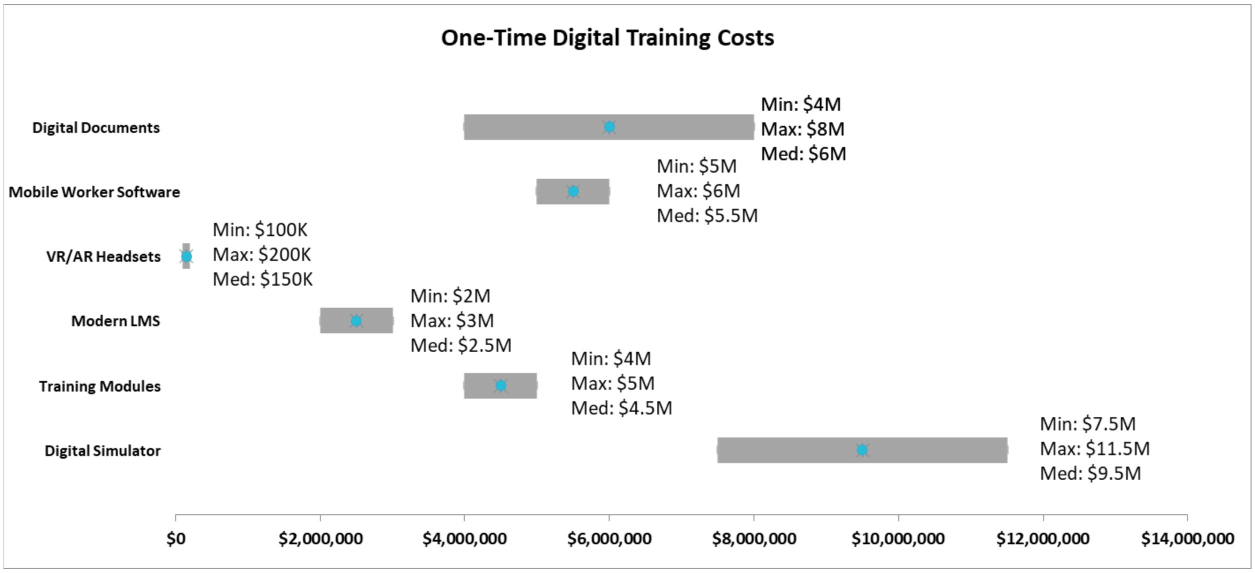

Figure 52. One-time advanced training costs.

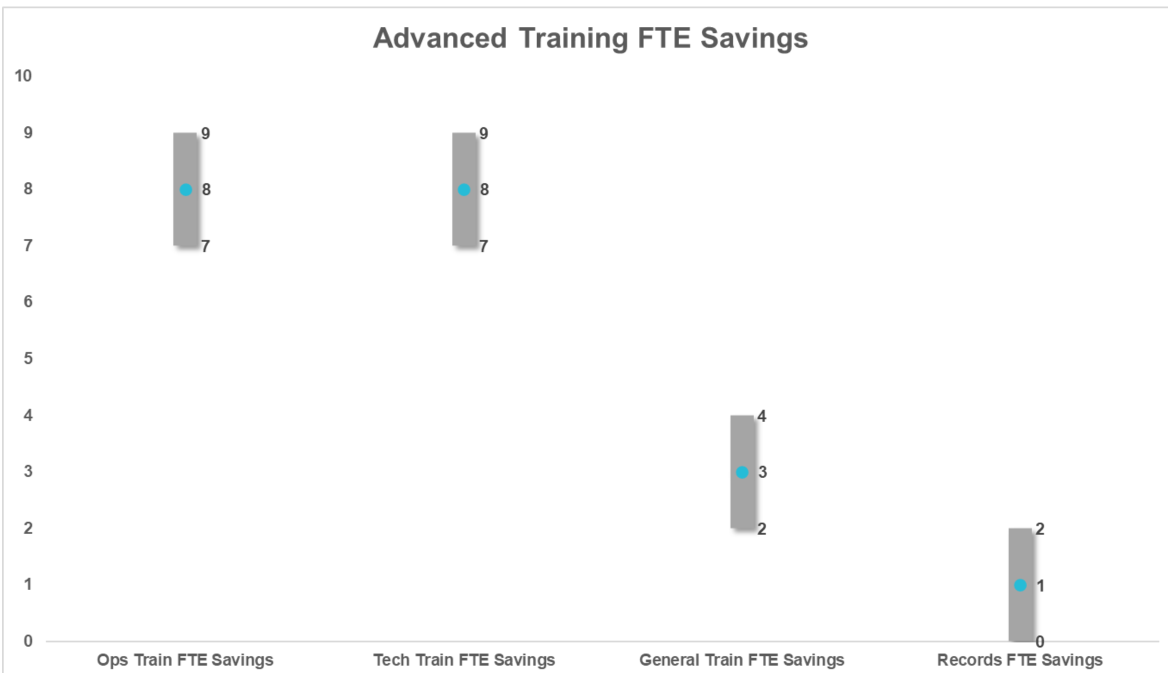

Figure 53. Advanced training FTE savings.

6.4.6 Areas of Uncertainty (Investment, Ongoing, Savings)

Determining areas of uncertainty is found by calculating the standard deviation of each technological upgrade. The one-time purchase and implementation of digital simulator software represent an input with higher model uncertainty. Due to the uncertainty associated with digital simulator software, the cost range used is between $7.5M and $11.5M. This minimum and maximum value range has a standard deviation of $2M.

The cost of this technology ranges significantly due to differing simulator designs, regulatory requirements, and functional scope. as well as differences between vendor pricing and low levels of commercial installments. Further, uncertainty surrounding vendor choice and pricing, the use of internal vs. external implementation partners, and low levels of commercial installments is reflected by the high standard deviation.

The one-time purchase of digital documents software also represents significant uncertainty within this model. Research estimated costs ranging between $4M and $8M, with a standard deviation of $2M. Like the digital simulator upgrade, this variation is due to vendor choice, complexity and size of the training program, and low levels of installed projects from which to acquire data.

6.4.7 Ongoing Costs

All technologies required for this modernization have associated ongoing costs. These costs represent maintenance and service contracts held with the original service or component supplier for each technology or periodic internal maintenance upgrades. These service contracts or internal upgrades are required to ensure support for ongoing hardware and software functionality. It is estimated once every five years the software systems will require maintenance and upgrades.

6.4.8 Model One-Time Costs, Ongoing Costs, and FTE Saving Input Values

6.4.9 Projected Savings

Minimum and maximum input values, as shown in Table 21, (acquired by utility participation and deliberate research) were used in a NPV Monte Carlo simulation. Each outcome was plotted along a normal distribution curve. A positive NPV indicates a favorable business case for the project investment, indicating the project is expected to return more free cash to the utility. A negative NPV indicates that the business case is not favorable, and that the project will return less free cash to the utility. For this analysis, the NPV can range between –$15.2M and $29.1M, with an 87% chance of achieving a positive NPV outcome, see Figure 54. The NPV has a standard deviation of $5.2, see Figure 55.

Table 21. Advanced business case inputs.

Model Input	**Minimum**	**Maximum**	**Standard Deviation**
One-Time Hardware and Software Costs			
Digital Simulator with Auto-Update Software	$7,500,000	$11,500,000	$2,000,000
Training Modules	$4,000,000	$5,000,000	$500,000
Modern Learning Management System	$2,000,000	$3,000,000	$500,000
Virtual Reality or AR Headsets	$100,000	$200,000	$50,000
Mobile Worker Software	$5,000,000	$6,000,000	$500,000
Digital Documents Handling Software	$4,000,000	$8,000,000	$2,000,000
Total:	*$22,600,000.00*	*$33,700,000.00*	*$5,550,000*

Model Input	**Minimum**	**Maximum**	**Standard Deviation**
Ongoing Hardware and Software Costs			
Digital Simulator with Auto-Update Software	$100,000	$500,000	$200,000
Training Modules	$100,000	$200,000	$50,000
Modern Learning Management System	$200,000	$400,000	$100,000
Virtual Reality or AR Headsets	$50,000	$100,000	$25,000
Mobile Worker Software	$200,000	$300,000	$50,000
Digital Documents Handling Software	$200,000	$300,000	$50,000
Cost of Plant Ownership Every 5 Years	8%		
Total:	*$850,000*	*$1,800,000*	*$475,000*

Model Input	**Minimum**	**Maximum**	**Standard Deviation**
FTE Savings			
FTEs Saved in Operations Training	$1.141M (7FTE)	$1.467M (9FTE)	$163,000
FTEs Saved in Technical Training	$1.141M (7FTE)	$1.467M (9FTE)	$163,000
FTEs Saved in General Training	$0.326M (2FTE)	$0.652 (4FTE)	$163,000
FTEs Saved in Training Records	$0 (0FTE)	$0.326M (2FTE)	$163,000
Total:	*$2,608,000*	*$3,912,000*	*$652,000*

Cost of Capital	8.75%	10.50%	0.88%
FTE Cost Increase	3%		
Yearly Salary Blended Rate per FTE	$163,000		

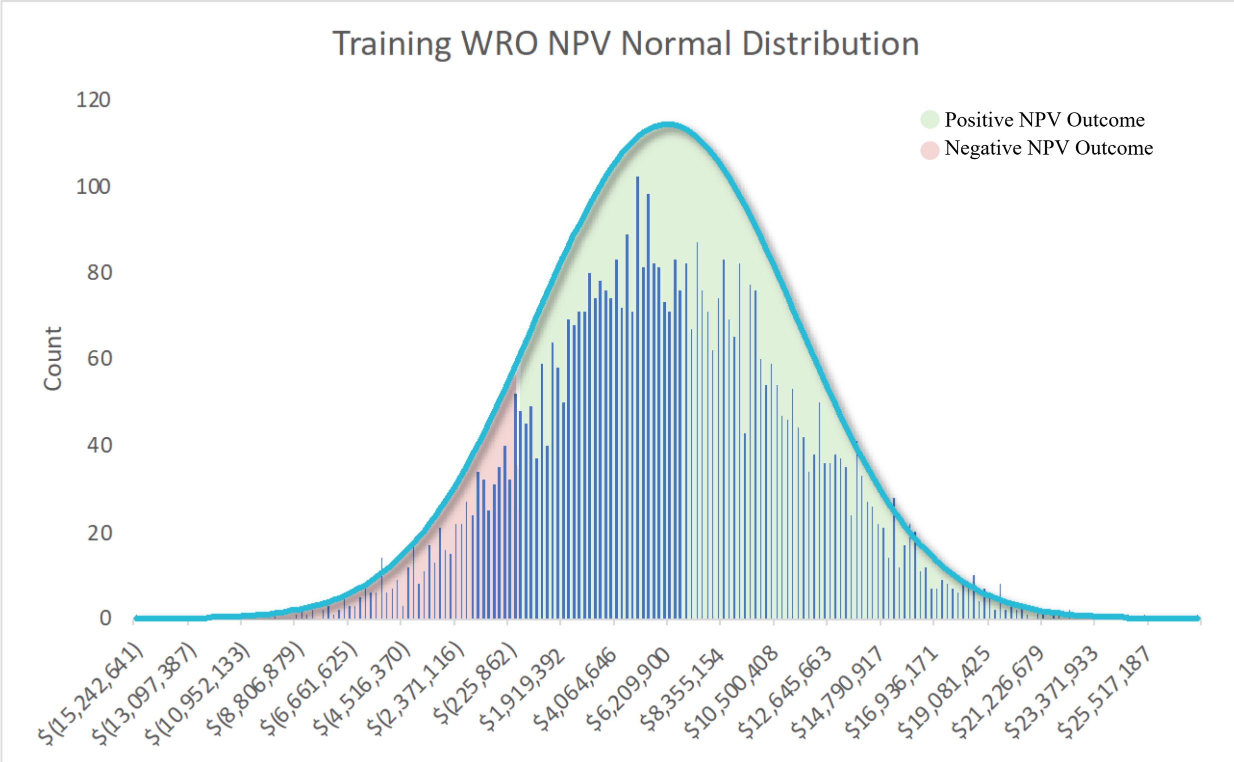

Figure 54. NPV distribution of advanced training technology.

