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Revision 0

Light Water Reactor Sustainability Program

Digital Architecture Planning Model

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SUMMARY

As part of the U.S. Department of Energy's Light Water Reactor Sustainability Program, the Digital Architecture (DA) Project focuses on providing a model that nuclear utilities can refer to when planning deployment of advanced technologies. The digital architecture planning model (DAPM) is the methodology for mapping power plant operational and support activities into a DA that unifies all data sources needed by the utilities to operate their plants.

The DA is defined as a collection of information technology capabilities needed to support and integrate a wide spectrum of real-time digital capabilities for performance improvements of nuclear power plants. DA can be thought of as integration of the separate instrumentation and control and information systems already in place in nuclear power plants, which are brought together for the purpose of creating new levels of automation in plant work activities.

A major objective in DAPM development was to survey all key areas that needed to be reviewed in order for a utility to make knowledgeable decisions regarding needs and plans to implement a DA at the plant. The development was done in two steps. First, researchers surveyed the nuclear industry in order to learn their near-term plans for adopting new advanced capabilities and implementing a network (i.e., wireless and wire) infrastructure throughout the plant, including the power block. Secondly, a literature review covering regulatory documents, industry standards, and technical research reports and articles was conducted. The objective of the review was to identify key areas to be covered by the DAPM, which included the following:

1. The need for a DA and its benefits to the plant
2. Resources required to implement the DA
3. Challenges that need to be addressed and resolved to implement the DA
4. Roles and responsibilities of the DA implementation plan.

The DAPM was developed based on results from the survey and the literature review. Model development, including the survey results and conclusions made about the key areas during the literature review, are described in this report.

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ACRONYMS

CFR	Code of Federal Regulation
CM	change management
DA	digital architecture
DAPM	digital architecture planning model
EMI	electromagnetic interference
I&C	instrumentation and control
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IT	information technology
NRC	U.S. Nuclear Regulatory Commission
RAS	reliability, availability, and serviceability
RASM	reliability, availability, serviceability, and manageability
RFI	radio frequency interference
ROI	return on investment

Digital Architecture Planning Model

1. INTRODUCTION AND BACKGROUND

A digital architecture (DA) is defined as a collection of information technology (IT) capabilities needed to support and integrate a wide spectrum of real-time digital capabilities for performance improvements of nuclear power plants. DA can be thought of as integration of the separate instrumentation and control (I&C) and information systems already in place in nuclear power plants, which are brought together for the purpose of creating new levels of automation in power plant work activities. The DA research project is a part of the Instrumentation, Information, and Control Systems Technologies Pathway of the U.S. Department of Energy's Light Water Reactor Sustainability Program.

The goal is to develop a methodology for mapping power plant operational and support activities into the DA. As a first step for developing the methodology, researchers identified an initial set of requirements for DA. Thomas and Oxstrand (2015) compiled a report that provides the DA requirements to enable an objective basis for planning the necessary IT infrastructure for a future digital nuclear plant. It was concluded that the largest burden on the DA will come from use of automated work packages and computer-based procedures because the majority of all activities that interact with the plant is controlled by written instructions. In addition, information contained in these applications is needed by a number of related plant activities.

This requirements effort highlighted the difficulty of determining the maximum impact of the DA requirements on the IT infrastructure. However, the effort did provide an understanding about the degree to which the different technologies impose a burden on the IT infrastructure; this is valuable as the methodology development progresses.

The second step of methodology development was to determine the extent to which the power plants' existing I&C and IT structure can support the future digital technology environment. Researchers conducted a gap analysis to determine the current state of DAs at typical power plants and to identify gaps between the current state and the vision of full deployment of technology over time. The gap analysis was conducted by two parallel activities: site visits and a web-based survey. The methodology, results, and conclusions from the gap analysis are described in a report by Oxstrand et al. (2015a).

The gaps identified are as follows:

1. Plans for plant-wide deployment of a wireless network
2. Understanding the limitations and possibilities of the wireless network
3. Use of existing technologies for real-time collaboration
4. Plans for integrating advanced technologies in the outage control center
5. Plans for modernizing the main control room
6. Use of online monitoring technologies.

A major step in the methodology development is to survey all key areas that need to be reviewed in order for a utility to make knowledgeable decisions regarding needs and create a plan to implement DA at the plant. The survey of the key areas can be described as a digital architecture planning model (DAPM), which is the main focus of this report. DAPM development, including a survey and literature review, is described in Section 2. Section 3 contains the DAPM, sorted by key areas.

This report addresses Milestone: M3LW-16IN0603124 – Complete a report documenting a digital architecture planning model.

2. DIGITAL ARCHITECTURE PLANNING MODEL DEVELOPMENT

As mentioned above, researchers have studied the initial requirements for DA and identified gaps between the state of DAs currently used at power plants and the end-vision of full technology deployment over time. The next step in the research effort is to develop a planning model for DA; DAPM was developed in two steps. First, researchers surveyed the nuclear industry to gain a better understanding about their near-term plans for wireless networks and adopting new advanced capabilities. DAPM was then developed based on results from the survey and a literature review, which identified key areas of interest.

2.1 Survey

The main objectives of the survey were to (1) gain a deeper understanding of the utilities plans for wireless networks in the power block and (2) gather input on the utilities' plans to adopt new capabilities in the plants (e.g., control room modernizations and online monitoring capabilities).

2.1.1 Survey Development

A web-based format was used for the survey to make it as streamlined and easy as possible to both reach out to participants and for participants complete the survey at a time that worked well for them. The web-link to the survey was active for 30 days.

The survey contained 17 questions that were a mix of multiple choice and open-ended questions (examples of the questions are listed as follows and Appendix A contains all questions used in the survey).

- What are the plans for a wireless network in the power block at your plant?
- To what extent does the wireless network cover the power block?
- What are the main intended purposes for the wireless network in the power block?
- What are some obstacles that you see could prevent wireless networks in the power block?
- Is your utility pursuing any of the following capabilities or upgrades (e.g., main control room upgrades or modernization, outage control room upgrades or modernization, online monitoring capabilities, and/or electronic work management)?

2.1.2 Participants

As illustrated in Figure 1, a total of 13 individuals participated in the survey, with 12 of them being nuclear utility employees and one representing a vendor. A total of 11 utilities (i.e., 10 United States and one international) were represented. Even though only 40% of all utilities in the United States were represented in the survey, these 10 utilities represent both 60% of the total number of plants and 60% of the total number of reactor units in the United States. The utilities who responded were Arizona Public Service, Duke Energy, Entergy Operations, Exelon, NextEra Energy, Pacific Gas and Electric, PSEG Nuclear, Southern Nuclear, Talen Energy, and Xcel Energy.

All 12 participants that were employed by nuclear utilities represent separate power plants. The participants' roles at their utilities ranged from senior manager, IT manager, simulator specialist, to supervisor.

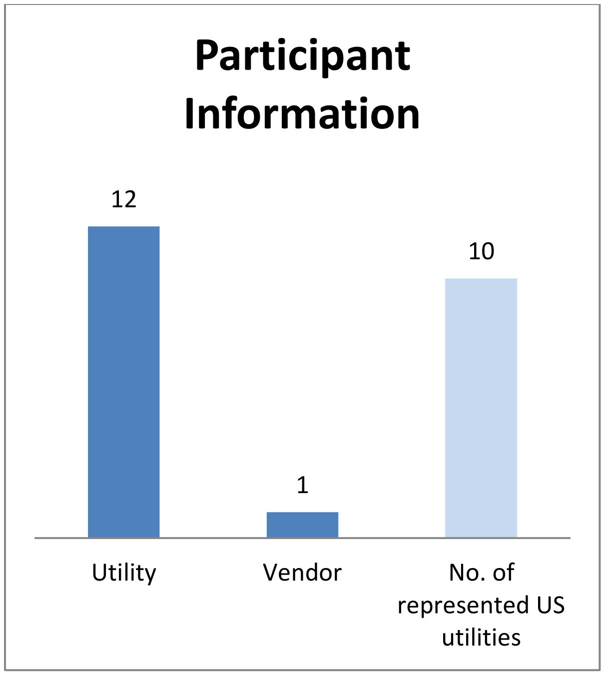


Figure 1. Participants in the web survey.

2.1.3 Data Analysis

Data collected from the survey were analyzed by the researchers. Two of the participants represent the same utility, but are from two separate nuclear power plants. Therefore, input from both participants was kept rather than aggregate them into one.

Because one of the participants represented a vendor rather than a utility, a separate analysis was conducted to investigate the impact on the result when the vendor's answers were excluded from the data analysis. Results from this additional analysis (i.e., vendor excluded) are presented in this report.

Answers to open-ended questions were both analyzed individually and in an aggregated fashion. Only the aggregated answers will be reflected in this report.

2.1.4 Results

This section provides the results that were deemed most relevant to development of DAPM. The results are discussed in more detail in Section 3. The discussion will cover how the survey results relate to the challenges that a plant could face during a DA implementation. The complete set of results from all participants can be found in Appendix B. Appendix C contains the results that changed when only the 12 utility representatives were analyzed.

Participants from 7 of the 12 power plants represented in the survey indicated that a wireless network has been or will be installed in the power block. Hence, five of the participating nuclear power plants have no plans to install any wireless networks in their power blocks. As shown in Figure 2, all seven plants already have a power block business wireless network installed. Three of them also have a secure network installed in the power block. The remaining four plants plan to install the secure network in 2 to 5+ years.

