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Anna Hall, Jeffrey C Joe



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**Idaho National Laboratory
Idaho Falls, Idaho 83415**

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Anna Hall^{a*} and Jeffrey C. Joe^a

^a*Human Factors & Reliability Department, Idaho National Laboratory, Idaho Falls, USA*

*Corresponding author: Anna Hall, Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415-3840. email: anna.hall@inl.gov

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Within the current United States (U.S.) nuclear power fleet, main control room modernization (CRM) is an important step towards cost savings. In recent decades, plants have been engaged in upgrades to varying degrees. This process requires a nuanced, balanced, and timely approach that ensures continued safety and long-term sustainability. In 2012 a survey was issued to individuals from the nuclear industry to learn their perspectives on a range of CRM issues. The survey targeted the benefits and challenges for utilities undertaking this process, including the main drivers and barriers to technology upgrades, regulatory compliance, and the effects these factors have on concepts of operations, strategic approaches, and staffing. In 2022, the survey was issued again to understand whether CRM perceptions had changed in the last 10 years. Our findings identify changes in industry thinking from a decade ago. We reveal perspective shifts that represent increased optimism and, in some instances, increased doubt regarding the opportunities and challenges inherent in CRM and implementation. We also report nuanced differences in CRM perspectives between utility and surrounding non-utility nuclear industry respondents.

Keywords: Control room modernization, industry perspectives, survey

Introduction

The existing fleet of U.S. nuclear power plants is among the oldest in the world, with a mean age of 41.6 years. Most were built in the 1970s and 1980s. Over the last two decades, owners of commercial nuclear power plants in the U.S. have been engaged with main control room modernization (CRM) to varying degrees. One of the goals of the Department of Energy's Light Water Reactor Sustainability (LWRS) Program, which includes researchers at the Idaho National Laboratory (INL), is to assist the commercial nuclear power industry with their CRM efforts. As part of this effort, a survey was issued in 2012 to members of a nuclear industry working group to collect their views on a range of issues related to CRM. A summary of the key utility findings and their implications is reported elsewhere¹. In 2022, the same survey was issued by email to

individuals from the U.S. nuclear power industry, including members of the original working group. These findings were compared to those from 10 years ago. Taken together, our research identifies changes in industry thinking regarding the opportunities and challenges inherent in CRM and implementation.

Method

In 2012, the survey was issued to utility representatives of the LWRs Program Advanced Instrumentation, Information, and Control Systems and Technologies Utility Working Group during the Winter LWRs Program Working Group Meeting using a real-time audience polling technology. The sample comprised individuals from utilities, and non-utilities, which we define as individuals engaged broadly in the wider supporting industry such as nuclear power vendors, researchers and other solution providers. Respondents saw the questions in a PowerPoint presentation and were instructed to answer based on their utility or corporate level (i.e., those from non-utilities). Questions were forced choice with no open responses. Depending on the question there were N=10 respondents from utilities (i.e., employed directly at commercial nuclear power plants) and N=10 from non-utility (including the Electric Power Research Institute, Halden, and INL, except for one individual who indicated “other”).

In 2022, the survey was issued by email via Qualtrics to 64 individuals from the nuclear power industry. Participants based their answers on either the utility or non-utility standpoint. There were respondents from Halden and INL; however, the majority of non-utility responses were not from research institutes. Non-utility affiliations included X-Energy, MPR, Sargent & Lundy and ScottMadden. Responses were collected May–August 2022, with N=9 individuals from utilities and N=18 from non-utilities, depending on the question.

The survey consisted of 31 multiple choice questions, covering a range of CRM topics. For the approaches to CRM questions, participants were asked to look at Figure 1 depicting ways that human-system interface (HSI) and instrumentation and control (I&C) modernization can be carried out.