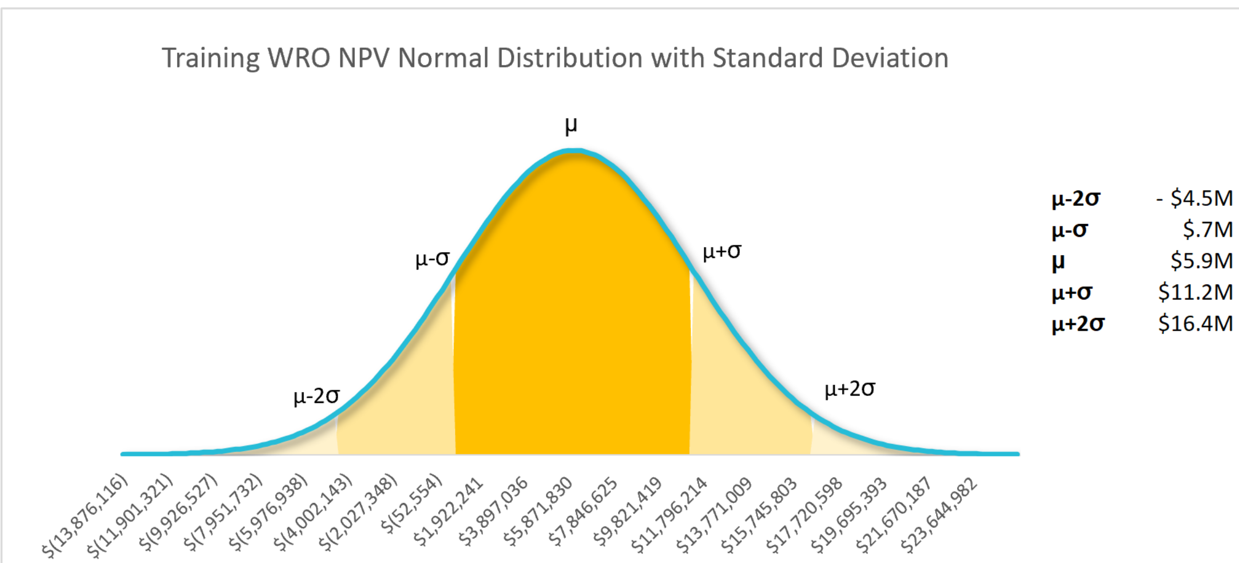

Figure 55. Digital training NPV normal distribution with standard deviation.

To provide more detail into the possibility of achieving a positive NPV outcome, Table 22 indicates the percent chance of achieving NPVs above the breakeven point. For example, investing in advanced training has a 15% chance of resulting in an NPV of $11.3M or more, and a 10% chance of resulting in an NPV of $12.5M or higher.

Table 22. Percent chance of achieving positive NPV outcomes.

Chance of Achieving NPV	NPV Value or Greater
37%	$7.7M
30%	$8.5M
25%	$9.3M
15%	$11.3M
10%	$12.5M

6.4.10 Lessons Learned from Early Implementations

6.4.10.1 General Lessons Learned

Training modernization with an on-demand training program avoids cost and speeds time to worker productivity. It solves the problem of hiring timing coordination with human resources (HR), with no need to wait for cohorts or training classes to start.

Video content and video libraries alone will not modernize a program. Feedback from learners has shown that aligning procedural and work method guidance to reinforce concepts through visuals and repetition is most effective.

Advanced continuing training or refresher training is becoming more important than it was pre-COVID, as standards have deteriorated rapidly from mid-career workers who have not had as much field oversight. Early adopters have seen a four-to-one workload reduction from classroom instructor-led training (ILT) to advanced, modern training methods.

6.4.10.2 Training Organization

Organizational opportunities beyond the nuclear site may present themselves to utilities exploring training modernization. In the course of research for this ION work reduction opportunity, researchers encountered an organizational model where nuclear training was combined at the corporate level. The new corporate training department included not only nuclear plant training but other generation sites including coal and gas as well. While this report considers efficiencies gained at the nuclear site level, additional full-time equivalent savings may be available with a similar corporate training department that includes other generation's programs.

6.5 Remote Assistance and Automated Troubleshooting

6.5.1 Scope of Work Reduction Opportunity Analyzed

Over time, commercial nuclear work practice methods were enhanced to improve accuracy in work execution and assurance of equipment reliability. With nuclear safety as the paramount objective, striving for excellence in work product outcomes is necessary for a well-functioning, productive plant. However, more robust, and rigorous work methods come with tradeoffs. While accuracy and assurance have increased, efficiency has decreased.

In many cases, multiple workers are assigned tasks that could be accomplished by a single worker. Extra workers are added to tasks at times for the sole purpose of peer checking work in progress and assuring expected results are achieved. The practical result is that work quality and work efficiency become mutually exclusive. This paradigm contributes to the competitive struggles of commercial nuclear power due to higher operation and maintenance costs for field work and troubleshooting.

Existing and emerging technologies for mobile workers can begin to resolve the tradeoff between the quality and efficiency of nuclear power plant work. Many of the work execution and human performance tasks are candidates for enhancement by technology. The enhancements will free workers to focus on aspects of the job that require their skills and knowledge and less on lower skill or lower quality tasks.

The result will be more efficient work with less labor accompanied by the same or higher levels of assurance in work quality and safety.

6.5.2 Current Methods

6.5.2.1 Troubleshooting

Nuclear plant troubleshooting can take many forms. Some troubleshooting is simple and informal with a worker observing an unwanted or unexpected event and deducing its cause from readily available information like field conditions. Other troubleshooting is more formal utilizing a troubleshooting procedure, a formal troubleshooting plan, pre-determined steps, multiple work group coordination, and approval signatures.

This report is concerned with the type of troubleshooting that requires technical deduction of component failures by maintenance, engineering, or operations. Components fail in multiple known ways, commonly known as failure modes. Failure modes are recorded in the maintenance rule and are monitored using plant parameters, operator's logs, work requests, condition reports, and other sources. Components can only fail in only so many ways. Plant personnel are aware of these modes and have devised processes for collecting data that would indicate triggering of a component failure mode.

6.5.2.2 Plant Support

Plant support can take many forms as well. The typical plant support activity involves employees who are outside the traditional locally stationed O&M staff. Plant support includes system engineers, component engineers, design engineers, licensing professionals, QA, corporate subject matter experts, and others. Support personnel outside O&M are called upon to assist in plant evolutions, observe component conditions, diagnose the component failure, perform task observations, assist in a walkdown, attend meetings where plant issues are discussed, and an array of other important operational activities. Currently, the majority of plant support takes place in person and inside the protected area where support staff makes themselves physically available to plant operators and maintenance workers.

6.5.3 ION Methods

6.5.3.1 Automated Troubleshooting

Automated troubleshooting is the computerized monitoring and on-board diagnosis of power plant component failure modes. This is accomplished by installing digital technology designed to monitor an individual component's mechanical or electrical parameters like vibration or motor current. The mechanical or electrical parameters are monitored for changes that indicate a failure or a degraded condition of that component's ability to function. The digital sensor can be programmed to recognize when a parameter has exceeded its normal performance band and send an alert to a subject matter expert or software attendant. In more advanced applications, and in conjunction with automated planning and scheduling, the sensor could trigger a new work request in the plant's work management system effectively monitoring, diagnosing, and alerting the plant to its own preventative maintenance needs.

6.5.3.2 Remote Plant Support

Utilizing personnel located at the plant site is an effective way to resolve issues and maintain high nuclear performance. However, not all subject matter experts are or can be, located at the plant. Many fleets have component experts in a central location with other less qualified support staff located at the plant site. Other experts and support staff are equally dispersed throughout the company, other plant sites, and even throughout the United States fleet. It is also reasonable to consider a company's motor expert or turbine specialist may not be employed in the nuclear business unit and may be assigned to the utility's coal or gas business unit.

Accessing the expertise of employees that may not be co-located can be achieved using digital technology. Performing a walkdown with a body camera or showing a subject matter expert the condition of a component with a headset allows visual and verbal communication while not co-located. It produces live video images of the component or walkdown to the screen of a remote employee along with verbal collaboration between two or more individuals. VR and AR headsets allow for the transfer of documents, instructions, drawings, and other useful aides to be shared between the remote and local workers.

Digital video, voice, and collaborative devices free support staff from being required to be present at the site in case of a need to collaborate. It also frees the O&M staff from performing critical work during normal work hours as experts may be available in different time zones or able to assist from home without driving to the facility. With remote support enhanced, support staff can become more specialized, be located in faraway places, avoid dose, mispositions, and safety incidents, and more easily conform to the plant's ideal schedule.

6.5.4 Technology and Investments Required for Remote and Automated Troubleshooting

6.5.4.1 On-Board Diagnostics

Modern digital plant components have on-board M&D features that can replace testing and troubleshooting that are now conducted manually and locally. These features monitor various component failure modes, conduct constant health checks (several times a second), diagnose faults, failures, and degraded conditions, and report these results to established monitoring points on a real-time basis. For this reason, they eliminate troubleshooting activity by pinpointing and communicating which components and subcomponents are degraded. Many times, this degradation is reported early, even while the component is still performing within its design basis.

This technology is also used in the digital I&C work reduction opportunity.

6.5.4.2 Virtual Reality or Augmented Reality Headsets

A VR-headset is a head-worn tool with a display that covers the eyes, presenting an immersive 3D experience to users. VR headsets can either be self-contained, with built-in computers to handle videos and animation, or connected to a computer powering content. VR headsets contain various combinations of sensors, such as accelerometers, proximity sensors, gyroscopes, etc. to detect the user's motion.

An AR headset is a head-worn tool that allows users to view images and content that is overlaid onto the real environment. Like the VR-Headset, AR headsets can either be self-contained or powered by a computer. Some headsets can serve as both AR and VR headsets.

VR/AR technology can be used to generate collaborative scenarios within NPP to enhance tasks and achieve value addition by remote employees. Collaboration while performing maintenance tasks on plant components (turbines, motors, heat exchanges, etc.) as well as performing critical functions within plant control rooms is achievable.

This technology is also used in:

- Mobile Worker Technology – Remote Plant Support
- Mobile Worker Technology – Fieldwork Task Consolidation.

6.5.5 Technology Deployment Readiness

Table 23 indicates the deployment readiness of each of the technologies discussed above.

Table 23. Technology deployment readiness.

Technology	Widely Deployed	Narrowly Deployed	Not Deployed
On-Board Diagnostics		X	
VR/AR Headsets		X	

6.5.6 Necessary R&D Needed to Achieve ION Gen 1 Business Model Cost Reductions Within 5 Years

Since M&D centers are being employed by electric utilities there is experience from the application of these technologies that can be mined for favorable or unfavorable outcomes. Other United States nuclear facilities and corporations can benefit from the employment of self-diagnostic sensors and software. Research of existing applications will benefit other facilities.

Remote assistance can benefit from actual field experiments and the selection of technology for various scenarios encountered at a nuclear site. Collaboration inside containment may require a more robust solution. Performance of headsets in maintenance conditions where workers are accessing small spaces may be limiting. Researching the actual use of these devices and experimenting on their efficacy would help the industry become familiar with the technology and increase its adoption.

6.5.7 ION Model: Net Present Value Analysis

Based on INL's research of remote assistance and automated troubleshooting as described in the ION model, this work reduction opportunity has a 100% chance of achieving a positive NPV outcome as indicated in Figure 56.

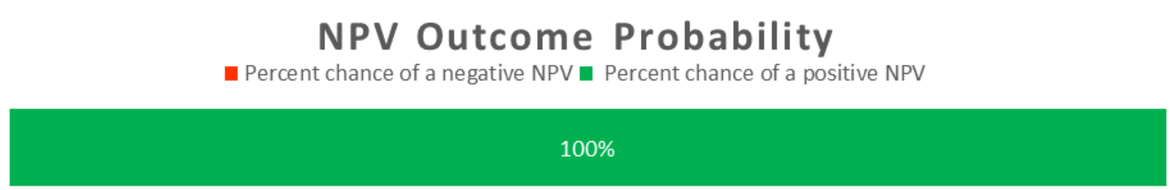

Figure 56. The probability of a positive or negative NPV outcome for the remote assistance and automated troubleshooting work reduction opportunity.