Table 1 provides the distribution of the participants' answers when asked about the coverage of the two types of wireless. In two plants, the business network covers 90 to 100% of the power block; while at other plants, both the secure and the business networks only cover 0 to 25% of the power block. The majority (i.e., 4 out of 7) stated that the wireless network was or will be installed all at once rather than installed incrementally.

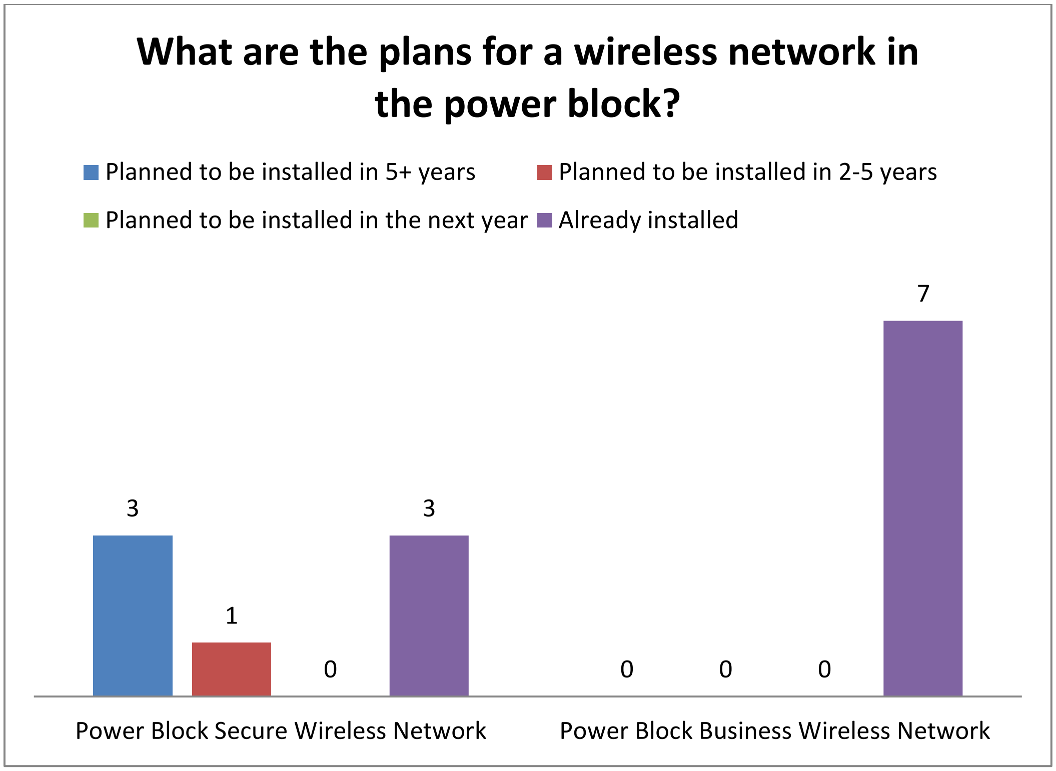


Figure 2. Plans for a wireless network in the power block.

Table 1. Percent coverage of wireless networks in the power block.

	0 to 25%	25 to 50%	50 to 75%	75 to 90%	90 to 100%
Secure Wireless Network	2	1	0	0	0
Business Wireless Network	3	2	0	0	2

The most common intended purpose of the wireless networks in the power block is to support execution of electronic work orders and instructions. The categories “Work status information for scheduling and task planning,” “Video monitoring of (critical) tasks,” “Enabling communication between craft, supervisors, and others,” and “Online monitoring,” were all rated as equally important purposes for the wireless network.

Three of the participating plants set up temporary wireless networks in the power block during outage (Figure 3). These networks are primarily used for communication and video monitoring.

Aside from the power block, the participants were asked about the availability of a wireless network in other locations in the plant. As shown in Figure 4, seven plants have wireless network in their outage control center and in their office and meeting rooms. Three plants have wireless network implemented in their main control room and two other plants have plans to install it in their main control rooms.

Out of the participating plants, five have already implemented mobile work management systems, three have implemented upgrades or modernizations to their outage control rooms, and three have implemented upgrades or modernizations to their main control rooms. In addition, as seen in Figure 5, five plants have no plans to upgrade their outage control centers and four have no plans to upgrade their main control rooms.

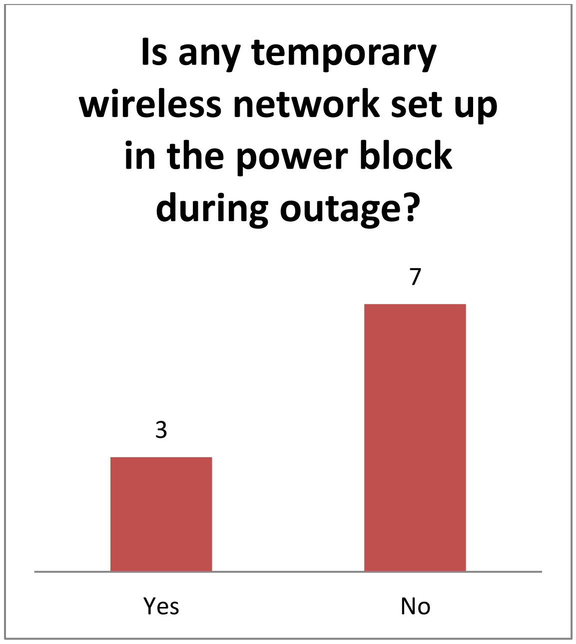


Figure 3. Use of temporary wireless during outage.

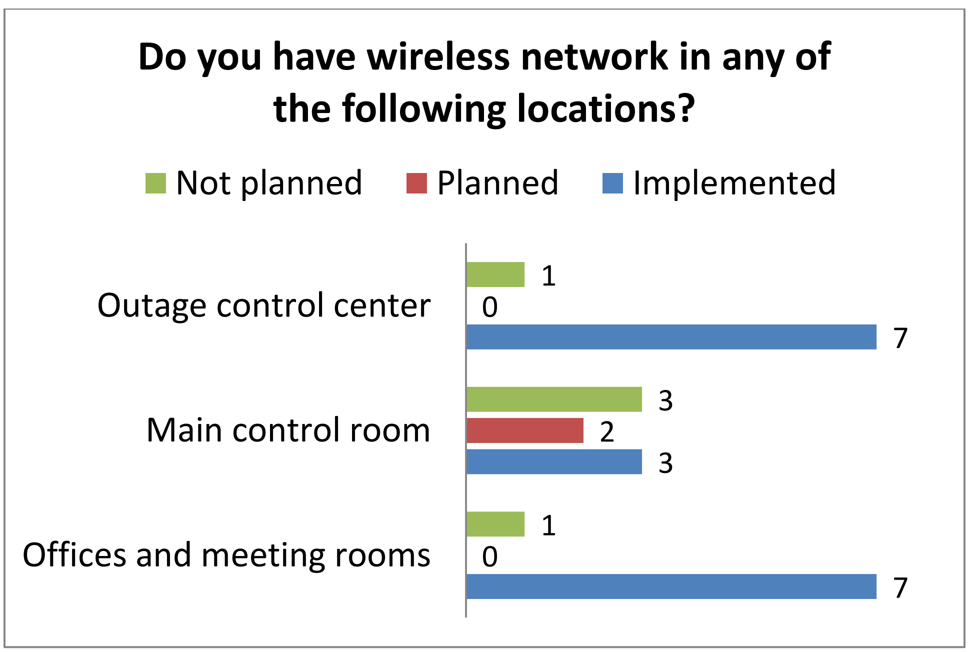


Figure 4. Wireless in other locations outside the power block.

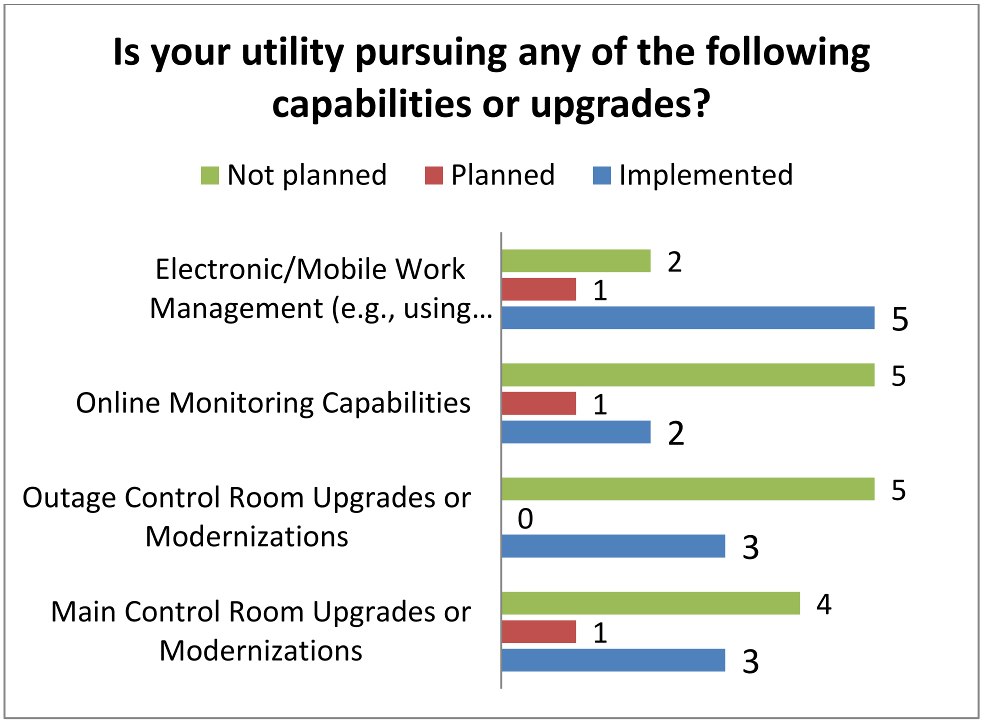


Figure 5. Pursuing any new capabilities or upgrades.