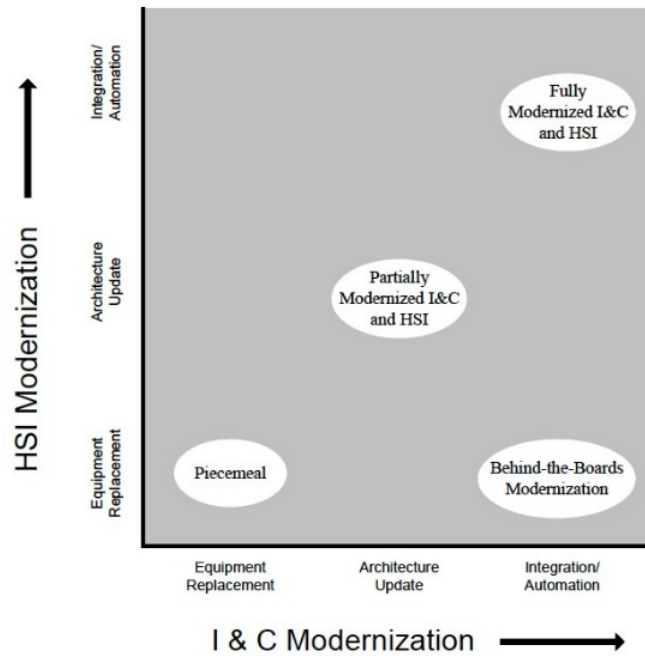


Figure 1. Approaches to CRM.
Image courtesy of the Electric Power Research Institute.

For the majority of quantitative survey data, utility and non-utility respondents shared similar perspectives regardless the industry sector to which they belonged, and so responses were pooled. All quantitative findings were reported as percent of participant endorsement for each forced-choice response. Category totals may not sum to exactly 100% due to rounding.

In the 2022 survey only, we additionally asked open-ended questions regarding CRM and the future of the U.S. nuclear power industry more generally, captured in the respondents' own words. In some instances, we found perspectives to be meaningfully different as a function of industry sector, and these data are reported separately for utility and non-utility respondents to

highlight instances in which perspectives were not aligned. Completion time had a mean of 27.95 minutes, standard deviation of 22.72, and had a range of 2.92–105.65 minutes, excluding outliers. This indicates that the respondents spent an appropriate amount of time reading the questions, and did not just quickly answer without properly reading them. In both 2012 and 2022, the research was approved by the INL Internal Review Board, and all respondents consented to the research (2022 IRB approval # INL000164).

Results

Quantitative findings

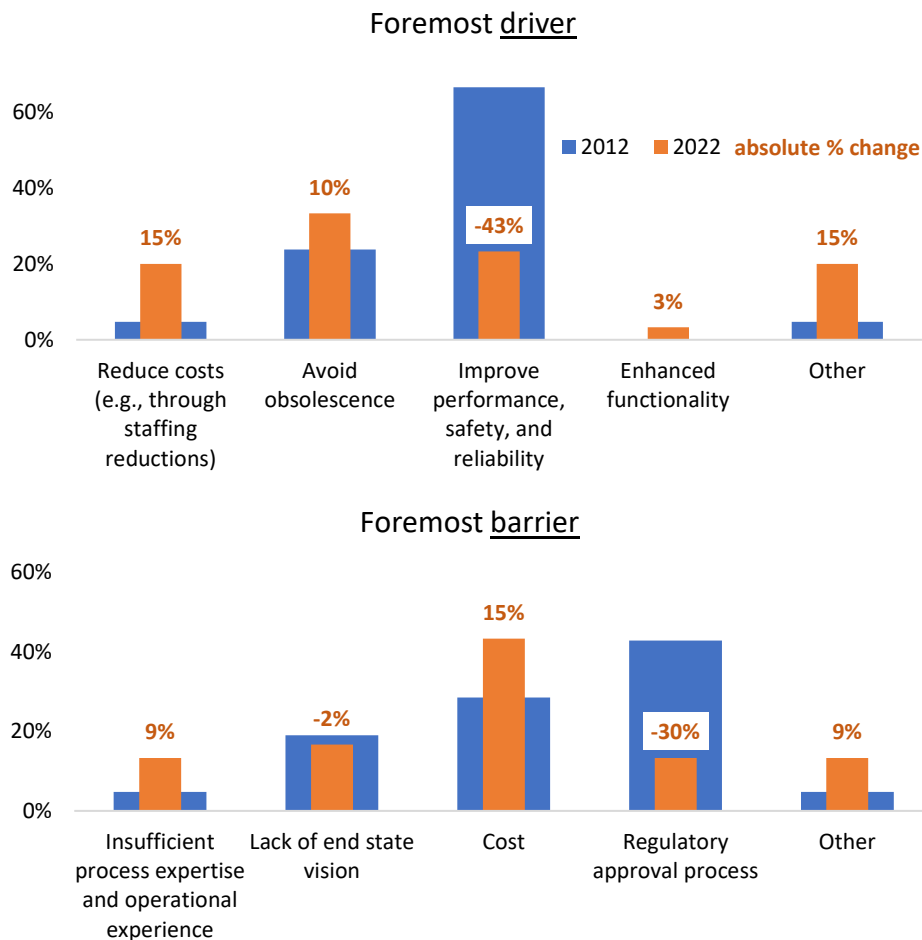


Figure 2. Drivers of, and barriers to, CRM.