6.5.8 Validation Methodology

In the previous report, the ION model used single value model input estimates. This method attained a deterministic estimate of the cost and savings associated with each work reduction opportunity.

The next phase of ION model preparation involved collecting a range of data points for each input. Additional data points were found by reaching out to nuclear utilities and gathering input. Other data points were mined from complementary research. These actions achieved a range for each input to the model representing the range of actual values and the uncertainty found in estimating large multiyear projects. As a result of obtaining data ranges as opposed to single values, the ION model can now utilize the stochastic method for analysis.

Inputs to the Remote and Automated Troubleshooting section of the ION model included the following:

1. One-time and ongoing cost of the following technological upgrades
    a. On-Board diagnostics

    b. VR/AR headsets
    c. Sensors for failure modes.
2. Number of full-time equivalent hours saved in the following areas
    a. Remote plant support
    b. Automated troubleshooting.

The following Figure 57 represent ranges captured for each model input in graphical form.

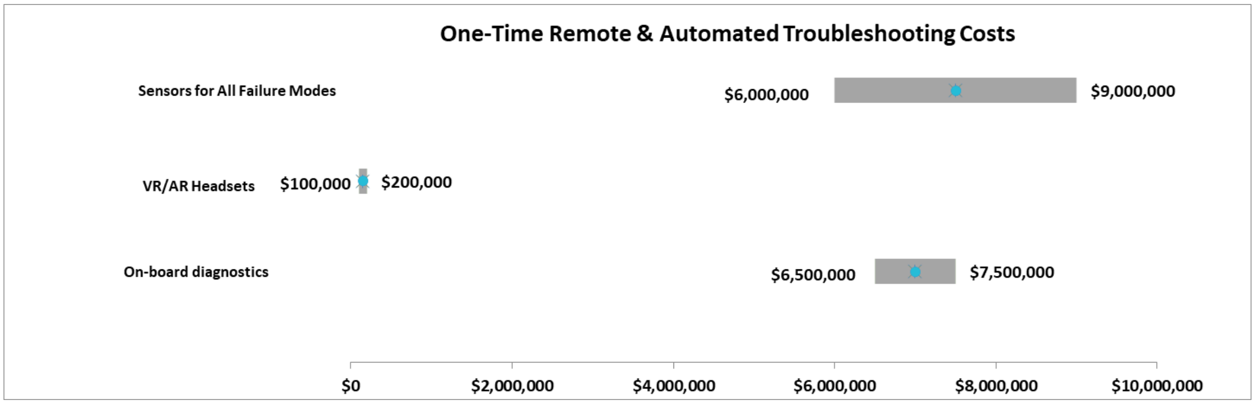

Figure 57. One-time remote and automated troubleshooting costs.

6.5.9 Areas of Uncertainty (Investment, Ongoing, Savings)

Determining uncertainty is found by calculating the standard deviation of each technological upgrade. The one-time purchase of on-board diagnostics software and hardware represents an input with higher uncertainty. The cost range for this technology was determined to be between $6.5M and $7.5M. This minimum and maximum value range has a standard deviation of $500K.

Cost varies significantly due to which components the utility chooses to be in the scope of the upgrade. Additional uncertainty results from vendor choice and pricing and the use of internal vs. external implementation partners.

6.5.10 Ongoing Costs

All technologies required for this modernization have associated ongoing costs. These costs represent maintenance and service contracts held with the original service or component supplier for each technology or periodic internal maintenance upgrades. These service contracts or internal upgrades are required to ensure support for ongoing hardware and software functionality. It is estimated once every five years the software systems will require maintenance and upgrades. Figure 58 shows in graphical form the inputs used in the statistical analysis.

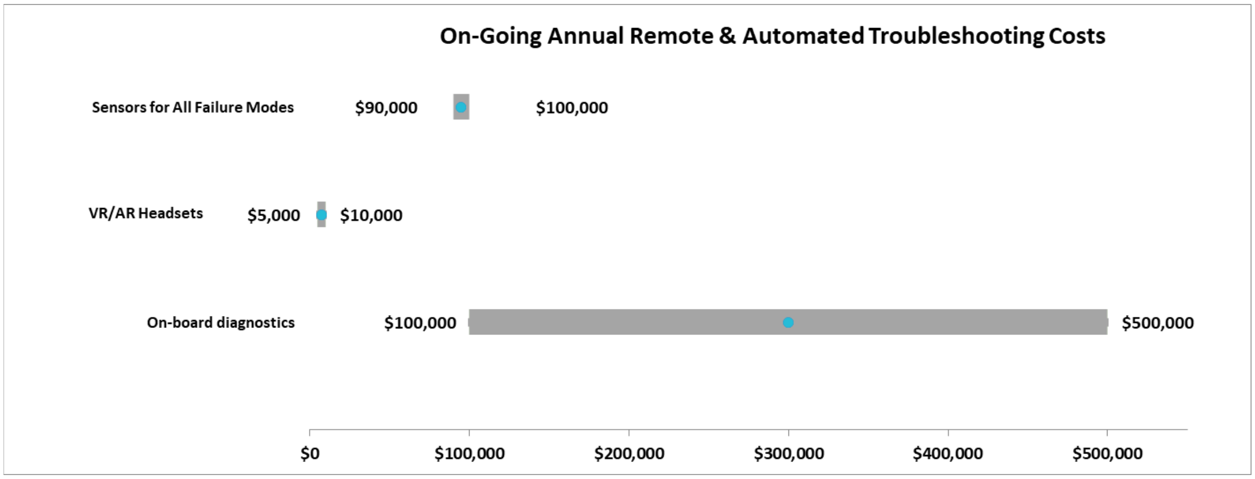

Figure 58. Ongoing annual remote and automated troubleshooting costs.

6.5.11 Model One-Time Costs, Ongoing Costs, and FTE Saving Input Values

Table 24 below contains the business case inputs (one-time and ongoing costs, and FTE savings) for the Remote Assistance and Automated Troubleshooting analysis.

Table 24. Remote Assistance and Automated Troubleshooting business case inputs.

Model Input	Minimum	Maximum	Standard Deviation
One-Time Hardware and Software Costs			
On-board diagnostics	$6,500,000	$7,500,000	$500,000
VR/AR headsets	$100,000	$200,000	$50,000
Sensors for failure modes	$6,000,000	$9,000,000	$1,500,000
Total:	*$12,600,000*	*$16,700,000*	*$2,050,000*
Ongoing Hardware and Software Costs			
On-board diagnostics	$100,000	$500,000	$200,000
VR/AR headsets	$5,000	$10,000	$2,500
Sensors for failure modes	$90,000	$100,000	$5,000
Total:	*$195,000*	*610,000*	*$207,500*
FTE Savings			
Remote Plant Support FTE savings	8	10	1
Automated Troubleshooting FTE savings	21	23	1
Total:	*29*	*33*	*2*
Cost of Capital	8.75%	10.50%	0.88%
FTE Cost Increase	3%		
Yearly Salary Blended Rate per FTE	$163,000		

6.5.12 Projected Savings

Minimum and maximum input values to the ION model as shown in Table 23 were used to find a population of net present values. Employing a Monte Carlo simulation, the model arrived at a standard distribution of 5,000 expected outcomes. Each outcome was plotted along a normal distribution curve.

A positive NPV indicates a favorable business case for the project investment, indicating the project is expected to return more free cash to the utility. A negative NPV indicates that the business case is not favorable and that the project will return less free cash to the utility. For this analysis, the NPV can range between $2.2M and $35.7M, with a 100% chance of achieving a positive NPV outcome, see Figure 59. The NPV has a standard deviation of $4.5M (see Figure 60).

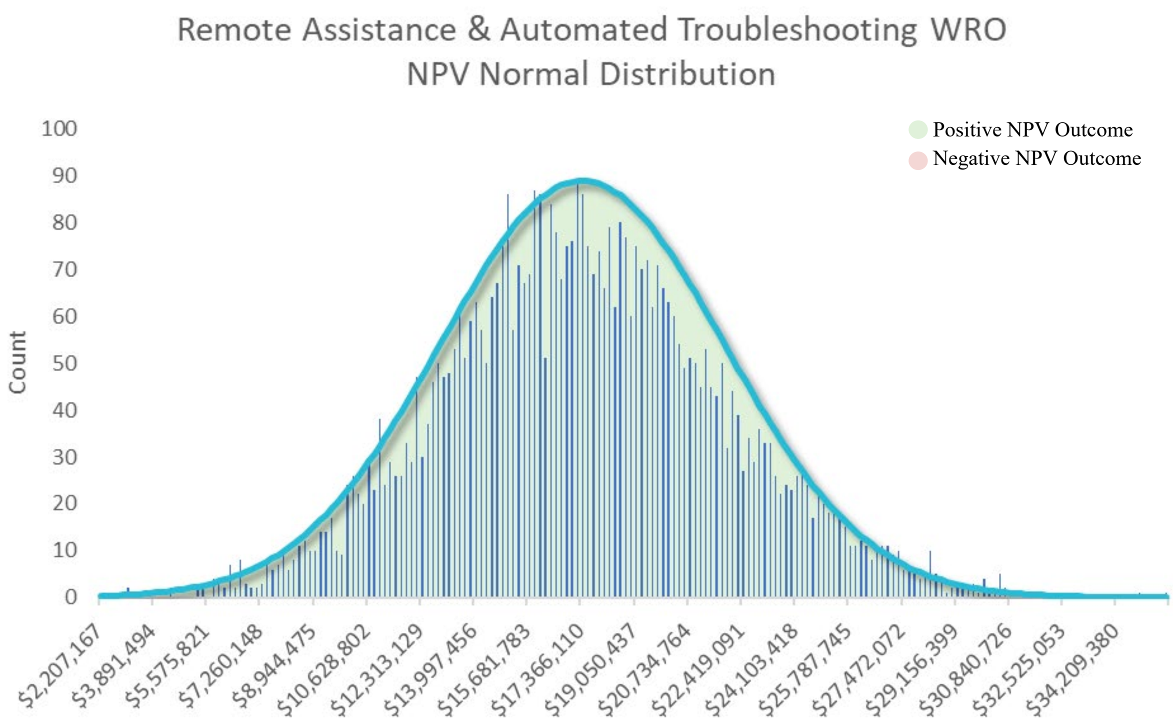

Figure 59. NPV distribution of remote and automated troubleshooting technology.

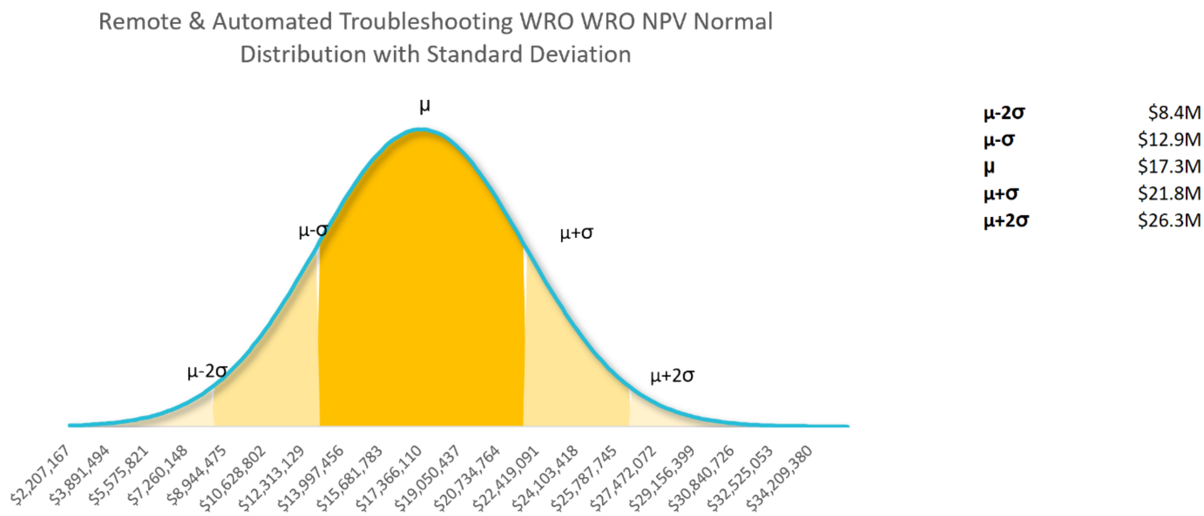

Figure 60. NPV distribution of remote and automated troubleshooting technology.