Figure 6 illustrates the perceived obstacles that could prevent wireless networks in the power block. Cybersecurity was called out as the main obstacle, followed by radio frequency interference and economic feasibility. This result provided the DAPM with the industry perceived priorities of potential challenges described in Section 3.

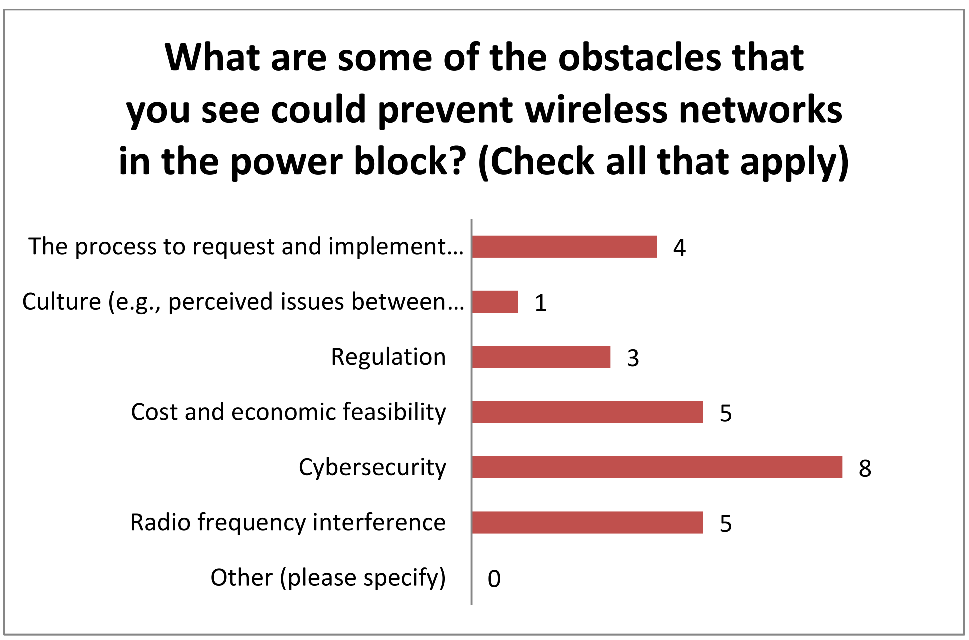


Figure 6. Perceived obstacles to prevent wireless networks in the power block.

As seen in Figure 7, over 90% of the utility representatives have experienced use of mobile technology (either at work or outside work). This result indicated that technology gap is not projected as a significant DAPM challenge.

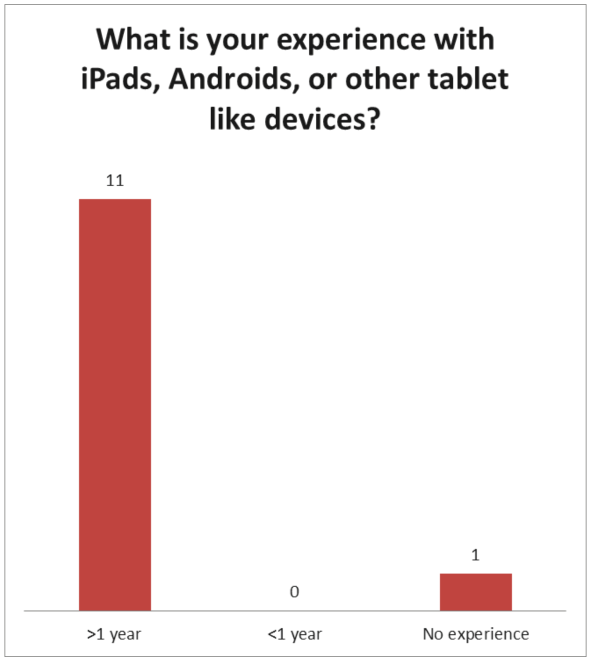


Figure 7. Participants' experience with mobile devices.

2.2 Literature Review

A literature review was conducted to identify key areas to include in the DAPM. A variety of literature was reviewed in a broad spectrum of areas. The literature review covered areas from human factors and wireless protocols, to cyber security.

Nineteen documents from the U.S. Nuclear Regulatory Commission (NRC) were reviewed: six were technical reports (NUREGs), eleven were regulatory guidance documents (Reg Guides), and two are Code of Federal Regulations (CFRs). Table 2 lists all NRC documents reviewed. Other standards and guidelines (such as from the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers [IEEE]) were reviewed as well. These documents are listed in Table 3.

In addition, a vast number of research articles and reports covering all key areas were reviewed including eight technical reports published by Idaho National Laboratory. All literature that was reviewed is found in the reference section of this document.

Table 2. NRC documents reviewed.

Document	Title	Year
NUREG-0700	Human-System Interface Design Review Guidelines	2002
NUREG-0711	Human Factors Engineering Program Review Model	2002
NUREG-0800	Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Instrumentation and Controls	2010
NUREG/CR-6431	Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants	2000

Table 2. (continued).

Document	Title	Year
NUREG/CR-6939	Coexistence Assessment of Industrial Wireless Protocols in the Nuclear Facility Environment	2007
NUREG/CR-6991	Design Practices for Communications and Workstations in Highly Integrated Control Rooms Office	2009
Reg Guide 1.180	Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems	2003
Reg Guide 1.152	Criteria For Use of Computers in Safety Systems of Nuclear Power Plants	2011
Reg Guide 1.153	Criteria for Safety Systems	1996
Reg Guide 1.168	Verification, Validation, Revisions, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	2004
Reg Guide 1.169	Configuration Management Plans for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	1997
Reg Guide 1.170	Software Test Documentation for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	1997
Reg Guide 1.171	Software Unit Testing for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	1997
Reg Guide 1.172	Software Requirements Specifications for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	1997
Reg Guide 1.173	Developing Software Life-Cycle Processes for Digital Computer Software Used in Safety Systems of Nuclear Power Plants	1997
Reg Guide 1.209	Guidelines for Environmental Qualification of Safety-Related Computer-Based Instrumentation and Control Systems in Nuclear Power Plants	2007
Reg Guide 5.71	Cyber Security Programs for Nuclear Facilities	2010
10 CFR 50.59	Changes, tests, and experiments	2007
10 CFR 73.54	Protection of digital computer and communication systems and networks	2015

Table 3. Standards and other guidelines reviewed.

Document	Title	Year
IEC 62003	Nuclear power plants – Instrumentation and control important to safety – Requirements for electromagnetic compatibility testing	2009
IEEE Standard 1012-2004	IEEE Standard for Software Verification and Validation	2004
EPRI 3002000528	Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment: Revision 4 to TR-102323	2013
EPRI 1019186	Implementation Guideline for Wireless Networks and Wireless Equipment Condition Monitoring.	2009

Based on the literature reviewed, the researchers identified several elements from key areas to be included in the DAPM. The following section will categorize these elements in four main categories then discuss them in detail.

3. DIGITAL ARCHITECTURE PLANNING MODEL

The result from the survey (for an example, see Table 1) shows a tendency for large scale and rapid implementation of DA, which signifies the necessity for a DAPM. The DAPM was developed based on results from the survey and the literature review, as well as on insights gained from the previous activities in this research effort. The goal of DAPM is to guide the decision-making process that is related to the need and implementation approach. Therefore, DAPM will address the following areas:

- Need of DA and its benefit to the nuclear power plant
- Required resources to implement and maintain DA
- Challenges in implementing and utilizing DA
- Roles and responsibilities of DA implementation plan.

The following subsections will explain each of these areas in more details.

3.1 Needs and Benefits of a Digital Architecture

The three main areas by which a DA can enhance operation of a nuclear power plant are economics, safety, and security. These areas will mainly affect DAPM in terms of level of investment in DA, the DA implementation and utilization time plans, and the project management structure of the DA.

The level of investment reflects the size and capabilities of the DA, which is proportional to the impact of DA applications. The implementation and utilization time are inversely proportional to the expected benefits (i.e., the time is shorter as the expected benefits increase). This is especially valid if the DA plan prioritizes applications with high impact. As the overall impact of the DA increases, the level and extent of the dedicated resources increase as well.

The survey results indicate that a significant number of participants has been proactive in implementing one of the elements of DA (wireless) into key areas of the plant, yet have no plans to fully utilize its benefit. This emphasizes the need for a detailed study of needs and benefits. This study should also investigate the impact of economics, safety, and security.