Drivers. Compared to 2012, there was a 43% reduction in modernization being driven to improve performance, safety, and reliability (Figure 2-upper panel). Instead, participants indicated reduced costs and avoiding obsolescence as primary reasons to modernize. Qualitative responses for the “other” category included a desire to create a main control room that can be used by younger generations, extending plant life, and several comments regarding obsolescence concerns. Notably, avoiding obsolescence was the modal response in 2022.

Barriers. Figure 2-lower panel shows that cost became a greater concern. However, there was a large (30%) reduction in regulatory approval concerns (note—in 2022, *none* of the utility participants rated concerns over regulatory approval as a barrier to CRM). There was also a slight increase in endorsing insufficient process expertise and operational experience. Qualitative responses for the “other” category included perceptions of high risk, a lack of examples of project delivery success, and different barriers for safety- and non-safety systems.

Table 1. Plans to use component upgrades

	No plans		Limited use		Extensive use		Not sure		Already in use
	2012	2022	2012	2022	2012	2022	2012	2022	2022
Workstations	0	0	5	7	45	28	30	10	55
Panels	10	18	29	14	33	14	14	7	46
Soft controls	0	7	15	17	65	41	10	3	31
Advanced diagnostics	3	2	31	29	48	48	6	7	14
Intelligent alarms	0	14	15	28	70	31	5	10	17
Overview displays	5	10	5	21	80	45	5	0	24
Computer-based procedures	10	17	15	24	60	38	5	7	14
Automated controls	11	7	32	38	42	28	5	7	21
Operator aids	0	7	15	28	70	41	5	3	21
Integrative technologies	0	0	25	42	60	38	5	6	13

2012 percentages do not add up to 100% - remainder respondents selected “non-applicable.”

Plans for digital component upgrades. The largest change since 2012 was a decrease in extensive use plans for most hardware upgrades (Table 1). Depending on the component, this was either a function of the increase in no or limited use plans, or that it was already in use, a

response choice only available in the 2022 survey. Participants were less unsure about workstations than in 2012, a majority (55%) indicating that these were already in use. Although only 14% of 2022 respondents indicated that advanced diagnostics were already in use, plans to use them in either a limited or extensive capacity were similar at both time points (similarly high).

Plans to use extensively intelligent alarms changed the most (decreased), shifting towards an increase in no or limited use plans (up 27%), with a smaller portion (17%) indicating they were already in use. The large decline in extensive use plans for soft controls showed the opposite pattern, with 31% indicating already in use and a much smaller portion endorsing no or limited use plans (up 9%). For overview displays, computer-based procedures, operator aids, and integrative technologies, the reason extensive use plans were >20% lower were more evenly spread between an increase in no or limited use plans and the components already being in use.

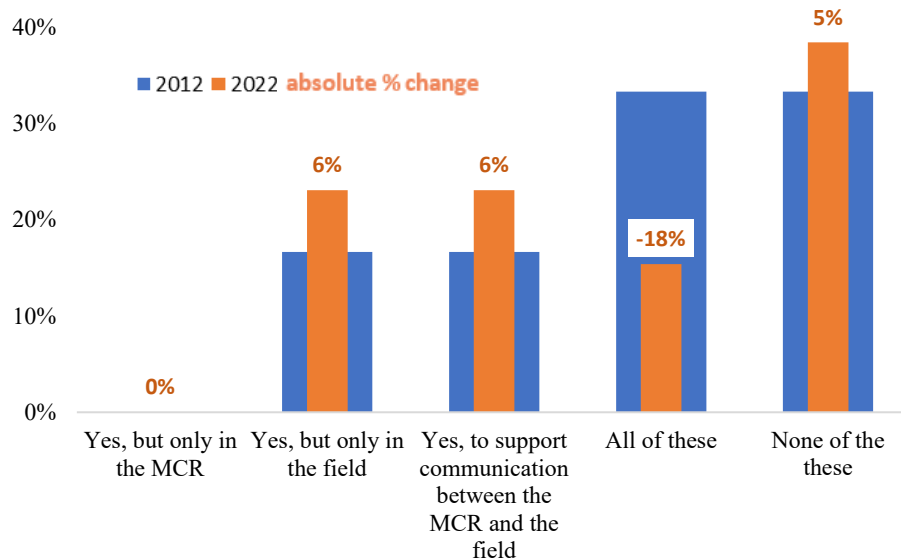





Figure 3. The ways in which wireless controls plan to be used
MCR = main control room