To provide more detail on the possibility of achieving a positive NPV outcome, Table 25 indicates the chance of achieving NPVs above the breakeven point. For example, investing in remote assistance and automated troubleshooting technologies has a 50% chance of resulting in an NPV greater than $17.2M and a 10% chance of achieving an NPV of $23.2M or greater.

Table 25. NPV per percentile.

Chance of Achieving NPV	NPV Value or Greater
50%	$17.2M
40%	$18.4M
30%	$19.5M
20%	$21.0M
10%	$23.2M

6.5.13 Lessons Learned from Early Implementations

Research into this work-reduction opportunity did not produce meaningful lessons learned.

7. ION GENERATION 1 OPTIMIZED NPP ORGANIZATION

Current nuclear plant organizational structures have been influenced over time by the emphasis on safety and reliability. These changes and enhancements are not to be derided. The safety record of the domestic nuclear fleet and the productivity as measured by the capacity factor have achieved what few thought possible in the early years of commercial nuclear power. International and domestic events, near misses, a strong culture of sharing operational experience, the pursuit of revenue, and the regulatory environment have all contributed to the shaping of current trends in nuclear power plant staffing.

However, as the plants have matured and previous operational and even safety issues were addressed, plant organizations did not put the same effort into reverting to a sustainable model, instead relying on the newly acquired resources to stay and maintain a new status quo. Additional responsibilities mostly inherited from more rigorous processes required larger staff. For years it was more convenient and expeditious to add and maintain additional responsibility both to the plant and central organizations than fight for a smaller staff.

With the introduction of digital technologies and their applications to NPP, the ION model opens the door to more efficient organizations. Through ION, technological, organizational, cultural, and process changes can be implemented that will result in streamlined or eliminated work and allow for a drastic rethinking and reordering of the organizational structure.

Work reduction opportunities outlined in this study require significant leadership buy-in, as well as capital investment, long-term thinking, and change management. Work reduction opportunities enable the company not only to reduce the size of the organization (internally and externally), but also distribute a considerable number of positions and functions out of the owner-controlled area.

The revised structure of the organization is built around the premise that the plant organization has all the resources it needs to operate the plant on a day-to-day basis. All other resources exist to support plant operation, perform long-term planning, and dive deeper into equipment health aspects that are needed for a strategic approach to power plant operation.

7.1 Direct Headcount

Figure 61 shows a model organization chart for a single site, two-unit plant at a nominal 1000MW per unit. Specific details regarding discipline breakdown have been omitted for the sake of clarity. There are significant opportunities to incorporate cross-functional positions (i.e., combining some of the tasks normally performed by RP and maintenance technicians) into an expanded responsibility set within plant operations and non-licensed operators.

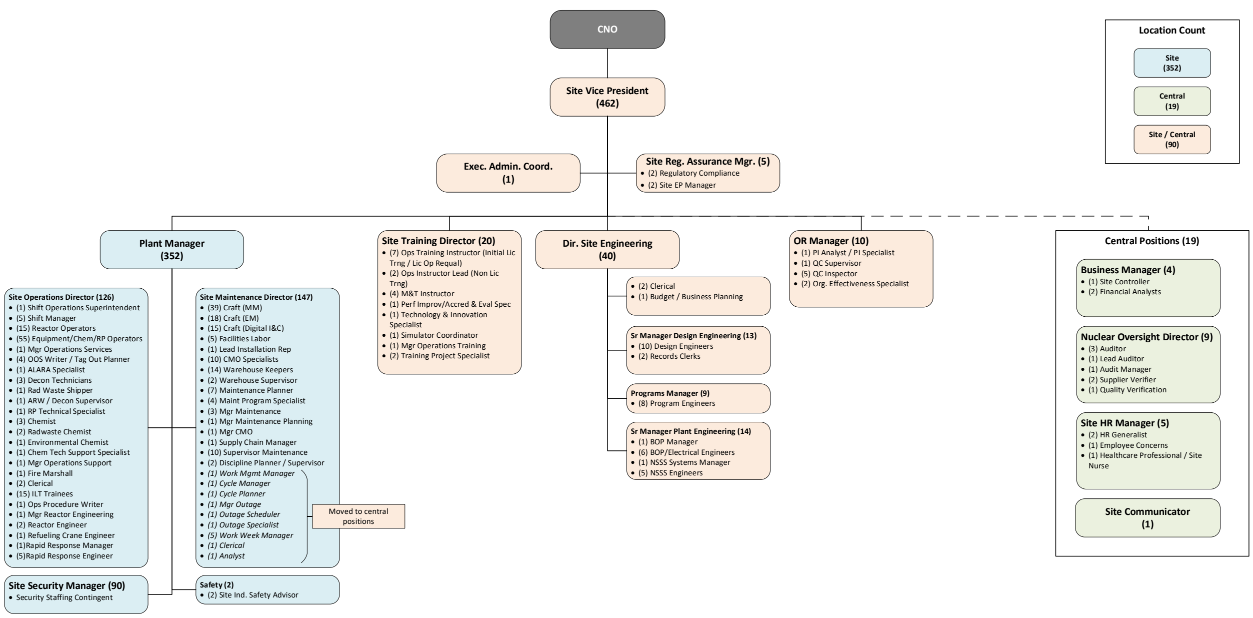

Figure 61. Proposed ION organizational chart.

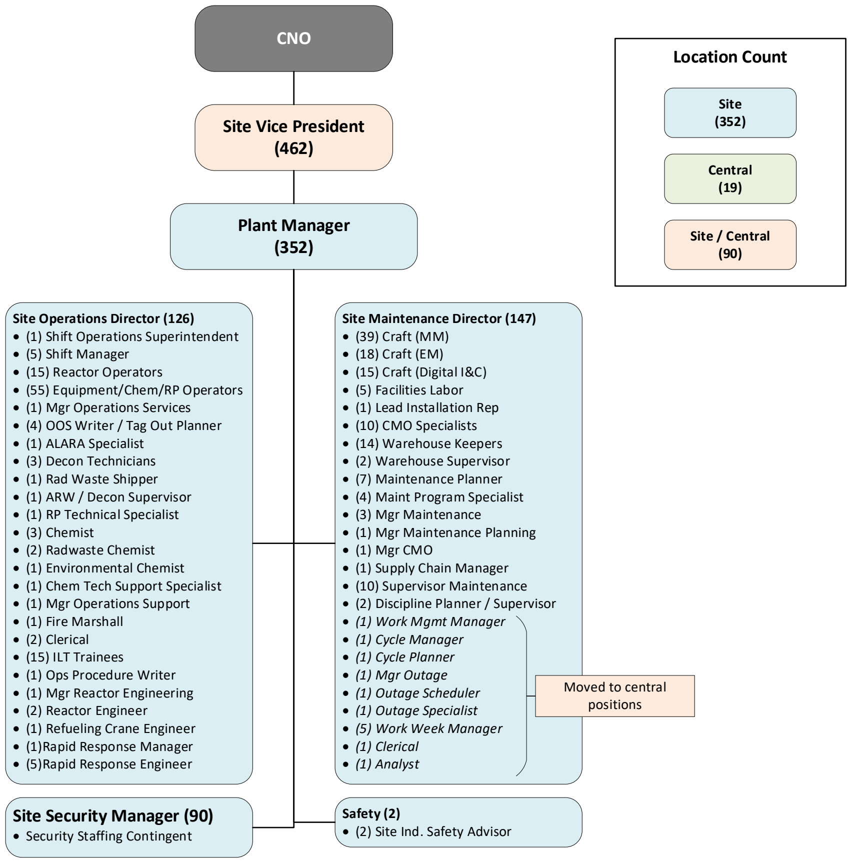

Figure 62. Detailed plant manager organization.

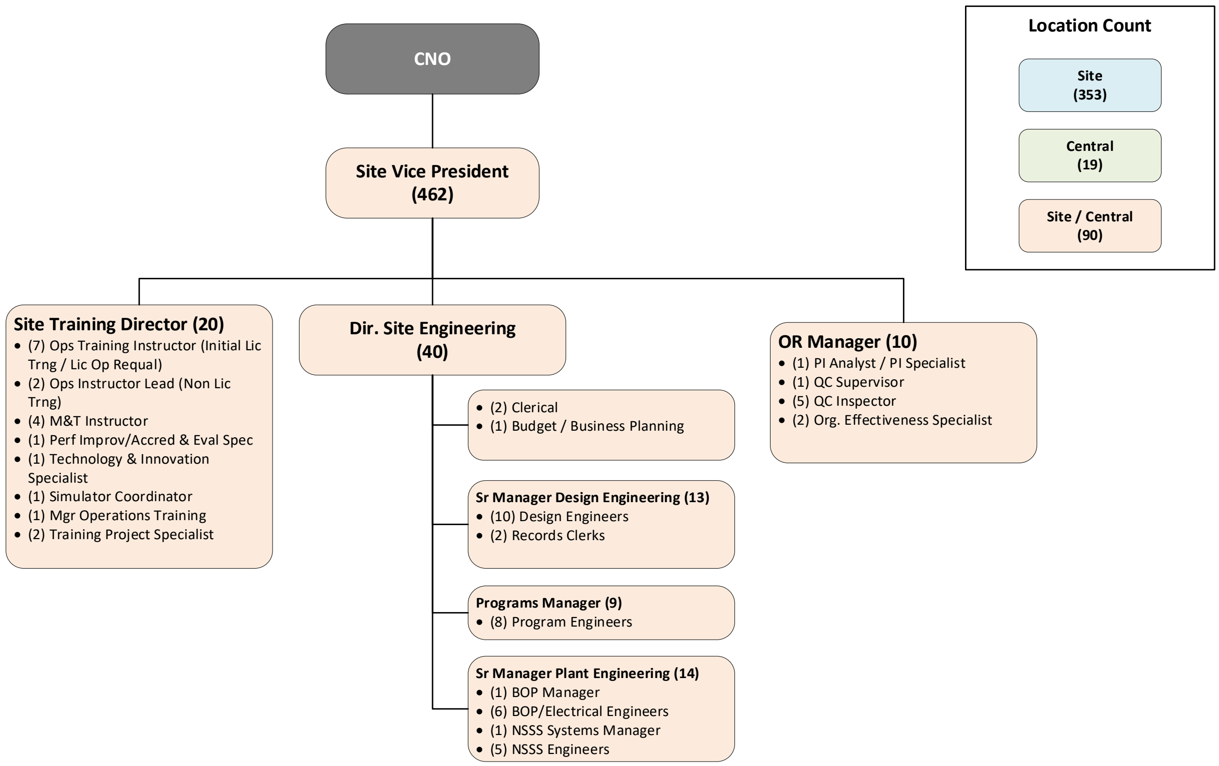

Figure 63. Detailed site support organization, on-site, or centralized.