In addition, the DA plan should consider gaps in the operation and management process that DA could close. One of these gaps is due to current plants using multiple systems that operate as isolated islands. A comprehensive and capable middleware could link these islands by integrating the separate data sources and result in several areas of process improvement. Once the plants have implemented a DA, the middleware would use the DA to enable sharing of the information among the DA applications as needed.

3.1.1 Economics

The area of economics is probably the first area to explore in the benefit analysis of DA; it is often the main drive of introducing or upgrading DA. An economics study should explore the extent and means by which introducing or upgrading DA will economically benefit the plant. This will control the direction and applications that the DA will target. The survey conducted as part of this effort found that 41.7% of survey participants indicated cost is one of the main obstacles in implementing wireless communication in nuclear power plants. This emphasizes the significance of performing an economic feasibility study. Unfortunately, this is not a simple task, because there are multiple factors to consider when determining the economic feasibility of DA. The cost-associated factors (such as equipment and resources, including manpower and software packages) can be easily identifiable. Because more than 50% of the plants participating in the survey indicated that a wireless network had been implemented in the power block of the plant, these plants likely have dedicated IT departments or personnel that are capable of performing a good estimation of these costs.

The return on investment (ROI) part of feasibility is not as simple. The ROI of DA can be broken into each of the applications that will benefit from DA. The survey concluded that there is almost an equal interest in online monitoring, electronic work orders, enabling communication between staff, video monitoring, work status information for scheduling and task planning, component position indication and intranet connectivity (Figure 5). The economic benefit of DA on each of these applications is dependent on its level of implementation and utilization and should include direct and indirect benefits. An earlier effort at Idaho National Laboratory developed a business case for one of these applications (i.e., mobile work packages, which can be found in Thomas et al. [2015]).

3.1.2 Safety

In addition to the economic advantage of the DA applications, several of the applications have a significant safety enhancement impact. This impact is due to the fact that several of these efforts address issues of human factors concern and reduce the chances of human error. For example, online monitoring of equipment reduces human error associated with determining the current power plant configuration; also, electronic work packages and computer-based procedures improves human performance associated with the work processes according to Oxstrand et al. (2015b) and Oxstrand et al. (2015c). The use of technolgies such as barcodes to verify a correct component reduces the risk of taking action on an incorrect component. A detailed description of the impacts and benfits to both human and system performance when transitioning to a computerized procedure system can be found in Oxstrand and Le Blanc (2016).

Despite the fact that safety is not usually as appealing as the economic advantage, a safer plant would result in higher power capacity, efficiency, and availability. The DA plan should consider this area of benefit in evaluating the need for DA.

3.1.3 Security

Though not trivial, the listed DA applications could expand the scope to include security areas of utilization. For example, security staff can use electronic work packages (similar to other plant workers) to perform their security-related procedures. Wireless position tracking of equipment can also be used to validate the identities of workers in the plan. The DA plan should develop a detailed list of potential security benefits of DA and should consider these benefits in evaluating the need for DA.

3.2 Required Resources to Implement Digital Architecture

This section targets the non-challenging resources required to implement DA, which include manpower, finance, and time. The importance and means for providing each of these resources in nuclear power plants will vary from one utility or plant to another. A brief description of such means is presented the following subsections.

3.2.1 Manpower

The availability of dedicated manpower is a key factor not only for DA implementation, but also for its maintenance. The two main aspects to consider with respect to needed manpower are:

1. The increase of the permanent manpower to support the DA
2. The reduction of the permanent manpower of non-DA fields due to the efficiency improvement introduced by the DA applications

A large-scale implementation of DA would require a relatively large investment in the DA manpower. However, this will result in a large impact on other plant processes and reduce their needed manpower. A size and capacity threshold after which DA would reduce the overall needed manpower in a plant does exist. In addition, an optimal DA size and capacity that corresponds to minimal overall manpower of the plant exists. The DA plan should find the threshold and optimal points.

Implementation of DA in a nuclear plant can be manpower demanding at the initial stage of implementation and utilization. To overcome this transient manpower demand, the DA plan should consider the possibility of temporarily subcontracting the needed manpower at these stages. Once DA is implemented, a gradual reduction of the subcontracted manpower would ensure a steady shift of responsibilities between the temporary subcontracted manpower and the permanent dedicated DA manpower.

3.2.2 Finance

The cost for DA implementation, utilization, and maintenance from the economic study should be used in the DA plan to project the project cost over time, which should then be used in the capital budgeting process. The budgeting process should take into account the variety of return terms of the DA applications, i.e., applications with a short-term benefit will provide an indirect flow of income, resulting from savings; while applications with a long-term benefit might require long term funding.

3.2.3 Time

A long-range time plan for implementation, utilization as well as maintenance and upgrades (i.e., refreshing the technology as it becomes obsolete) should be developed. The time plan should incorporate the common implementation stages such as design, procurement, installation, commissioning, testing, training, and migration, and should allow sufficient lead time for each stage of the project.

Nuclear power plants have strict operational and maintenance schedules. These schedules are likely to have higher priority over planned upgrades, including the DA time plan. This behavior could cause an unrealistically long implementation and utilization time of DA. In addition, this time will be vulnerable to alteration through its progress to further delay DA implementation or utilization. The developed DA plan should ensure this does not happen. Milestones should be realistically defined and a strict progress tracking process should be implemented.

3.3 Challenges

Because different forms of DA have been widely implemented in many industries, including critical industries, DA in a nuclear power plant shares some general challenges with these industries (e.g., cybersecurity) in addition to the nuclear industry-specific challenges. The following subsections will describe both general and industry-specific challenges that need to be evaluated as part of the DA plan.

3.3.1 Bandwidth

The bandwidth requirements vary greatly according to DA application. The amount of traffic that will be transferred through DA directly impacts the DA design and complexity. As indicated by the survey, the common intended purposes of the wireless networks in the power block are all applications that might require a large amount of bandwidth. Example of applications in the power block are electronic work orders and instructions, work status information for scheduling and task planning, and video monitoring of (critical) tasks. Currently, some plants are using temporary wireless networks in the power blocks during outages (see Figure 3). These temporary networks provide additional capability and bandwidth for communication and video monitoring. This also indicated that using temporary wireless networks can be utilized as an alternative solution to some of the DAPM challenges during normal operations.

The extent of the equipment and processes performed at various locations of the plant results in extreme bandwidth demand peaks in certain areas. These areas represent bandwidth bottlenecks in the DA architecture and need to be carefully evaluated. An example bandwidth evaluation can be found in Thomas and Oxstrand (2015).

The required bandwidth for implementing the DA applications should be quantified and planned to meet both capacity and performance. Capabilities such as load balancing and distribution should be enabled. Redundant paths of traffic should be facilitated to reduce the risk of a single point of failure. This is important as DA applications become an integral part of operations. A sufficient bandwidth margin should be ensured to sustain performance during transient fluctuations. The DA plan should include a strategy for the network to evolve as DA applications are implemented and as the applications grow in use. This implies that DA should enable expandability in terms of coverage and capacity.

During DA implementation and utilization, a process for resolving issues and implementing changes should be put in place. In addition, a systematic management and evaluation process of the ever-changing demands must be implemented. Capacity-related information should be collected to evaluate DA performance. Trending information should be used to evaluate the available bandwidth capacity utilization with respect to each of the DA applications. This information can be used in future projects to increase utilization of specific applications.

3.3.2 Change Management

Because 70% of change programs do not achieve their planned outcomes, indicated in Barnard and Stoll (2010) from Balogun and Hailey (2004), successful implementation of DA requires development of a change management plan as part of the DA plan, which is often associated with organization development and an organization change plan. This change management plan should apply to all aspects of the DAPM.

Change management is a field of science that is widely addressed in literature and textbooks. A brief survey of strategies for change management can be found in Barnard and Stoll (2010). The survey compares steps from different models for change (e.g., creating a vision, communicating it, establishing a sense of urgency, and enforcing the change). A nuclear industry-specific change management study can be found in Reiman et al. (2006). Management of change resistance to technology advancement is a key part of the change management plan. This is a recognized challenge that is related to psychological behavior and is historically present in various technological advancements (Bauer 2010). Several studies have been performed to handle this obstacle, with examples found in Barnard and Stoll (2010).Trainings, extensive communication, active involvement of resistant parties, and incentives are examples of potential methods to overcome this resistance. The fact that DA facilitates technologies that are widely available in other industries should be leveraged while developing plans to tackle change resistance. The experiences of these industries in implementing their version of DA should also be used in plan development.

3.3.3 Cybersecurity

Cybersecurity was found in the survey to be the most common perceived obstacle of implementing a wireless communication network in a nuclear power plant (i.e., indicated by 67% of the survey participants; see Figure 6). Because wireless is one part of the wired and wireless communication of DA, a cybersecurity strategy that targets DA as a whole will need to be developed as part of the DA plan. An earlier cybersecurity evaluation can be found in Thomas et al. (2014). Cybersecurity threats have been tackled in other critical industries such as financial institutes or defense systems, which utilize extremely secure means for communication. Therefore, it is logical that this challenge can be tackled in a nuclear power plant if properly addressed.