Plans to use wireless controls. The largest change over time was that 18% fewer respondents indicated plans to use wireless controls across multiple contexts (Figure 3). This was reflected in a slight uptick in plans for none of these, as well as in the field only, and to support communication between the main control room and the field (+6%). The modal response in 2022 was that wireless controls would not be used at all (38%).

Table 2. Perspectives on a new concept of operations

	Operator is hands on at a detailed level. (Equipment replacement)		Operator performs higher-level monitoring. (Architecture update)		Operator is supervisor of automation. (Integration / automation)		Operator can operate the plant at all three levels.		None of these.	
										
Which one..	2012	2022	2012	2022	2012	2022	2012	2022	2012	2022
...do you prefer?	0	4	5	18	25	18	70	61	0	0
...is the most feasible for implementing at your plant?	17	18	33	36	17	4	33	43	0	0
...will improve your plant's performance, safety and reliability the most?	0	6	11	21	21	33	68	3%	0	2
...will your utility likely adopt?	11	11	32	39	5	11	47	36	5	4

A new concept of operations. Participants were asked to view an image depicting three concepts of operations following HSI and I&C modernization. Each concept represented the degree to which the operator actively operates the plant as a function of increased digitization and automation. Table 2 shows that as with 2012, most respondents still preferred the ability to choose which level of automation is used, and there was a 10% increase in implementation feasibility for this concept of operations. In terms of improving performance, safety, and reliability, there was strong sentiment in 2012 that this was best achieved with operators being able to switch between levels of automation, which has waned over time. More recently, there

are mixed feelings about how to best accomplish this (i.e., endorsement spread across all levels in 2022). And unlike 2012, the most popular response for likelihood of utility adoption was the middle level of automation in operations (operator performs higher-level monitoring).

Table 3. Approaches to CRM

Which one...	Piecemeal		Partially Modernized I&C and HSI		Behind-the-Boards Modernization (I&C only)		Fully Modernized I&C and HSI		None of these	
	2012	2022	2012	2022	2012	2022	2012	2022	2012	2022
...do you prefer?	0	0	17	25	6	0	78	75	0	0
...is the most feasible for implementing at your plant?	6	21	53	50	12	7	29	21	0	0
...is the most cost-effective in the <u>short</u> term (3–10 years)?	26	37	63	44	0	0	5	19	5	0
...is the most cost-effective in the <u>long</u> term (20–30 years)?	0	0	11	25	0	7	89	68	0	0
...will improve your plant’s performance, safety, and reliability the most?	0	0	5	15	11	6	84	79	0	0
...is the most likely to occur at your utility?	11	11	56	54	6	14	22	21	6	0

Approaches to CRM. Next the participants were asked to look at Figure 1 depicting ways that HSI and I&C modernization can be carried out. The perspective that no forms of modernization were necessary was rare in 2012 and absent in 2022 (Table 3). There was little change in preference after 10 years, with approximately 75% of respondents still preferring fully modernized. This preference was reflected in high ratings for long-term cost-effectiveness and improved plant performance, safety, and reliability (although long-term cost-effectiveness was down 21%—the largest decline across all categories from 2012). Nonetheless, respondents deemed partially modernized the most feasible and most likely, and the largest increase over time was the perspective that piecemeal would be most feasible (up 15%). Finally, in terms of which is more cost-effective in the short term, the lower levels were still the most popular; piecemeal increased by 20% since 2012.

Maintenance and staff. These are still highly relevant topics for CRM strategies, although there were some subtle changes over the last 10 years (Table 4). In 2022, there was no longer any uncertainty about how these topics factored into modernization strategies. Maintenance issues grew the most in importance (“completely factored in” up 29%) and was the most relevant issue in 2022. Staff training was most relevant in 2012, but shared importance with staff qualifications in 2022.