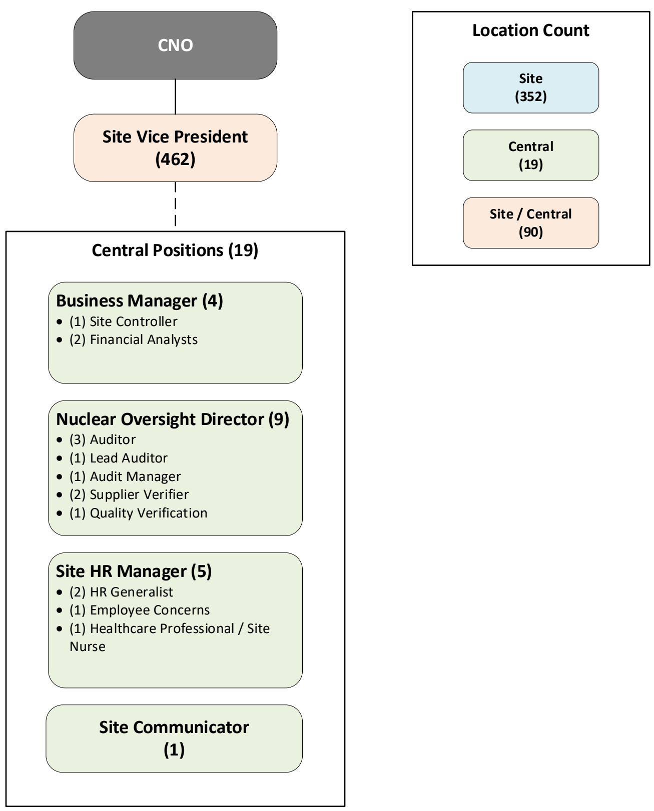

Figure 64. Detailed positions centrally located.

Service Contracts

New types of service contracts and product support contracts will need to be initiated to support the ION Gen 1 business model. These tasks will primarily support specialty engineering and maintenance functions. The contracts are characterized by certain provisions that allow a utility to outsource important work functions without concern for effectiveness in sensitive operational, safety, regulatory, or business outcomes.

They would include such business advantages as:

- Seamless integration with the plant staff through advanced digital collaboration technology, including effective participation in critical field activities from a remote location
- Services are available immediately and on-demand with task authorizations handled outside the normal flow of work. The plant would call on these resources with the same ease as calling a support person in the utility organization
- Creative arrangements allow a service or supplier organization to assume technical risk, relieve the plant of certain capital investments, and pay for outcomes such as component performance and availability, rather than for the component itself.

The service or component supplier will need to be compensated for these more flexible and effective business arrangements. However, in many cases, enabling the utility to avoid the ongoing expense and management attention to maintain these highly technical and evolving competencies will more than offset these contract costs, especially as these suppliers can spread their costs over a wide customer base.

A detailed breakdown of services by online, outage, or specialty will need to be conducted through future ION Phase 2 work with a partner utility to determine the linkage and need for services after the reduction of internal labor.

8. SUMMARY

Researchers presented the ION concept in 2021 in INL/EXT-21-64134. The report identified thirty-seven work-reduction opportunities for nuclear utilities to consider in their pursuit of a competitive footing with other generation sources. The goal was to reach parity (or better) with other generation sources as measured by the LCOE. Each of the work-reduction opportunities explored in INL/EXT-21-64134 requires digital, technological, and process upgrades to the operating business model of the nuclear facility. The upgrades benefited the operating budgets of the plants themselves through reduction and automation of work processes producing full-time equivalent savings as each is implemented.

Researchers determined to continue to refine and strengthen the analysis partnered with nuclear operators for the next stage of ION development. The top five most impactful work-reduction opportunities were selected for further enhancement. Technology, cost, and savings assumptions and estimates from the original report were disclosed to partner utilities in an effort to refine and enhance their accuracy. Feedback and data collection from these utility partners resulted in a range of values for each work reduction opportunity's implementation cost and full-time equivalent savings.

The ranges of cost to implement along with expected savings provided an opportunity to expand the model and include multiple outcomes. Primarily, the ION concept as presented in INL/EXT-21-64134 could be classified as deterministic. In other words, the analysis presented one outcome as a result of undertaking the ION business model. Now that multiple data points were known for cost and savings, researchers could produce a stochastic, or probabilistic, model. This model reports many outcomes (5,000) using the ranges acquired through utility participation. Researchers also employed the NPV formula which discounts future cash flows into a singular present value.

Figure 65 summarizes the probability of achieving a positive NPV for each of the work reduction opportunities analyzed in this report. Based on the analysis, Remote and Automated Troubleshooting, and Condition-Based Maintenance has the highest probability of achieving a positive NPV, and Digital I&C has the lowest probability of achieving a positive NPV. (As aforementioned, Digital I&C upgrades are fundamental and essential to any nuclear facility which expects to operate for decades to come and should not be viewed primarily as a solely cost-saving opportunity). Figure 65 summarizes the NPV ranges of each of the work reduction opportunities.

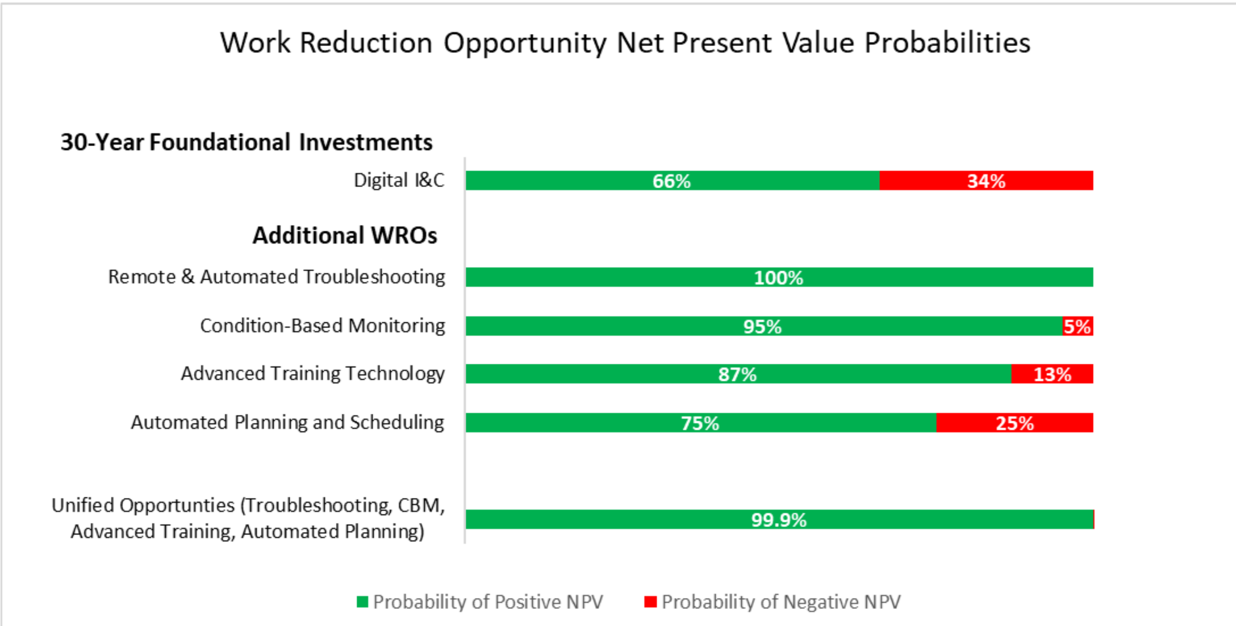

Figure 65. Work reduction opportunity probabilities.

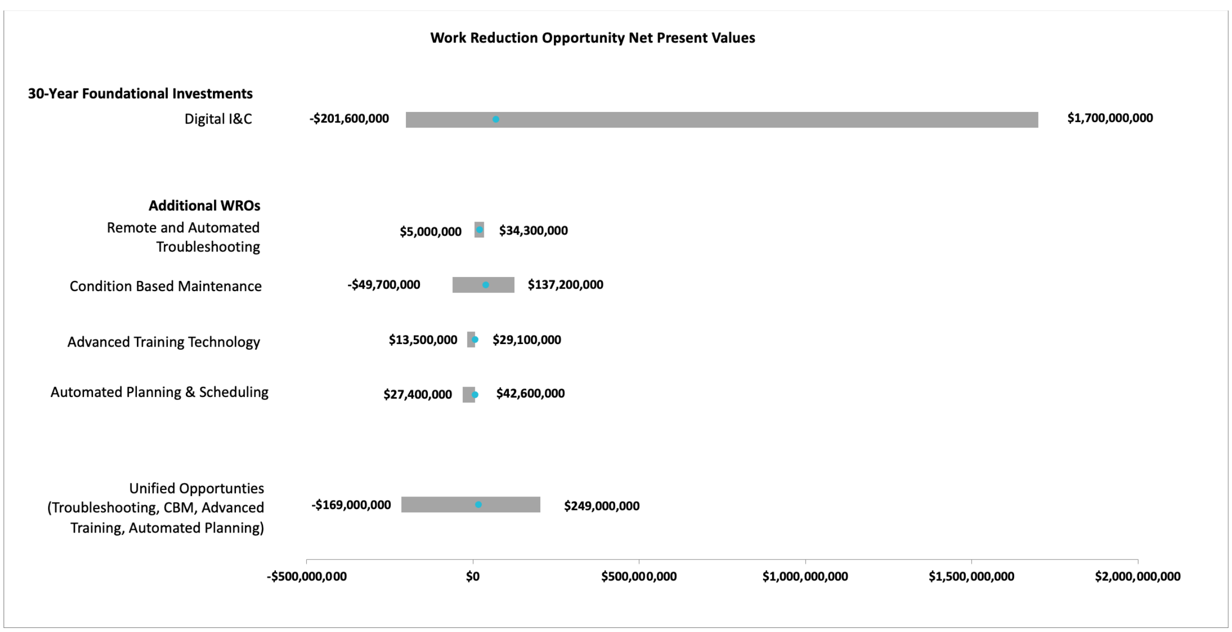

Figure 66. Work reduction opportunity NPV range.

To summarize the results of this study, implementing the five work reduction opportunities analyzed in this report can yield significant positive financial results and become part of a cost savings effort that will ensure plants operational health for years to come. Depending on the order of implementation, plants can begin observing significant financial savings early, which can aid in pursuing additional work reduction opportunities. Additionally, many of the technology upgrades required for the work reduction opportunities in this study can impact additional opportunities, such as a wireless network system, computer-based procedures, and VR/AR headsets. Therefore, the costs of additional opportunities will be reduced when combined. Evaluating additional opportunities, such as drone or robotic inspections, and radiation protection automation can further improve a plant's probability of financial health.

9. NEXT STEPS

In 2021, the INL team began research on ION Gen 1 with the goal of applying the IO methodology to make nuclear generation costs competitive by 2026. This work resulted in agreement on the ION construction and modernization domains, an overall LCOE target for an ION Gen 1 plant, detailed labor reduction targets by function, and a representative organizational structure. The team also identified initial work reduction opportunities for each domain and enablers that reduce ongoing O&M costs for a conventional, two-unit nuclear generation plant.

To continue the comprehensive report and achieve industry buy-in on the ION work reduction opportunities, additional research is needed to validate initial model assumptions, validate actual United States utility industry implementation costs, and document investments in innovation needed to transition from legacy operating models to ION.

Therefore, continued collaboration with U.S. nuclear operators is needed to further refine the economic analysis supporting the IONs goal of enabling light water reactor (LWR) market competitiveness.

Additional research avenues have become known, such as:

- Evaluating remaining work reduction opportunities (not analyzed in this report) to determine if they provide the additional O&M savings needed to achieve sustainable electricity production cost targets such as Campaign Maintenance, work reduction opportunities associated with nuclear plant security, RP automation, and drone or robotic inspections
- Evaluating remaining ION Gen 1 work reduction domain areas (WRO Domain Areas supporting implementation within 3 to 5 years)
- Indicating the areas available to the nuclear plant operator that will increase the probability of a financially successful implementation
- Identifying additional modernization work reduction domains for out-year research that support the ION strategy if the analyzed domain areas do not deliver needed savings.

These research avenues will produce further detail into the efficacy and importance of the ION business model. They also engage the domestic nuclear utility industry allowing researchers to discuss, refine, and promote ION.