Security is defined in the IEEE standard for system and software verification and validation (Institute of Electrical and Electronics Engineers 2004) as: “The protection of computer hardware or software from accidental or malicious access, use, modification, destruction, or disclosure. Security also pertains to personnel, data, communications, and the physical protection of computer installations.” In the context of the nuclear power industry, cybersecurity can be defined as protection of information, instruments and control signals, data, software and hardware components, and mediums of communication or power from intentional malicious acts for the purpose of stealing, destroying, or altering information of a plant, preventing the normal functionality of the plant equipment or processes, or change directly or indirectly the plant condition. The nature of DA applications will determine the type of threats that apply from this definition.

The possibility of a cyberattack on process controls has been increasing in recent years; databases to track such attacks were established (e.g. in Byres and Lowe 2004). In fact, several cyberattacks did occur in the past, proving that the common perception of these systems being immune is false (Kim 2014, Pietre-Cambacédes et al. 2011). Nuclear power plants (similar to any other process-based industry) are vulnerable to cybersecurity attacks, especially when they increase their reliance on common DAs and communication techniques. Acknowledging this type of threat resulted in earlier efforts to perform cybersecurity assessments of a power plant (Fovino et al. 2011), and produce cybersecurity implementation method on a nuclear facility (Park et al. 2016).While the consequences of a cybersecurity attack are not very critical if the DA is designed to support the non-safety functions of the plant, the increasing level of attacks increases the associated risk, because the total risk increases as the probability of an attack increases (i.e., risk=consequence x probability of occurrence).

Item (a)(1) of the NRC regulation 10 CFR 73.54 (U.S. Nuclear Regulatory Commission 2015) specifies the functions that would need to be protected against cyber-attacks as follows:

- Safety-related and important-to-safety functions
- Security functions
- Emergency preparedness functions, including offsite communications
- Support systems and equipment which, if compromised, would adversely impact safety, security, or emergency preparedness functions.

If DA is expected to impact any of the above functions, then a cybersecurity plan and program are required. To accommodate this requirement, NRC issued Regulatory Guide 1.152, "Criteria for Use of Computers in Safety Systems of Nuclear Power Plants" (U.S. Nuclear Regulatory Commission 2011). This document lays down the overall guidelines that apply a defense-in-depth strategy for safety-related systems and are required if the DA is expected to affect the specified categories of 10 CFR 73.54(a)(1). Even if the DA does not fall in any of the specified categories, the guidelines can be very useful for development of a DA cybersecurity plan and program to protect non-safety functionalities (e.g., day-to-day, proprietary, or business information). If a cybersecurity program is required, Regulatory Guide 5.71 (U.S. Nuclear Regulatory Commission 2010a) defines the cybersecurity defense development process through the following main steps:

- Develop a cybersecurity plan in compliance with 10 CFR 73.54
- Establish and implement a cybersecurity program
- Maintain the cyber security program
- Retain and handle records.

These steps are described in detail in Regulatory Guide 5.71, along with their specific requirements. The guide contains a generic cyber security plan template and defines a useful list of technical and policy measures for developing a cybersecurity program.

The Nuclear Energy Institute developed a widely used document (Nuclear Energy Institute 2010) to support cyber security plan licensing. The document provides a comprehensive checklist of evaluations and requirements that need to be performed to ensure the security plan is in compliance with NRC regulations.

Once a plan is put in place, 10 CFR 50.59 (U.S. Nuclear Regulatory Commission, 2007a) regulates how to determine if an approval is required from NRC for any change, test, or experiment. If new software is introduced into the plant, it is often required to ensure a proper security analysis is performed at every stage of the software development and implementation lifecycle (i.e. concepts development, requirements definition, design, implementation, testing, installation, operation, maintenance, and decommissioning) (Institute of Electrical and Electronics Engineers 2004, U.S. Nuclear Regulatory Commission 2011).

3.3.4 Human Factors and Performance

Moving toward use of more advanced technology in the nuclear power plants will have a significant impact on the employees working in the plant. Upgrades to the main control room, outage control center, and computerized support for the work execution and preventive maintenance processes have potential to improve human performance and overall system performance. To ensure the most benefits from these advances, DA that is able to support the new demands needs to be in place. An insufficient DA or an improperly designed DA might have an undesired impact on performance. For example, to best support the future worker in the field, DA should enable easy and seamless access to work orders, additional information, just-in-time training, component position information, current operating mode, and information about plant status. A DA that does not adequately support this will force the worker to use multiple databases and systems to gather the information. This introduces potential human error traps and adds inefficiencies in the overall system.

One commonly raised concern associated with introducing advanced technology in nuclear power plants is the willingness to accept and adapt to using new technology and work processes. Oxstrand and Le Blanc (2014) concluded that even though nuclear power plant field workers might resist change initially, every worker who participated throughout the years of the authors' computer-based procedure research have quickly learned the new system and process and have been able to recognize how the technology will improve their everyday work. This is partly due to the fact that most people in the nuclear industry are used to adapting to new technology (such as a different operating system and mobile devices outside their work environment). This was also be supported by the survey conducted for DAPM development (Figure 7). Survey results indicated that the vast majority of the surveyed entries are familiar or had some exposure with mobile devices (such as tablets). As a result, the technology gap is not projected as a significant challenge to implementing DA. To ensure this challenge is not of concern, sufficient training and professional development strategies need to be put into place to ensure the technology gap is well overcome ahead of actual implementation.

With any innovation to an organization, there is a change management (CM) component, where CM takes innovations to a subset of the workforce. Updating infrastructure in a facility to include new technology is an expensive endeavor. Therefore, ROI is always a metric that is captured during any technology change. According to Prosci's case for change management (Prosci 2006), ROI can be achieved by focusing on three main factors: speed of adoption, ultimate utilization (i.e., participation), and proficiency. These three factors can be described as follows:

Speed of Adoption:	Having a good CM process can enhance how quickly people accept the change. Instituting a very strong implementation plan and over communicating the change enhances this phase. During any change there will always be resistance (i.e., active or passive). To mitigate resistance, coaching and training can assist in quelling concerns that workers may have. Change is personal and different for every person.
Ultimate Utilization:	To achieve full participation from all workers involved, CM can reinforce the Prosci model. This model promotes awareness, desire, knowledge, ability, and reinforcement of any change. If there is a breakdown in any of these areas, the worker may decide not to adopt the new technology.
Proficiency:	This area will show how well people have adopted a change. If the new job duties and processes are embraced, productivity will go up. When workers decide not to get on board, they will not dedicate any time to learning a new task or software system.

3.3.5 Physical Limitation

Physical limitations might prevent the ability to provide permanent power, wiring, and signals to DA devices in certain locations of the plant. This should be taken into consideration as part of the DA plan. One method that can be used to mitigate this is by using mobile DA infrastructure and devices when necessary. Wi-Fi hotspots or kiosk machines could be established just outside physically limited spaces or exclusion zones in order to allow workers to access the DA system in order to receive and transmit data. This still provides the benefits to the workers, even though it is not in real-time. This method has already been used by a small portion of the industry. The survey conducted for this project revealed that 27.3% of the surveyed entities use a temporary wireless network set up in the power block during outages (Figure 3). Additional research and development are needed to provide additional means for plants to access DA under these conditions.

3.3.6 Power Supply Availability

Powering the various devices that will establish the DA infrastructure and the devices that will utilize the DA should be considered as part of the DA plan. This is mainly a challenge in areas that do not have the necessary power supply infrastructure. For example, a systematic approach in addressing the power supply challenge of the DA components in areas that lack the necessary power infrastructure would categorize the DA components into power demand and availability requirement as shown in Table 4. The feasibility of powering these components depends on the power supply requirements of the DA components, because this varies by device nature and role. For example, high-range and high-bandwidth wireless routers would be considered as high-power and high-availability-type devices, while instruments that are rarely needed would be considered low-availability devices, with a power requirement that depends on the instruments type. Some existing technologies with high availability and high power requirements (such as tablets) have already reached a power storage maturity level that would enable their immediate use in the DA.

Table 4. Categorization of powering DA components in areas that lack the necessary power infrastructure based on power demand and availability.

	Power Requirement		
Required Availability	**Low**	**Medium**	**High**
Low	Extremely Low	Significantly low	Low
Medium	Significantly low	Moderate	Significantly High
High	Low	Significantly High	High

The power categorization of DA component according to Table 4 would highlight the devices that require further exploration. The DA plan should develop means for introducing power into each category. This does not necessarily imply expansion of the current power supply infrastructure, because this would probably be the most expensive approach to address the power supply challenge. Instead, it might be more feasible to use several efforts that aim at powering wireless instruments in non-instrumented areas of the plant using power harvesting techniques (such as thermal, solar, vibrational, or wind harvesting technologies) (see Priya and Inman [2009] for a detailed description of some of the potential techniques) . Research and development of power-harvesting techniques for wireless instruments has been ongoing and has been proven as a potential solution (Sodano et al. 2004, Agarwal et al. 2015, Zhang et al. 2015). Other more advanced techniques (such as wireless powering; Valenta and Durgin 2014) are developing too, and could serve as potential future means for powering devices remotely. A trivial, possible, near-term solution to address the challenge of powering moderately or low-demanding DA components in areas that lack the necessary power infrastructure could implement battery-based and power-efficient devices. This would suggest on-demand-only utilization of the devices for the DA infrastructure to conserve power.