Table 4. Maintenance and staff strategies in CRM

	Completely Factored		Somewhat Factored		Somewhat Disregarded		Completely Disregarded		Not Sure	
	2012	2022	2012	2022	2012	2022	2012	2022	2012	2022
Maintenance of control room technologies	35	64	35	25	0	11	0	0	30	0
Qualifications of plant staff	42	43	37	54	5	4	0	0	16	0
Training requirements for plant staff	60	39	20	54	5	7	0	0	15	0

Timeframe for CRM. A 3–10 year timeline was still the modal response (Figure 4). In 2022, 4% selected already modernized—a response choice only available in the 2022 survey. Notably, there were no respondents in 2022 that indicated no modernization plans, down 16% from 2012.

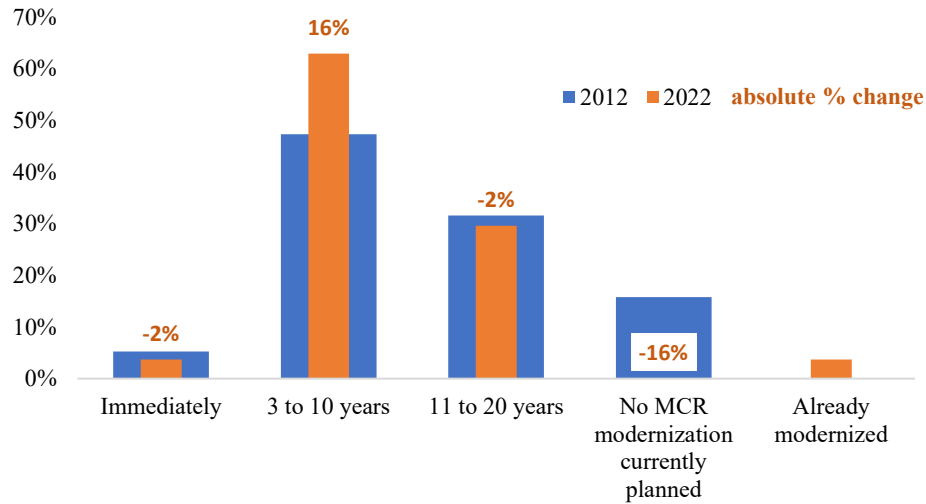


Figure 4. Timeframe for CRM.

Qualitative findings

In the 2022 survey only, we asked open-ended questions that participants answered in their own words. We analyzed the textual responses and grouped them into specific themes. Where meaningful differences between utility and non-utility respondents were found, we detailed the results accordingly.

Table 5. Advantages and drawbacks to CRM.

	Utility	Non-utility
Advantages	<ul style="list-style-type: none"> Reduced obsolescence / increased longevity Increased plant safety and reliability New operator concept of operations 	<ul style="list-style-type: none"> Reduced obsolescence / increased longevity Increased plant safety and reliability Decrease costs – (e.g., reduced staff) Attracting new talent
Drawbacks	Cost Digital obsolescence / cybersecurity Regulatory uncertainty Suboptimal or bad upgrades not delivering	

Advantages and drawbacks to CRM. Across both utility and non-utility respondents, there was a strong sentiment that the main advantages were reduced obsolescence, extended plant lifespan, and increased safety and reliability (Table 5). For the utilities, new operator

concepts of operations inherent in CRM were considered an advantage, as well as the additional information available to operators and increased redundancies. Interestingly, unlike the utility respondents, non-utility representatives considered reduced staff (i.e., cost reductions) a main advantage as well as CRM addressing concerns about keeping up with the times and the industry's ability to attract new junior talent unfamiliar with analog systems. Specifically, there was feedback from non-utilities regarding the likelihood of negative perceptions held by younger generations that nuclear power is old technology. These perceptions were not observed in utility respondents.

Utility and non-utility participants shared similar perspectives regarding the drawbacks to CRM. Cost was the strongest sentiment by far across all respondents. Embedded within cost, one utility respondent indicated perceived lack of CRM value by plant management. Digital obsolescence and cybersecurity were also universal concerns, with the perception that the fast pace of digital technology upgrades might render any I&C modernizing efforts quickly obsolete. There were concerns with the regulatory burden to modernization; for example, the Nuclear Regulatory Commission (NRC) making arbitrary demands with any new technology. Lack of end-state vision for the plants was also cited – i.e., CRM being conducted in isolation apart from a larger plant modernization strategy. Finally, it was noted that the industry does not currently have a strong track record of delivering upgrades in a timely and cost-effective manner, and a seeming lack in success paths continuity.