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Appendix A
Monte Carlo Analysis

This analysis detailed in this report employs a Monte Carlo method to forecast project financial performance. Monte Carlo uses probability distributions for updated one-time and ongoing costs for five work reduction opportunities. The Monte Carlo method supports a stochastic, or probabilistic, model that uses an input range rather than a single number input. The range of one-time and on-going costs is currently captured in Figure 67 of the Monte Carlo Analysis model developed for this report. Figure 67 illustrates the inputs to the remote assistance and automated troubleshooting model.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Remote Assistance Inputs											Summary Results	
2		Max	Min	Mean	StdDev	Random Number	Current Results		Original ION Value			Value	Name
3	On-board diagnostics	$ 7,500,000	$ 6,500,000	$ 7,000,000	$ 500,000	$ 7,151,668	c.OnBoard		$ 7,000,000			$ 17,323,432	s.NPV
4	VR/AR Headsets	$ 200,000	$ 100,000	$ 150,000	$ 50,000	$ 149,778	c.VRAR		$ 135,000			$ (14,677,725)	s.Cost
5	Sensors for All Failure Modes	$ 9,000,000	$ 6,000,000	$ 7,500,000	$ 1,500,000	$ 5,228,075	c.Sensor						
6		$16,700,000.00	$ 12,600,000.00	$ 14,650,000.00	**Total**	**$ 12,529,520**	**c.Cost**		**$ 7,135,000**			$ 3,023,386	s.YrSave
7												22.8689%	s.IRR
8	Remote Plant Support FTE save	10	8						9				
9	Remote Plant Support save	$ 1,630,000	$ 1,304,000	$ 1,467,000	$ 163,000	$ 1,046,038	c.RemoteSave					Percent chance of a positive NPV	
10												100%	
11	Automated Troubleshooting FTE save	23	21						22				
12	Automated Troubleshooting save	$ 3,749,000	$ 3,423,000	$ 3,586,000	$ 163,000	$ 3,665,500	c.AutoSave						
13													
14					**Total**	**$ 4,711,538**	**c.AandRYrSave**		**31**				
15	Blended Cost per FTE	$ 163,000							**$ 5,053,000**				
16	Yearly FTE Cost Increase	3%											
17													
18	Discount rate	10.50%	8.75%	9.63%	0.88%	9.636%	c.Rate						
19													
20													
21	On-board diagnostics	$ 500,000	$ 100,000	$ 300,000	$ 200,000	$ 158,386.51	c.OnBoardGo						
22	VR/AR Headsets	$ 10,000	$ 5,000	$ 7,500	$ 2,500	$ 8,093.28	c.VRARGo						
23	Sensors for All Failure Modes	$ 100,000	$ 90,000	$ 95,000	$ 5,000	$ 91,369.56	c.SensorGo						
24		$ 610,000	$ 195,000	$ 402,500									
25	Ongoing cost increase every 5yrs	8%											

Figure 67. Example input to Monte Carlo analysis spreadsheet.

Column "A" contains each of the supporting technologies required to support the remote and automated troubleshooting opportunity. Columns "B" and "C" contain the minimum and maximum one-time and ongoing costs and FTE savings reported by participant utilities. Columns "D," "E," and "F" contain the calculated mean and standard deviation of the inputs, and a random number used to calculate the model iterations. Column "G" contains the value name used to refer to values in other sheets. Column "I" contains the original values used in last year's ION report. These values are not referred to in the spreadsheet and are only included for reference and comparison purposes. Column "L" contains summary results of the model iteration. Values included are the NPV, total one-time costs, total annual savings, and internal rate of return of the opportunity. This column also includes the probability of achieving a positive net present value.

The next sheet in Monte Carlo model contains the cash flow calculation used to generate outcomes. (Figure 68) The model includes one-time costs, on-going costs, and FTE savings then calculates the net present value of the business case.

	L	M	N	O	P	Q	R	S	T	U	V	W	X
2		Stochastic Model											
3													
4		Rate	9.64%										
5		Year	0	1	2	3	4	5	6	7	8	9	10
6		On-board diagnostics	$ (7,151,668)					$ (158,386.51)					$ (184,742.02)
7		VR/AR Headsets	$ (149,778)					$ (8,093.28)					$ (9,440.00)
8		Sensors for All Failure Modes	$ (5,228,075)					$ (91,369.56)					$ (106,573.46)
9		Remote Plant Support save		$ 1,077,419	$ 1,109,742	$ 1,143,034	$ 1,177,325	$ 1,212,645	$ 1,249,024	$ 1,286,495	$ 1,325,090	$ 1,364,842	$ 1,405,788
10		Automated Troubleshooting save		$ 1,077,419	$ 1,109,742	$ 1,143,034	$ 1,177,325	$ 1,212,645	$ 1,249,024	$ 1,286,495	$ 1,325,090	$ 1,364,842	$ 1,405,788
11		Total	$ (12,529,520)	$ 2,154,838	$ 2,219,484	$ 2,286,068	$ 2,354,650	$ 2,167,440	$ 2,498,048	$ 2,572,990	$ 2,650,179	$ 2,729,685	$ 2,510,820
12			m.Cost	m.YrSave									
13													
14													
15		Net Present Value	$10,207,974	m.NPV									
16		Internal Rate of Return	18.99%	m.IRR									

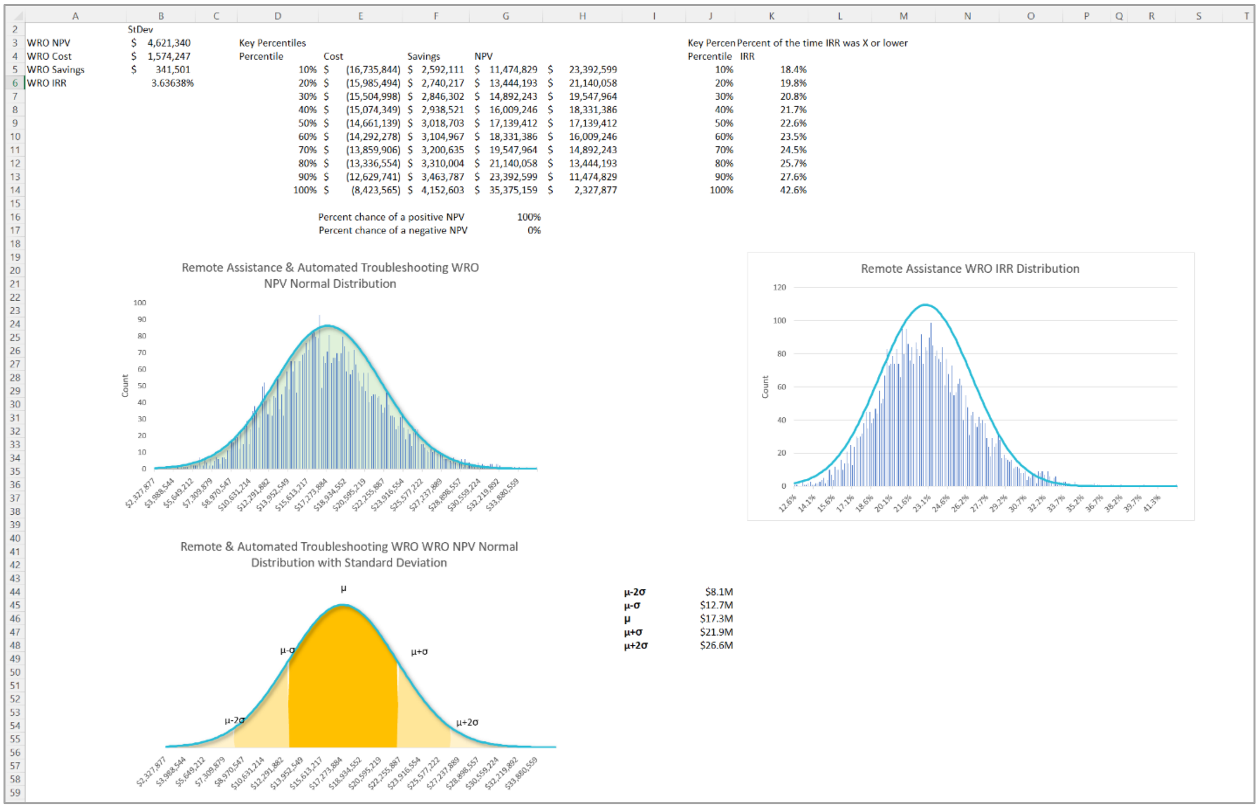
Figure 68. Monte Carlo analysis model.

The data sheet contains an Excel data table in columns A-E. This data table contains the returned NPV, costs, and savings. This data table contains five thousand outcomes of the model. The results of the data table are then sorted in columns K-Q. This portion of the sheet segments in the NPVs into two hundred bins ordered from lowest to highest value and calculates the number of iterations from the five thousand outcomes that fall into each bin. Subsequent columns are used to generate standard deviation charts.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1								MinNPV	$ 2,327,877									
2	Data Table							MaxNPV	$ 35,375,160		NPV Frequency	NPVBins						
3	Seq	NPV	Cost	YrSave	IRR			MinCost	$ (20,833,944)		Seq		NPVItems	NormDist	Standard Deviat	2x Standard De	3x Standard Deviation	
4	Refs:	$ 10,207,974	$ (12,529,520)	$ 2,154,838	18.989%			MaxCost	$ (8,423,566)		1	$ 2,327,877	0	4.46465E-10				
5	1	$ 18,982,690	$ (17,041,838)	$ 3,078,631	19.955%			MinSave	$ 1,716,634		2	$ 2,493,944	1	5.01357E-10			5.01357E-10	
6	2	$ 10,805,054	$ (14,660,549)	$ 2,398,265	18.079%			MaxSave	$ 4,152,603		3	$ 2,660,010	0	5.62271E-10			5.62271E-10	
7	3	$ 17,485,833	$ (14,085,328)	$ 2,942,740	22.874%			NumBinsTrain	200		4	$ 2,826,077	0	6.29772E-10			6.29772E-10	
8	4	$ 19,316,686	$ (14,120,925)	$ 2,858,291	22.319%						5	$ 2,992,144	0	7.04467E-10			7.04467E-10	
9	5	$ 22,175,391	$ (15,063,437)	$ 3,183,988	23.275%			MinIRR	12.57%		6	$ 3,158,211	0	7.87004E-10			7.87004E-10	
10	6	$ 20,124,230	$ (13,907,520)	$ 3,229,961	25.254%			MaxIRR	42.62%		7	$ 3,324,277	1	8.78077E-10			8.78077E-10	
11	7	$ 25,095,276	$ (15,865,307)	$ 3,531,514	24.525%						8	$ 3,490,344	0	9.78425E-10			9.78425E-10	
12	8	$ 19,773,029	$ (15,937,049)	$ 3,370,205	23.399%			NPV STDEV	$ 4,621,340		9	$ 3,656,411	0	1.08883E-09			1.08883E-09	
13	9	$ 18,482,187	$ (15,502,200)	$ 3,058,033	21.561%						10	$ 3,822,478	0	1.21014E-09			1.21014E-09	
14	10	$ 16,212,372	$ (12,625,586)	$ 2,910,038	25.045%			+1 stdev	$ 21,944,772		11	$ 3,988,544	0	1.34322E-09			1.34322E-09	
15	11	$ 20,806,856	$ (14,440,974)	$ 3,175,134	24.321%						12	$ 4,154,611	0	1.48901E-09			1.48901E-09	
16	12	$ 19,961,497	$ (12,298,880)	$ 3,023,274	26.993%			-1 stdev	$ 12,702,093		13	$ 4,320,678	1	1.6485E-09			1.6485E-09	
17	13	$ 23,332,030	$ (13,400,111)	$ 3,145,097	25.564%						14	$ 4,486,745	0	1.82272E-09			1.82272E-09	
18	14	$ 14,491,903	$ (15,275,271)	$ 2,959,819	21.273%			average	$ 17,323,432		15	$ 4,652,811	1	2.01274E-09			2.01274E-09	
19	15	$ 19,204,322	$ (16,670,249)	$ 3,424,167	22.652%						16	$ 4,818,878	1	2.21971E-09			2.21971E-09	
20	16	$ 31,361,059	$ (14,671,916)	$ 3,603,688	26.984%			+2 stdev	$ 26,566,111		17	$ 4,984,945	1	2.4448E-09			2.4448E-09	
21	17	$ 20,788,809	$ (14,050,095)	$ 3,242,884	25.476%						18	$ 5,151,012	1	2.68925E-09			2.68925E-09	
22	18	$ 17,282,916	$ (15,829,681)	$ 2,980,863	20.740%			-2 stdev	$ 8,080,753		19	$ 5,317,078	0	2.95431E-09			2.95431E-09	
23	19	$ 16,782,501	$ (15,201,232)	$ 2,890,940	21.057%						20	$ 5,483,145	3	3.24132E-09			3.24132E-09	
24	20	$ 25,516,422	$ (15,846,710)	$ 3,321,265	22.756%						21	$ 5,649,212	2	3.55161E-09			3.55161E-09	
25	21	$ 19,481,926	$ (12,347,690)	$ 3,087,225	27.475%						22	$ 5,815,279	2	3.8866E-09			3.8866E-09	
26	22	$ 18,486,627	$ (12,838,717)	$ 3,108,463	26.367%						23	$ 5,981,345	2	4.24768E-09			4.24768E-09	
27	23	$ 11,575,908	$ (17,024,067)	$ 2,746,095	17.378%						24	$ 6,147,412	7	4.63632E-09			4.63632E-09	
28	24	$ 22,958,283	$ (13,728,381)	$ 3,218,045	25.833%						25	$ 6,313,479	2	5.054E-09			5.054E-09	
29	25	$ 19,429,090	$ (13,953,047)	$ 3,063,205	24.071%						26	$ 6,479,546	2	5.50218E-09			5.50218E-09	
30	26	$ 12,400,395	$ (15,321,320)	$ 2,878,462	20.924%						27	$ 6,645,612	7	5.98239E-09			5.98239E-09	
31	27	$ 26,131,749	$ (15,701,103)	$ 3,739,220	26.154%						28	$ 6,811,679	4	6.49611E-09			6.49611E-09	
32	28	$ 16,008,264	$ (14,746,485)	$ 2,976,103	22.307%						29	$ 6,977,746	2	7.04484E-09			7.04484E-09	
33	29	$ 31,933,346	$ (15,819,472)	$ 3,663,081	25.424%						30	$ 7,143,813	6	7.63006E-09			7.63006E-09	
34	30	$ 19,342,645	$ (15,287,797)	$ 2,812,421	20.046%						31	$ 7,309,879	2	8.25323E-09			8.25323E-09	
35	31	$ 24,081,246	$ (15,777,963)	$ 3,490,548	24.398%						32	$ 7,475,946	5	8.91578E-09			8.91578E-09	
36	32	$ 16,704,533	$ (16,549,144)	$ 3,310,062	22.098%						33	$ 7,642,013	7	9.61909E-09			9.61909E-09	
37	33	$ 24,684,576	$ (15,271,212)	$ 3,543,263	25.399%						34	$ 7,808,080	6	1.03645E-08			1.03645E-08	
38	34	$ 22,366,610	$ (13,483,774)	$ 3,120,109	25.365%						35	$ 7,974,146	3	1.11532E-08			1.11532E-08	
39	35	$ 18,606,319	$ (14,706,209)	$ 3,144,802	23.614%						36	$ 8,140,213	7	1.19865E-08		1.19865E-08		