In areas where DA components do have the necessary power supply infrastructure, the DA plan should evaluate the power requirement and ensure the needed power capacity is sufficient to implement the planned DA and add a margin for future expansion. A plan for evaluating and increasing the power capacities during and after DA implementation should be developed. Criteria, such as power generation capabilities, cabling, wiring, breakers limits, and uninterruptable power supplies (to complement the power supply demand in cases of power supply discontinuity), should be included.

3.3.7 Regulation

This challenge would generally be limited to safety-related I&C systems and equipment. DA equipment being installed in the power block would generally have to undergo an 10 CFR 50.59 screening (and possibly an evaluation) to ensure that the equipment is not subject to prior NRC review before implementation and thereby require a license amendment under 10 CFR 50.90.

Regulations should not be over-interpreted as an obstacle. Twenty-five percent of the surveyed entities indicated that regulations are one of the obstacles associated with implementing wireless communication. DA is not new to control rooms, because there have been variations of digital assets in place since the 1980s or later. To comply with the NRC requirements, it is necessary to engage NRC at an early stage of the planning and to ensure the DA plan accounts for all relevant regulations and documents in various areas, including, but not limited to, the following:

- NRC Regulatory Guide 1.152 (U.S. Nuclear Regulatory Commission 2011)
- NRC Regulatory Guide 5.71 (U.S. Nuclear Regulatory Commission 2010a)
- NRC Regulatory Guide 1.180 (U.S. Nuclear Regulatory Commission 2003)
- NRC Regulatory Guide 1.153 (U.S. Nuclear Regulatory Commission 1996)
- NRC Regulatory Guide 1.168 (U.S. Nuclear Regulatory Commission 2004)
- NRC Regulatory Guide 1.169 (U.S. Nuclear Regulatory Commission 1997a)
- NRC Regulatory Guide 1.170 (U.S. Nuclear Regulatory Commission 1997b)
- NRC Regulatory Guide 1.171 (U.S. Nuclear Regulatory Commission 1997c)
- NRC Regulatory Guide 1.172 (U.S. Nuclear Regulatory Commission 1997d)
- NRC Regulatory Guide 1.173 (U.S. Nuclear Regulatory Commission 1997e)
- NRC Regulatory Guide 1.209 (U.S. Nuclear Regulatory Commission 2007c)
- NRC NUREG-0800 Instrumentation and Control (U.S. Nuclear Regulatory Commission 2010b)
- NRC NUREG-0700 (U.S. Nuclear Regulatory Commission 2002)
- NRC NUREG- 0711 (U.S. Nuclear Regulatory Commission 2012)
- NRC NUREG/CR-6991 (U.S. Nuclear Regulatory Commission 2009)
- NRC NUREG/CR-6939 (U.S. Nuclear Regulatory Commission 2007b)
- NRC NUREG/CR-6431 (U.S. Nuclear Regulatory Commission 2000).

3.3.8 Radiofrequency Interference and Electromagnetic Interference

The survey results show that 41.7% of the surveyed entities indicated that radiofrequency interference is one of the obstacles preventing implementation of wireless communication in the power block of the plant (see Figure 6). The effect of the radiofrequency interference/electromagnetic interference (RFI/EMI) should be considered, with special attention given to the safety-related processes, in the following two perspectives: (1) the possible effect of DA equipment on existing equipment in the plant and (2) the possible effect of plant equipment on DA equipment. An example of an evaluation of the later perspective can be found in Min et al. (2015). An RFI/EMI site survey might need to be conducted and evaluated as shown in (Hashemian et al. 2011).

To avoid interference with the existing plant's equipment, characterization of the environment and thorough testing should be used as a foundation. If plant equipment are found to operate in the same frequency band as the DA, techniques such as spread spectrum modulation should be considered to reduce the radio footprint of the DA. Techniques such as the use of line-of-sight technologies or lower frequency non-line-of-sight technologies should be explored.

The DA plan should evaluate and apply the NRC guidelines for an RFI/EMI evaluation (U.S. Nuclear Regulatory Commission 2003). Additional guidelines for EMI should also be considered (e.g., Electric Power Research Institute [2013], International Electrotechnical Commission [2009], and U.S. Nuclear Regulatory Commission [2000]).

3.3.9 Reliability, Availability, Serviceability, and Manageability

As DA is implemented and tools are added to a plant and worker's tool belt, a transition will occur from how work is performed and recorded in the plant. This transition to the use of better tools has been proven to increase worker efficiency and reduce human error (Oxstrand and LeBlanc 2014). However, concerns regarding impacts to plant operations when the use of technology and software is integrated into the work performed needs to be evaluated and mitigated. These concerns can be evaluated based on attributes that are related characteristics of any software, mechanical, or physical system. Three attributes were included in a phrase first used by IBM to define specifications for their mainframes and originally applied only to hardware: reliability, availability, and serviceability (RAS) (Siewiorek and Swarz 1998). A fourth attribute has recently started to be included to help emphasize the role that "manageability" (i.e., RASM) plays in supporting system robustness (Radle 2015). Today, RASM is relevant to more than just hardware and is a good method for designing your overall system and tool configuration.

3.3.9.1 Reliability. Reliability is the probability that a system will function as expected for a given duration in an environment. Considering that the system functions as expected implies that the information provided is correct and not corrupted (Radle and Mitchell 2015). Some key elements to consider in relation to reliability are understanding the importance of the cost of failure and an environmental readiness site survey should be performed.

3.3.9.2 Availability. Availability is the probability that the system is available to perform its function when requested at any given time (i.e., the amount of time a system is actually operating as a percentage of total time it should be operating) (Radle and Bradicich 2013a). Some key elements to consider for availability are understanding cost of downtime, system redundancy can prevent perceived downtime, and an environmental readiness site survey can also be helpful.

3.3.9.3 Serviceability. The ease and speed that a system can be repaired or maintained (Radle and Bradicich 2013b). Some key elements to consider for serviceability are the financial and resource cost that can occur during downtime and if serviceability improves both the reliability and availability of the system.

3.3.9.4 Manageability. Manageability is the measure of the features that support the ease, speed, and competence that a system can be discovered, configured, modified, deployed, controlled, and supervised (Radle et al. 2015). Some key elements of manageability are as follows: level of access and location of systems should be evaluated, isolation of faulty components should be enabled, and error logs, asset inventories, and service histories should be maintained to help in creating a strategy for replacing systems as needed.

These four attributes should be included in the DA plan in order to help the plant prepare for their DA implementation and guide them in selection of systems and tools that are to be utilized. Further details should be researched for best practices to provide guidance on using RASM in planning the DA system.

3.4 Roles and Responsibilities

The survey result shown in Figure 2 indicates that a significant number of utilities have the necessary IT expertise to perform some of the needed evaluations of the DAPM. However, more roles than IT experts are needed to successfully implement the DA plan. Within the DA plan it is necessary to engage all of the three parties that will play a major role in DA implementation; the utility, vendor, and regulator (International Atomic Energy Agency 2009). Ideally, the utility is the lead organization of the effort. The utility sets the requirements, taking into consideration the regulator requirements. These requirements are met by the utility, the vendor, or both. It is necessary to involve all three parties at every stage of the DA planning, implementation, and utilization and to encourage open communication.

Within the utility and vendor organizations, detailed and clearly defined roles and responsibilities of the teams' members should be established. The roles and responsibilities should be clearly documented and communicated to all elements of the DA. The detailed distribution of responsibilities is essential to the success of DA implementation. A lead department or disciplines should be defined for the project as a whole and for each task. These lead entities would be the main task or project drivers. Supporting departments or disciplines would allocate the needed resources and define the liaison representatives to support the task or project leads.

Overlapping responsibilities should be avoided as much as possible. This might not always be feasible, since the DA spans the two organizations: I&C (engineering) and business or process application (IT). This implies the need for an overarching organization with complementary roles and responsibilities. In addition to the organizational overlapping, activities overlapping need to be evaluated too. For example, in addition to the generic regulations review, which is handled as part of the regulations compliance responsible entity, a challenge-specific review would also be needed. This challenge-specific review is handled by the challenge-specific responsible entity in addition to the regulations compliance responsible entity. These scenarios would require planning for intensive communication and coordination among the involved parties.

As DA implementation evolves, the roles and responsibilities need to be reviewed to reflect any changes and to incorporate progress feedback. These changes should be clearly documented and communicated. In the context of DA, the roles and responsibilities at the planning stage would define and distribute the tasks to determine the feasibility of DA, its implementation plan and resources, and evaluate potential challenges. The roles and responsibilities will change at the implementation stage. Implementation of this new set of roles and responsibilities is not expected to significantly differ from other project's management and execution roles and responsibilities.

4. FUTURE WORK

The DAPM described in this report provides a general perspective of the main steps and challenges associated with introducing a DA into a nuclear power plant. As a direct outcome of DAPM development, the researchers have identified topics needing further investigation. For example, detailed studies need to be performed in each of the challenges listed in this report: bandwidth, change management, cybersecurity, human factors, physical limitation, power supply, regulations, RFI/EMI, risk, and RASM. In addition, an approach to determine the optimal size of DA that is needed to maximize its efficiency and impact while minimizing the needed resources will have to be developed.