Survival of the industry without CRM. While there were mixed feelings about this topic among non-utility respondents (approximately half and half), almost two thirds of utility respondents indicated that CRM was *not* necessary for industry survival (Table 6). This suggests less optimism towards CRM among individuals employed at the plants. Chief reasons among

those deeming CRM essential were obsolescence concerns, and the un-maintainability of reverse engineering. However, interestingly, continued reverse engineering was also cited as a reason not to modernize – there appears to be opposing perceptions about how effective reverse engineering will continue to be. Non-utility participants expressed concerns about decreased reliability and public trust—there was a sentiment that 60-year-old plants did not inspire public confidence. As with prior items, some non-utility representatives (but not utility) mentioned the idea that legacy nuclear will have a difficult time recruiting younger generations without modernization. Interestingly, CRM as only one element in the big picture of the industry’s survival was cited as a reason both for and against its necessity.

Table 6. Industry survival without CRM.

Utility		Non-utility	
No (38%)	Obsolescence / reverse engineering concerns Piecemeal CRM and new nuclear is needed	No (53%)	Obsolescence / cost concerns Decreased reliability Public trust will decrease Full plant modernization, not just CRM Newer generation recruitment concerns
Yes (62%)	CRM is a benefit but not driver in long-term plant viability Proven track record CRM just one element in the big picture Investment in SMRs will overtake investment in aging plants	Yes (47%)	Nuclear too important to overall power system It will survive but not thrive SMRs may fill the void Reverse engineering

SMR = small modular reactors

For those who deemed CRM nonessential to the industry’s survival, utility respondents provided sentiments that CRM is only one of many issues facing plant sustainability and should be considered within a wider context, and that some facility business strategies require maintenance but not modernization plans. Across utility and non-utility respondents alike, proven reliability and success of existing analog systems were cited as reasons not to upgrade, along with views that the future of nuclear power may lie with new small modular reactors and

not with modernizing the aging fleet. Some non-utility responses indicated that nuclear power overall is too important to the nation's power needs not to survive even without CRM—it may not thrive, but it will survive.

Where the nuclear power industry is headed. The strongest sentiment across all respondents was that for most existing plants CRM would occur in a slow, piecemeal, and targeted fashion with small and limited changes, until either end of life or until all utilities were fully modernized. Another shared perspective was that modernized operations might be best reserved for new nuclear. Additional non-utility responses were that nuclear would move toward more automated control with less operators, and that political climate influenced the industry's future, especially with reduced carbon emission goals. Finally, there were calls for a nuclear power end-state vision, with some non-utility respondents concerned about a lack of long-term vision of the future.

Discussion

In recent decades, U.S. nuclear power plants have been undergoing partial CRM upgrades, with both successes and challenges. In 2012, a survey was issued to industry professionals regarding their perspectives on CRM processes and technologies. Ten years later, the survey was issued again to identify whether perspectives had changed in both the potential and realized benefits of CRM. The main findings are that while some concerns remain unchanged over the last 10 years, some priorities have shifted, and new emergent perspectives have surfaced that reflect today's marketplace and political climate.

In 2012, the main driver was to improve performance, safety, and reliability, whereas in 2022 it was to avoid obsolescence. This is perhaps unsurprising given that most vintage control rooms were built with analog systems, and over the last decade, these technologies have become

increasingly less available for replacement purposes. Cost to modernize is still the primary barrier, but in 2022 it was even more of a concern—this was reflected both in the quantitative survey data as well as the qualitative answers. However, unlike in 2012, NRC approval was deemed less worrisome overall, and not at all a concern for the utilities. The increased regulatory optimism observed in the last decade coincides with the LWRS Program’s efforts to help utilities with the regulatory compliance aspects of their digital modernization efforts. Indeed, one of the LWRS Program’s missions is to provide guidance to the nuclear industry in navigating the regulatory aspects of the modernization process.