Figure 69. Monte Carlo Data Sheet.

The next sheet shown in Figure 70 contains the graphical outputs. These graphs are built using data in the previous sheets. Additionally, columns A and B contain the standard deviation values for the NPV, cost, savings, and IRR. Columns D-K contain the percent probabilities of observing costs, savings, NPVs, and IRR for the range of inputs reported by utility participants.



	StDev
WRO NPV	$ 4,621,340
WRO Cost	$ 1,574,247
WRO Savings	$ 341,501
WRO IRR	3.63638%

Key Percentiles

Percentile	Cost	Savings	NPV	
10%	$ (16,735,844)	$ 2,592,111	$ 11,474,829	$ 23,392,599
20%	$ (15,985,494)	$ 2,740,217	$ 13,444,193	$ 21,140,058
30%	$ (15,504,998)	$ 2,846,302	$ 14,892,243	$ 19,547,964
40%	$ (15,074,349)	$ 2,938,521	$ 16,009,246	$ 18,331,386
50%	$ (14,661,139)	$ 3,018,703	$ 17,139,412	$ 17,139,412
60%	$ (14,292,278)	$ 3,104,967	$ 18,331,386	$ 16,009,246
70%	$ (13,859,906)	$ 3,200,635	$ 19,547,964	$ 14,892,243
80%	$ (13,336,554)	$ 3,310,004	$ 21,140,058	$ 13,444,193
90%	$ (12,629,741)	$ 3,463,787	$ 23,392,599	$ 11,474,829
100%	$ (8,423,565)	$ 4,152,603	$ 35,375,159	$ 2,327,877

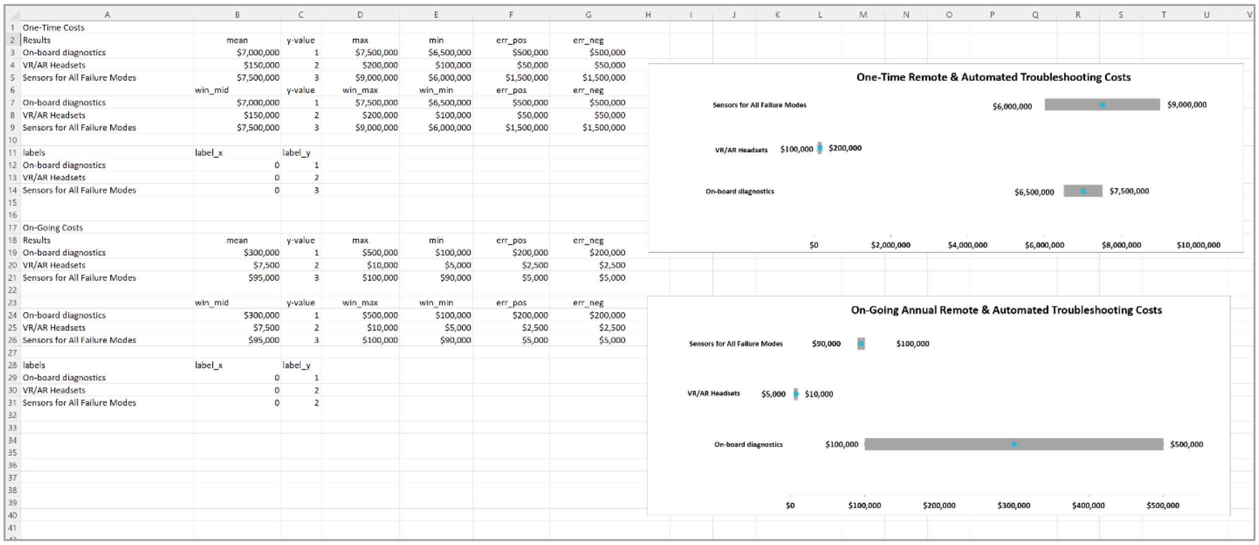
Percent chance of a positive NPV	100%
Percent chance of a negative NPV	0%

Key Percen Percent of the time IRR was X or lower

Percentile	IRR
10%	18.4%
20%	19.8%
30%	20.8%
40%	21.7%
50%	22.6%
60%	23.5%
70%	24.5%
80%	25.7%
90%	27.6%
100%	42.6%

Figure 70. Monte Carlo output and charts.

The final figure, Figure 71, contains the graphical representations of the one-time and on-going costs of the technologies required for the WRO. Columns “B,” “D,” and “E” contain the minimum, maximum, and average value for each of the technologies. Column “C” contains a Y-value used to build the graphs. Columns F-G contain the length of each bar. These values are calculated by subtracting the minimum and maximum input from the average input. Rows 11-14 are used to build the vertical axis containing the labels. The labels are created by plotting points along the Y-axis in-line with the cost bars.

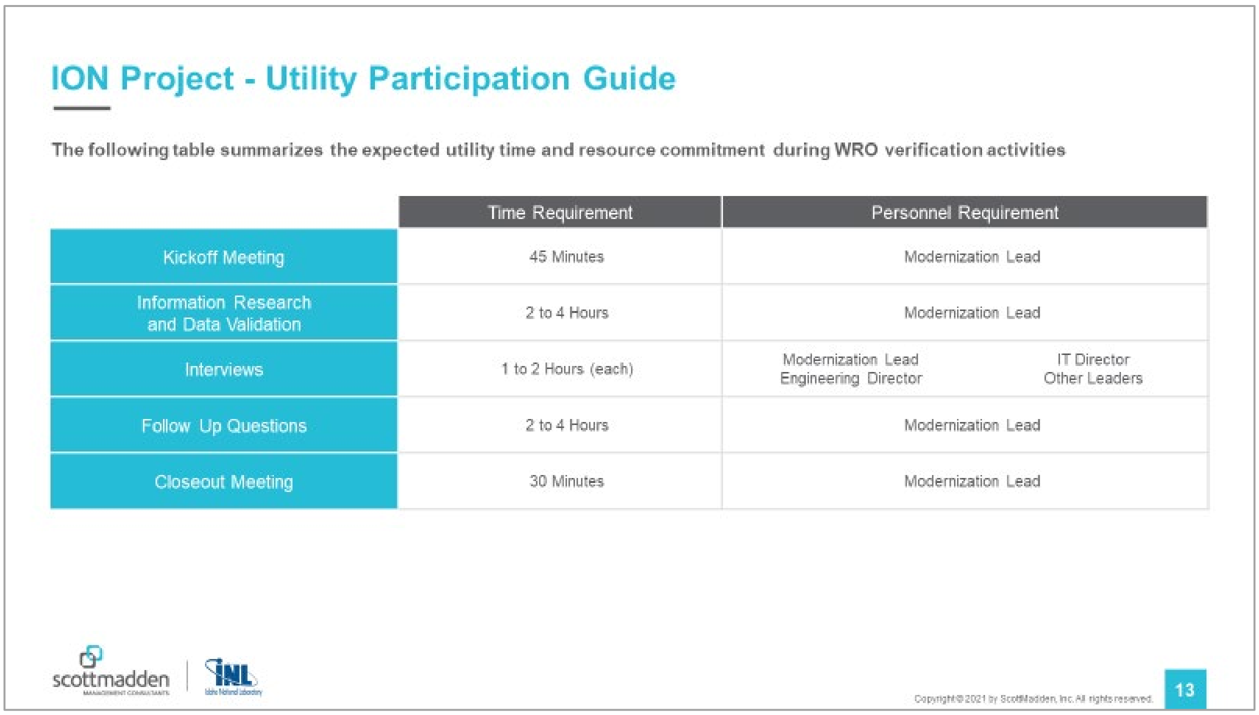


One-Time Costs						
Results	mean	y-value	max	min	err_pos	err_neg
On-board diagnostics	$7,000,000	1	$7,500,000	$6,500,000	$500,000	$500,000
VR/AR Headsets	$150,000	2	$200,000	$100,000	$50,000	$50,000
Sensors for All Failure Modes	$7,500,000	3	$9,000,000	$6,000,000	$1,500,000	$1,500,000
	win_mid	y-value	win_max	win_min	err_pos	err_neg
On-board diagnostics	$7,000,000	1	$7,500,000	$6,500,000	$500,000	$500,000
VR/AR Headsets	$150,000	2	$200,000	$100,000	$50,000	$50,000
Sensors for All Failure Modes	$7,500,000	3	$9,000,000	$6,000,000	$1,500,000	$1,500,000
labels	label_x	label_y				
On-board diagnostics	0	1				
VR/AR Headsets	0	2				
Sensors for All Failure Modes	0	3				
On-Going Costs						
Results	mean	y-value	max	min	err_pos	err_neg
On-board diagnostics	$300,000	1	$500,000	$100,000	$200,000	$200,000
VR/AR Headsets	$7,500	2	$10,000	$5,000	$2,500	$2,500
Sensors for All Failure Modes	$95,000	3	$100,000	$90,000	$5,000	$5,000
	win_mid	y-value	win_max	win_min	err_pos	err_neg
On-board diagnostics	$300,000	1	$500,000	$100,000	$200,000	$200,000
VR/AR Headsets	$7,500	2	$10,000	$5,000	$2,500	$2,500
Sensors for All Failure Modes	$95,000	3	$100,000	$90,000	$5,000	$5,000
labels	label_x	label_y				
On-board diagnostics	0	1				
VR/AR Headsets	0	2				
Sensors for All Failure Modes	0	2				

Figure 71. Monte Carlo Costs and Graphical Representation.