A more detailed policy-oriented report should be generated, which will provide a more comprehensive guideline from a set of suggestions and recommendations associated with each of the topics listed in this report. The detailed report will follow a structure similar to common guidelines developed by organization such as the International Atomic Energy Agency. An example of this layout can be found in International Atomic Energy Agency (2015).

A detailed business case needs to be developed for each of the applications benefitting from DA. The results of these studies would support the utilities' evaluation of potential DA applications. In addition, an economic feasibility study guide and examples for implementing DA need to be developed. The guide and examples will alert utilities to important considerations when performing similar tasks and provide the utilities with an overview of the potential benefits of performing the actual study.

Safety and security impact studies for each potential DA application also need to be developed. The utilities will use results from these studies when evaluating and prioritizing certain applications over others.

Day-to-day operations of a plant require many different tools and databases to provide information to the workers. Many of the systems are made by different vendors and written to be isolated in functionality. An approach needs to be researched to provide a seamless digital environment by focusing on the middleware in DA. The research should identify methods for providing data to the workers, managers, and owners in a "one-stop-shop" format to reduce the need for them to go directly to each system for the data they need.

It is expected that as the researchers and utilities continue to investigate the best path to implement DA to support advanced technology, additional considerations and challenges that need to be addressed through research will be identified.

5. REFERENCES

Agarwal, V., J. Richardson, and Y. Zhang, 2015, *Wireless Sensor Node Power Profiling Based on IEEE 802.11 and IEEE 802.15.4 Communication Protocols: Modeling and Simulation*, INL/EXT-15-37005, Idaho National Laboratory.

Balogun, J. and V. H. Hailey, 2004, *Exploring strategic change*, 2nd Edition, London: Pearson Education.

Barnard, M. and N. Stoll, 2010, "Organisational Change Management: A rapid literature review," *Australia: Centre for Understanding Behaviour Change*, University of Bristol.

Bauer, M, 1997, *Resistance to new technology: nuclear power, information technology and biotechnology*. Cambridge University Press.

Byres, E. and J. Lowe, 2004, "The Myths and Facts Behind Cyber Security Risks for Industrial Control Systems," *VDE Kongress* 166: 213–218.

Electric Power Research Institute, 2013, "Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment," Revision 4 to TR-102323, Palo Alto: EPRI 3002000528.

Electric Power Research Institute, 2009, "Implementation Guideline for Wireless Networks and Wireless Equipment Condition Monitoring," Knoxville: AMS Technonlogy Center.

Fovino, I., L. Guidi, M. Masera, and A. Stefanini, 2011, "Cyber Security Assessment of a Power Plant," *Electric Power Systems Research* 81(2): 518–526.

Hashemian, H. M., C. J. Kiger, G. W. Morton, and B. D. Shumaker, 2011, "Wireless sensor applications in nuclear power plants," *Nuclear Technology* 173(1): 8–16.

Institute of Electrical and Electronics Engineers, 2004, "IEEE Standard for Software Verification and Validation," IEEE Statndard 1012-2004.

International Atomic Energy Agency, 2009, "Implementing Digital Instrumentation and Control Systems in the Modernization of Nuclear Power Plants" Vienna: NP-T-1.4.

International Atomic Energy Agency, 2015, “Integrated Nuclear Infrastructure Review (INIR) Missions: The First Six Years” Vienna: IAEA-TECDOC-1779.

International Electrotechnical Commission, 2009, "Nuclear power plants - Instrumentation and control important to safety - Requirements for electromagnetic compatibility testing," IEC 62003.

Kim, D., 2014, "Cyber Security Issues Imposed on Nuclear Power Plants," *Annals of Nuclear Energy* 65: 141–143.

Min, M.G., J.-K. Lee, Y.-H. Ji, S.-H. Jo, and H.-J. Kim, 2015, "Evaluation of electromagnetic interference environment of theinstrumentation and control systems in nuclear power units," *Nuclear Engineering and Design* 285: 15–22.

Nuclear Energy Institute , 2010, *Cyber Security Plan for Nuclear Power Reactors,* NEI 08-09 Rev. 6

Oxstrand, J. and K. LeBlanc, 2014, *Computer-Based Procedure for Field Activities: Results from Three Evaluations at Nuclear Power Plants*, INL/EXT-14-33212, Idaho National Laboratory.

Oxstrand, J., K. Thomas, and K. Fitzgerald, 2015a, *Digital Architecture - Results from a Gap Analysis. Idaho Falls: Idaho National Laboratory*, INL/EXT-15-36662, Idaho National Laboratory.

Oxstrand, J., A. Al Rashdan, K. Le Blanc, A. Bly, and V. Agarwal, 2015b. *Light Water Reactor Sustainability Program Automated Work Package Prototype: Initial Design, Development, and Evaluation. Idaho Falls: Idaho National Laboratory* (INL/EXT-15-35825).

Oxstrand, J., K. Le Blanc, A. Bly, H. Medema, and W. Hill, 2015c. *Computer-Based Procedures for Field Workers - Result and Insights from Three Usability and Interface Design Evaluations. Idaho Falls: Idaho National Laboratory* (INL/EXT-15-36658).

Oxstrand, J., K. Le Blanc, (2016). "Supporting the future nuclear workforce with computer-based procedures," *Nuclear Future - The official journal of the Nuclear Institute* 12(1): 34-39.

Park, J., Y. Suh, and C. Park, 2016, "Implementation of Cyber Security for Safety Systems of Nuclear Facilities," *Progress in Nuclear Energy* 88: 88–94.

Pietre-Cambacédes, L., M. Tritschler, and G. Ericsson, 2011, "Cybersecurity Myths on Power Control Systems: 21 Misconceptions and False Beliefs," *IEEE Transactions on Power Delivery* 26(1): 161-172.

Priya, S. and D. J. Inman, 2009, *Energy Harvesting Technologies,* New York: Springer.

Prosci, 2006, "ROI of Change Management Model," retrieved from http://www.change-management.com/tutorial-2007prep-roi-CM-mod1.htm.

Radle, B., 2015, "What is RASM?" retrieved from *National Instruments*, http://www.ni.com/whire-paper/14410/en/.

Radle, B. and T. Bradicich, 2013a, "What is Availability?" retrieved from *National Instruments*, http://www.ni.com/white-paper/14413/en/.

Radle, B. and T. Bradicich, 2013b, "What Is Serviceability?" retrieved from *National Instruments*, http://www.ni.com/white-paper/14414/en/.

Radle, B. and B. Mitchell, 2015, "What is Reliability?" retrieved from *National Instruments*: http://www.ni.com/white-paper/14412/en/

Radle, B., M. Anderson, and J. Prewitt, 2015, "What is Manageability?" retrieved from *National Instruments*, http://www.ni.com/white-paper/14415/en/.

Reiman, T., P. Oedewald, C. Rollenhagen, and U. Kahlbom, 2006, "Management of change in the nuclear industry- Evidence from maintenance reorganizations."

Siewiorek, D. and R. Swarz, 1998, *Reliable Computer Systems: Design and Evaluation*, 3rd edition, A K Peters/CRC Press.

Sodano, H., D. Inman, and G. Park, 2004, "A Review of Power Harvesting from Vibration Using Piezoelectric Materials," S*hock and Vibration Design*: 197–206.

Thomas, K., M. Thow, T. Kenny, and L. Watkins, 2014, "Cyber Security Evaluation of II&C Technologies", INL/EXT-14-33609, Idaho National Laboratory

Thomas, K., S. Lawrie, C. Vlahapolis, and J. Niedermuller, 2015, P*ilot Project Technology Business Case: Mobile Work Packages*, INL/EXT-15-35327, Idaho National Laboratory.

Thomas, K. and J. Oxstrand, 2015, *Digital Architecture Requirements. Idaho Falls: Idaho National Laboratory*, INL/EXT-15-34696, Idaho National Laboratory.

U.S. Nuclear Regulatory Commission, 1996, RG 1.153, "Criteria For Use of Computers in Safety Systems of Nuclear Power Plants," Revision 2, U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 1997a, RG 1.169, “Configuration Management Plans for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 1997b, RG 1.170, "Software Test Documentation for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 1997c, RG 1.171, "Software Unit Testing for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 1997d, RG 1.172, "Software Requirements Specifications for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 1997e, RG 1.173, "Developing Software Life-Cycle Processes for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 2000, *Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants*, NUREG/CR-6431.

U.S. Nuclear Regulatory Commission, 2002, "Human-System Interface Design Review Guidelines," NUREG-0700.

U.S. Nuclear Regulatory Commission, 2003, RG 1.180, "Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems," Revision 1.

U.S. Nuclear Regulatory Commission, 2004, RG 1.168, "Verification, Validation, Revisions, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants."

U.S. Nuclear Regulatory Commission, 2007a, “Changes, tests, and experiments,” *Code of Federal Regulation*, 10 CFR 50.59.

U.S. Nuclear Regulatory Commission, 2007b, *Coexistence Assessment of Industrial Wireless Protocols in the Nuclear Facility Environment*, NUREG/CR-6939.

U.S. Nuclear Regulatory Commission, 2007c, RG 1.209, “Guidelines for Environmental Qualification of Safety-Related Computer-Based Instrumentation and Control Systems in Nuclear Power Plants," U.S. Nuclear Regulatory Commision.

U.S. Nuclear Regulatory Commission, 2009, *Design Practices for Communications and Workstations in Highly Integrated Control Rooms Office*, NUREG/CR-6991.