Alternatively, it is possible that, after decades of skepticism from the early 1980s onwards, the increased regulatory optimism is a function of nuclear power’s recent renaissance. The term “nuclear renaissance” first appeared in a U.S. publication in 1990 to largely deaf ears but was then repeated in a 1999 Wall Street Journal article, during which time increasing carbon emission concerns coupled with greater regulations surrounding fossil fuel-powered electricity generation created a more hospitable climate for nuclear power to re-emerge as an efficient, safe, and clean source of energy². Nuclear power’s profile has been gaining traction ever since as a vital contributor to the world’s clean energy portfolio (albeit with a significant setback in 2011 with the Japanese tsunami at Fukushima Daiichi). Thus, aggressive local, domestic, and international net-zero targets have brought the nuclear renaissance into the spotlight in the last decade, and public policy goals no doubt have a bearing on plant license extension requests that leverage digital technologies.

The mixture of findings for plans to use component upgrades revealed that there is large variability in perspectives depending on the component and its use within the industry (likely reflective of plant-specific attitudes across the U.S.). In 2022, some respondents identified

modernization risks to be too high because of a perceived lack of proven track record in successful upgrades and nuances between safety and non-safety upgrades being important to consider. Taken together, understanding these motivations is critical for industry services providers, energy researchers, and government regulatory staff alike, because it influences the courses of action taken in supporting CRM within the existing fleet. Specifically, the LWRS research group at INL is dedicated to bridging the gap between preferred and viable utility upgrade pathways, so CRM perspectives like these are critical in achieving that goal.

Compared to 2012, there was increased skepticism about wireless controls, and while the ability to select greater automation was still greatly preferred, the belief that this concept of operations would improve a plant's performance and safety metrics declined sharply. This perspective is like the observation that, while the majority (67%) still want full HSI and I&C modernization, there are declines in belief that this will be feasible or the most cost-effective action in the long term. Instead, partial and piecemeal modernization was more favored than 10 years ago and deemed more likely to occur.

In a bid to better understand state-of-the-art perspectives, we asked the 2022 participants to tell us their thoughts using their own words. Dominant themes emerged that largely converged with the quantitative survey data (i.e., reduced obsolescence and extended lifespan were the chief advantages and cost the chief drawback). However, nuanced perspectives were revealed that were impossible to capture with the forced-choice questionnaire, and subtle differences emerged between utility and non-utility respondents; the use of both quantitative and qualitative data collection is a strength of the mixed-methodology survey design.

The most interesting finding is that while a small majority of non-utility employees (53%) consider CRM vital to the industry's survival, a larger majority of plant employees (62%)

hold the opposite viewpoint. On one hand, there is the sentiment that modernization is necessary because of the importance of nuclear power to the U.S. energy portfolio and equipment obsolescence concerns. However, many respondents thought that the existing plants, tried and tested as they are, may be better operated if left alone, and investment into digital technologies should be reserved for advanced, new generation facilities, such as small modular reactors. This uncertainty and lack of agreement across the entire sample overall, dovetails with the finding that there is a perceived lack of vision for the future of the industry. Given the multitude of economic, regulatory, and political forces at play in the industry's future, creating a shared vision that will best support immediate needs while guiding modernization transitions will not be easy. Our findings point to the need for utilities and the surrounding industry including vendors and government entities to come together to engage in research and development to that end.

Understanding how key personnel perspectives regarding CRM have changed over the years is critical information to industry stakeholders. Our findings allow for the development of roadmaps and transition methods to be optimized industrywide and importantly, given the prevalence of mixed sentiments, suggest that solutions will be custom-made. However, these results must be considered within some relevant limitations. For the most part, the samples comprised different individuals from 2012 as in 2022, and so the study design did not employ a true test-retest methodology. Further, the utility and non-utility compositions were not equal across both time points, with the 2012 sample comprising approximately half from non-utilities and the 2022 comprising approximately two thirds. Last, the samples were relatively small which may impact the generalizability of the findings.

Conclusions

Altogether the desire for CRM is still high, but it appears that feasibility and likelihood to implement have decreased in the last 10 years. There is greater uncertainty, especially about specific upgrades (e.g., computer-based procedures), and the perception that upgrades in recent years have been suboptimal and not delivered. The open-ended questions from 2022 revealed that the perceived main advantages to CRM are reduced obsolescence and increased plant lifespan. There are cost concerns. Other considerations included the necessity of CRM in nuclear power's ability to recruit younger generations. Differences in CRM perceptions between utilities and the supporting industry were revealed, suggesting that more alignment is required to ensure everyone is working towards the same end-goal. Overall, the industry was split between optimism and doubt about CRM – there was enthusiasm for full modernization, but questions persist regarding a lack of a proven track record of benefit, budget, and time taken to upgrade.

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