Appendix B
Utility Participation

To gather and update one-time and ongoing costs for each technology required to support the five work reduction opportunities discussed in this report, multiple meetings were held with each participating utility. These meetings consisted of a project kick-off to introduce the participant to the ION concept and to review the project approach and timelines. The remaining four meetings consisted of workshops to review datapoints for each opportunity, discuss questions and concerns and close-out the project. Figure 72 contains the utility participation guide. This guide contains each of the five meetings and the titles of preferred utility participants.



ION Project - Utility Participation Guide

The following table summarizes the expected utility time and resource commitment during WRO verification activities

	Time Requirement	Personnel Requirement
Kickoff Meeting	45 Minutes	Modernization Lead
Information Research and Data Validation	2 to 4 Hours	Modernization Lead
Interviews	1 to 2 Hours (each)	Modernization Lead Engineering Director IT Director Other Leaders
Follow Up Questions	2 to 4 Hours	Modernization Lead
Closeout Meeting	30 Minutes	Modernization Lead

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Figure 72. Utility participation guide

ION concept summary material was used to inform utility participants of the existing and on-going research. This material included a summary of the methods and sources used to arrive at the scope, cost, and savings estimate of each work reduction opportunity. Additionally, a summary of the necessary competitive LCOE for a dual-unit nuclear plant was discussed. Figure 73 contains the ION concept introductory material.

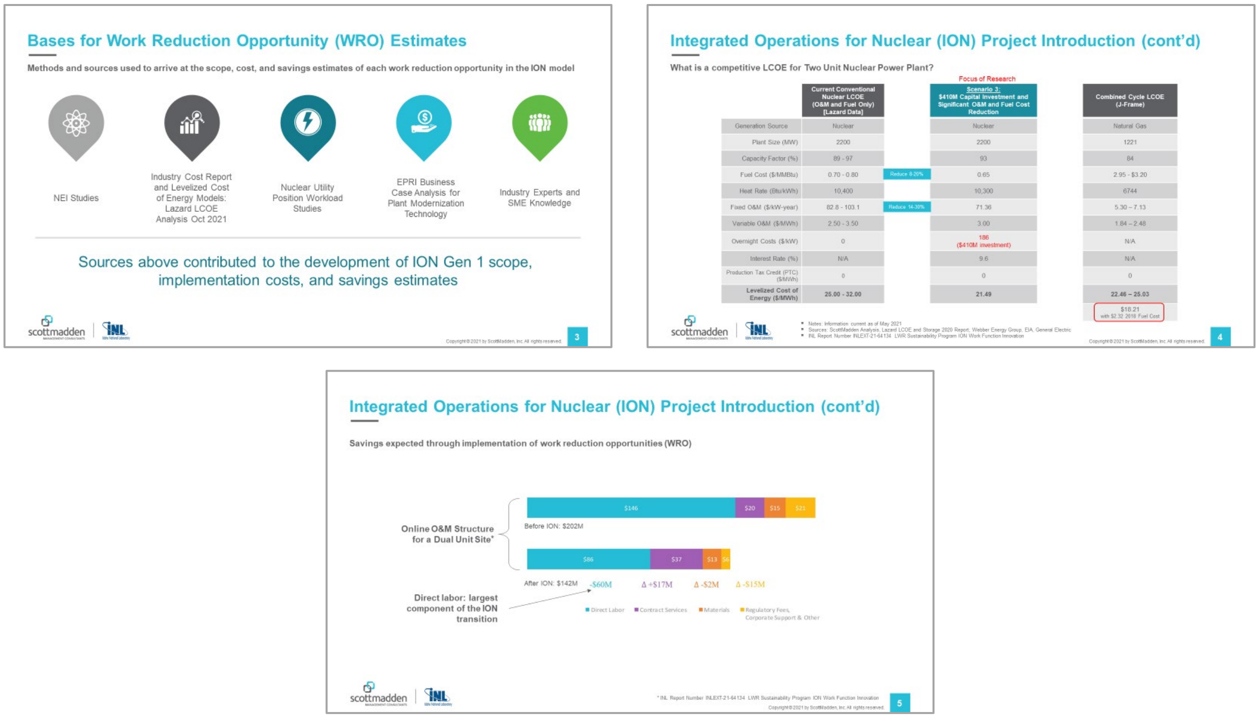


Figure 73. ION concept introductory material.

Figure 74 is an example of the project background and objectives. This material was used to inform participants of the second phase, or updates to the report intended to be made.

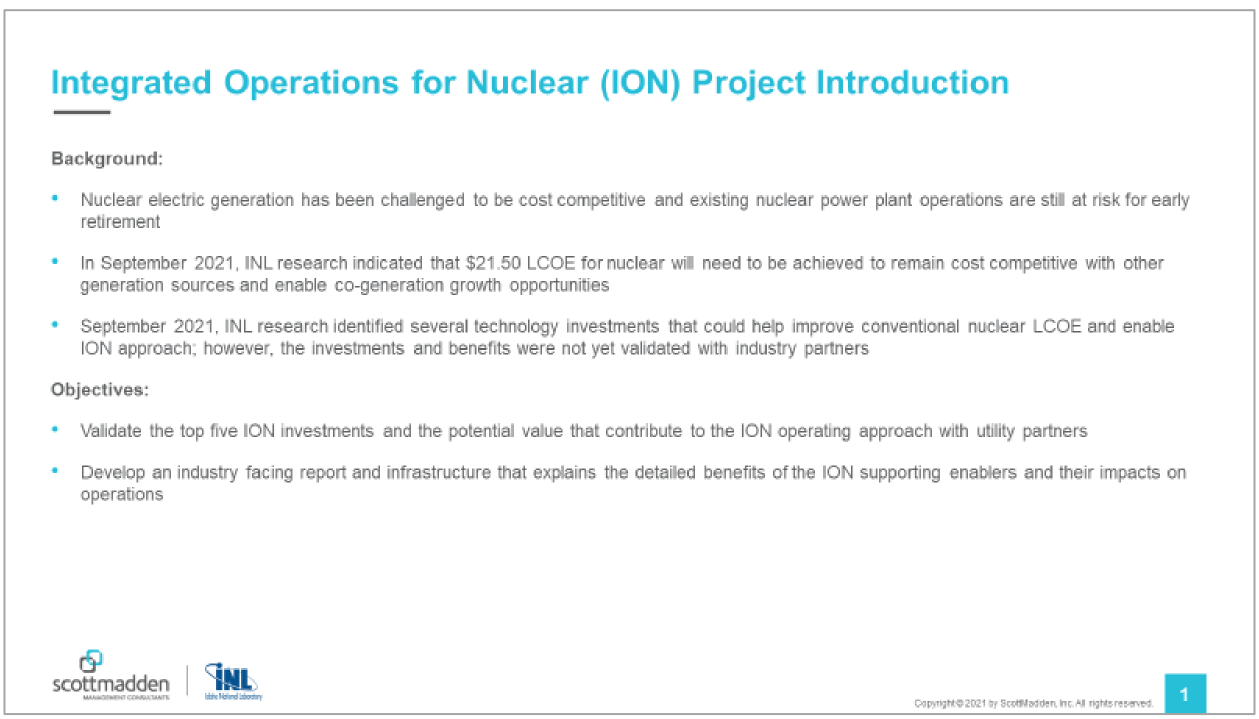
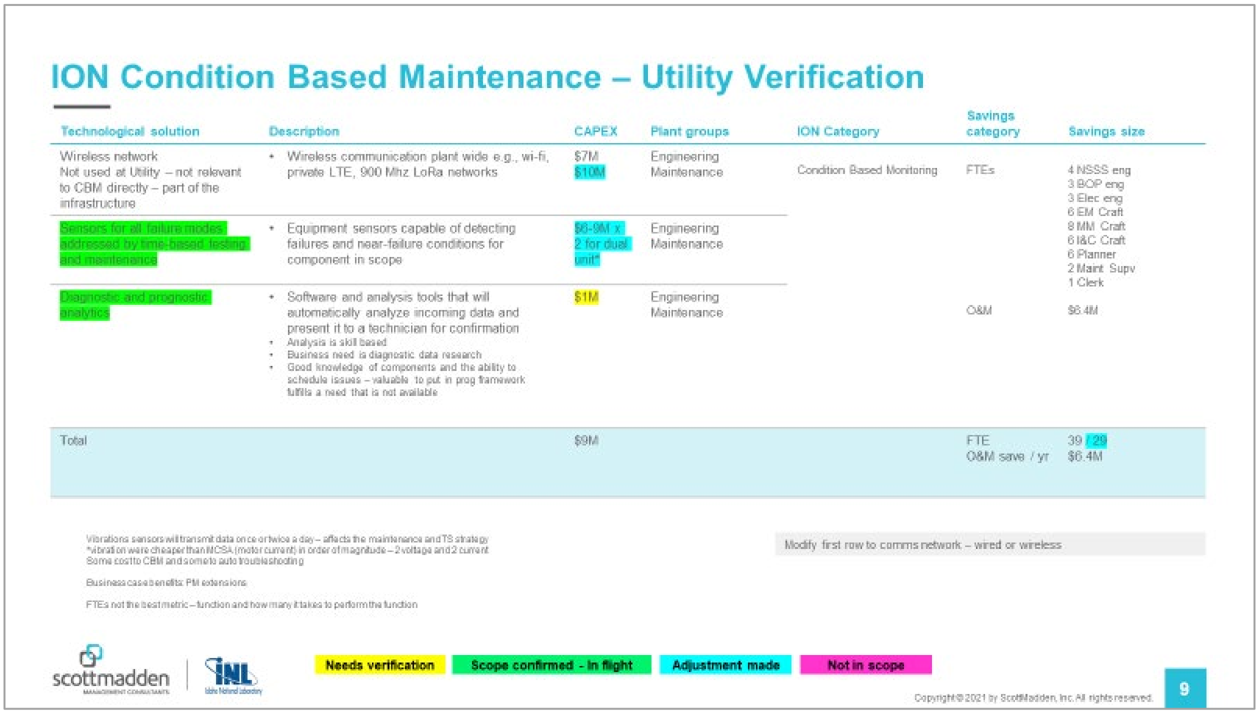


Figure 74. Project background and objectives.

Figure 75 is an example of a verification table used during workshops held with utility participants to gather updated costs for the condition-based monitoring WRO.



ION Condition Based Maintenance – Utility Verification

Technological solution	Description	CAPEX	Plant groups	ION Category	Savings category	Savings size
Wireless network Not used at Utility – not relevant to CBM directly – part of the infrastructure	• Wireless communication plant wide e.g., wi-fi, private LTE, 900 Mhz LoRa networks	$7M $10M	Engineering Maintenance	Condition Based Monitoring	FTEs	4 NSSS eng 3 BOP eng 3 Elec eng 6 EM Craft 8 MM Craft 6 I&C Craft 6 Planner 2 Maint Supv 1 Clerk
Sensors for all failure modes addressed by time-based testing and maintenance	• Equipment sensors capable of detecting failures and near-failure conditions for component in scope	$6-9M x 2 for dual unit*	Engineering Maintenance			
Diagnostic and prognostic analytics	• Software and analysis tools that will automatically analyze incoming data and present it to a technician for confirmation • Analysis is skill based • Business need is diagnostic data research • Good knowledge of components and the ability to schedule issues – valuable to put in prog framework fulfils a need that is not available	$1M	Engineering Maintenance		O&M	$6.4M
Total		$9M			FTE O&M save / yr	39 / 29 $6.4M

Vibrations sensors will transmit data once or twice a day – affects the maintenance and TS strategy
*vibration were cheaper than MCSA (motor current) in order of magnitude – 2 voltage and 2 current
Some cost to CBM and some to auto troubleshooting

Business case benefits: PM extensions

FTEs not the best metric – function and how many it takes to perform the function

Modify first row to comms network – wired or wireless

Needs verification | Scope confirmed - In flight | Adjustment made | Not in scope

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Figure 75. Condition-based monitoring data verification table.