U.S. Nuclear Regulatory Commission, 2010a, RG 5.71, "Cyber Security Programs for Nuclear Facilities."

U.S. Nuclear Regulatory Commission, 2010b, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Instrumentation and Controls," NUREG-0800 Revision 6.

U.S. Nuclear Regulatory Commission, 2011, RG 1.152, "Criteria for Safety Systems," U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission, 2012, *Human Factors Engineering Program Review Model*, NUREG-0711, Revision 3.

U.S. Nuclear Regulatory Commission, 2015, "Protection of Digital Computer and Communication Systems and Networks," *Code of Federal Regulations*, 10 CFR 73.54.

Valenta, C. and G. Durgin, 2014, "Harvesting Wireless Power: Survey of Energy-harvester Conversion Eifficiency in Far-field Wireless Power Transfer Systems," *Microwave Magazine:* 108–120.

Zhang, Y., D. Butt, and V. Agarwal, 2015, *Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks*, INL/EXT-15-36260, Idaho National Laboratory.

Appendix A
Web Survey

Welcome!

The researchers at Idaho National Laboratory would like your help to better understand the current state as well as the future plans for infrastructure throughout the existing fleet of light water reactors in the USA. Your input will be very valuable to move the research forward.

Thank you for taking a couple of minutes out of your busy day to support our research!

* 1. Participant information

Utility:

Plant (if applicable):

Role/title:

* 2. What is your experience with iPads, Androids, or other tablet like devices?

- ◯ >1 year
- ◯ <1 year
- ◯ No experience

The following gives two scenarios/options for wireless networks in the power block:

Power Block Secured Wireless Network: A secure network used only by instruments, electrical and mechanical field workers. For example: it is used as an instrument status and monitoring network.

Power Block Business Wireless Network: This network could, for example, be used to download documents and drawings while at the work location, send task status reports back to a supervisor, stream critical task videos, and access materials and component data bases.

* 3. Have any of the wireless network options been installed, or will be installed, in power blocks operated by your utility?

- ◯ Yes
- ◯ No

* 4. What are the plans for wireless network in the power block?

	Already installed	Planned to be installed in the next year	Planned to be installed in 2-5 years	Planned to be installed in 5+ years
Power Block Secure Wireless Network	○	○	○	○
Power Block Business Wireless Network	○	○	○	○

* 5. To what extent does the wireless network cover the power block?

	0-25%	25-50%	50-75%	75-90%	90-100%
Power Block Secure Wireless Network	◯	◯	◯	◯	◯
Power Block Business Wireless Network	◯	◯	◯	◯	◯

* 6. What are the main intended purposes for the wireless network in the power block? (Check all that apply)

- [ ] Online monitoring
- [ ] Execution of electronic work orders and instructions
- [ ] Enabling communication between craft, supervisors, and others
- [ ] Video monitoring of (critical) tasks
- [ ] Work status information for scheduling and task planning
- [ ] Component position indication
- [ ] Other (please specify)

* 7. How do you see your implementation of wireless networks in the power block being installed?

- ◯ Wireless network was or will be installed incrementally over time
- ◯ Wireless network was or will be installed all at once

* 8. What are some of the obstacles that you see could prevent wireless networks in the power block? (Check all that apply)

- [ ] Radio frequency interference
- [ ] Cybersecurity
- [ ] Cost and economic feasibility
- [ ] Regulation
- [ ] Culture (e.g., perceived issues between organizations, individuals' resistance to change, and general attitudes in the company)
- [ ] The process to request and implement changes in the plant
- [ ] Other (please specify)

* 9. Is any temporary wireless network set up in the power block during outage?

- Yes
- No

* 10. For what purpose is the temporary wireless network used?

* 11. Do you have wireless network in any of the following locations?

	Implemented	Planned	Not planned
Offices and meeting rooms	○	○	○
Main control room	○	○	○
Outage control center	○	○	○

* 12. When will the wireless be installed at these locations?

	Planned to be installed in the next year	Planned to be installed in 2-5 years	Planned to be installed in 5+ years
Offices and meeting rooms	○	○	○
Main control room	○	○	○
Outage control center	○	○	○

* 13. Is your utility pursuing any of the following capabilities or upgrades?

	Implemented	Planned	Not planned
Main Control Room Upgrades or Modernizations	◯	◯	◯
Outage Control Room Upgrades or Modernizations	◯	◯	◯
Online Monitoring Capabilities	◯	◯	◯
Electronic/Mobile Work Management (e.g., using handheld devices to execute work orders)	◯	◯	◯

* 14. When will these capabilities or upgrades be installed?

	Planned to be installed in the next year	Planned to be installed in 2-5 years	Planned to be installed in 5+ years
Main Control Room Upgrades or Modernizations	◯	◯	◯
Outage Control Room Upgrades or Modernizations	◯	◯	◯
Online Monitoring Capabilities	◯	◯	◯
Electronic/Mobile Work Management (e.g., using handheld devices to execute work orders)	◯	◯	◯

* 15. If adopting any of the described new capabilities, who would supply just-in-time training or recurring training on the new processes? (Check all that apply)

- [ ] IT
- [ ] Engineers
- [ ] Training Department
- [ ] Subcontractors
- [ ] N/A
- [ ] Other (please specify)

* 16. It is in general easy to work with the corporate and/or plant IT departments to implement changes and technology upgrades?

Yes, because...

No, because...

17. Do you have any additional comments related to new capabilities, new technology, and/or change management?

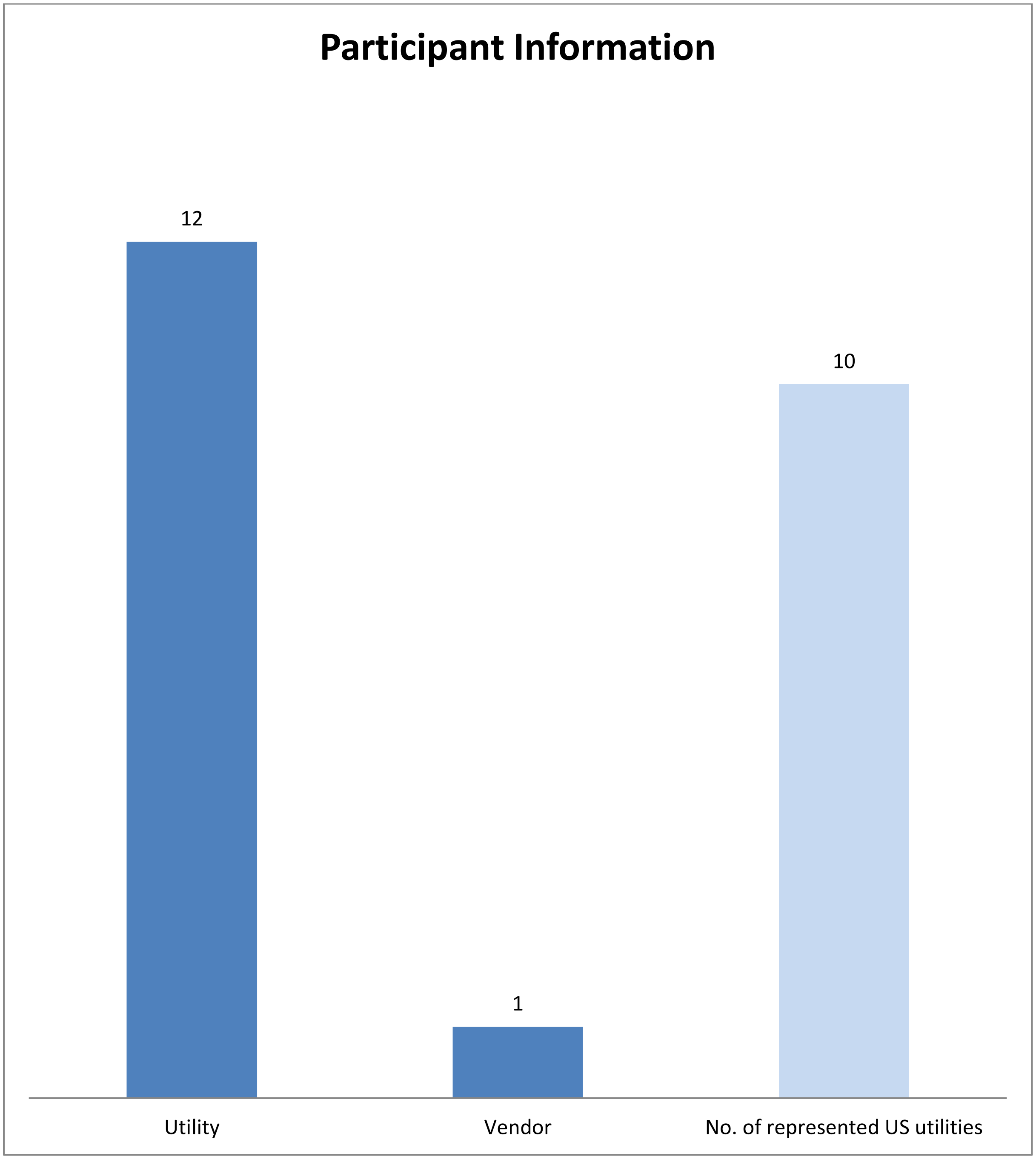
Thank you!

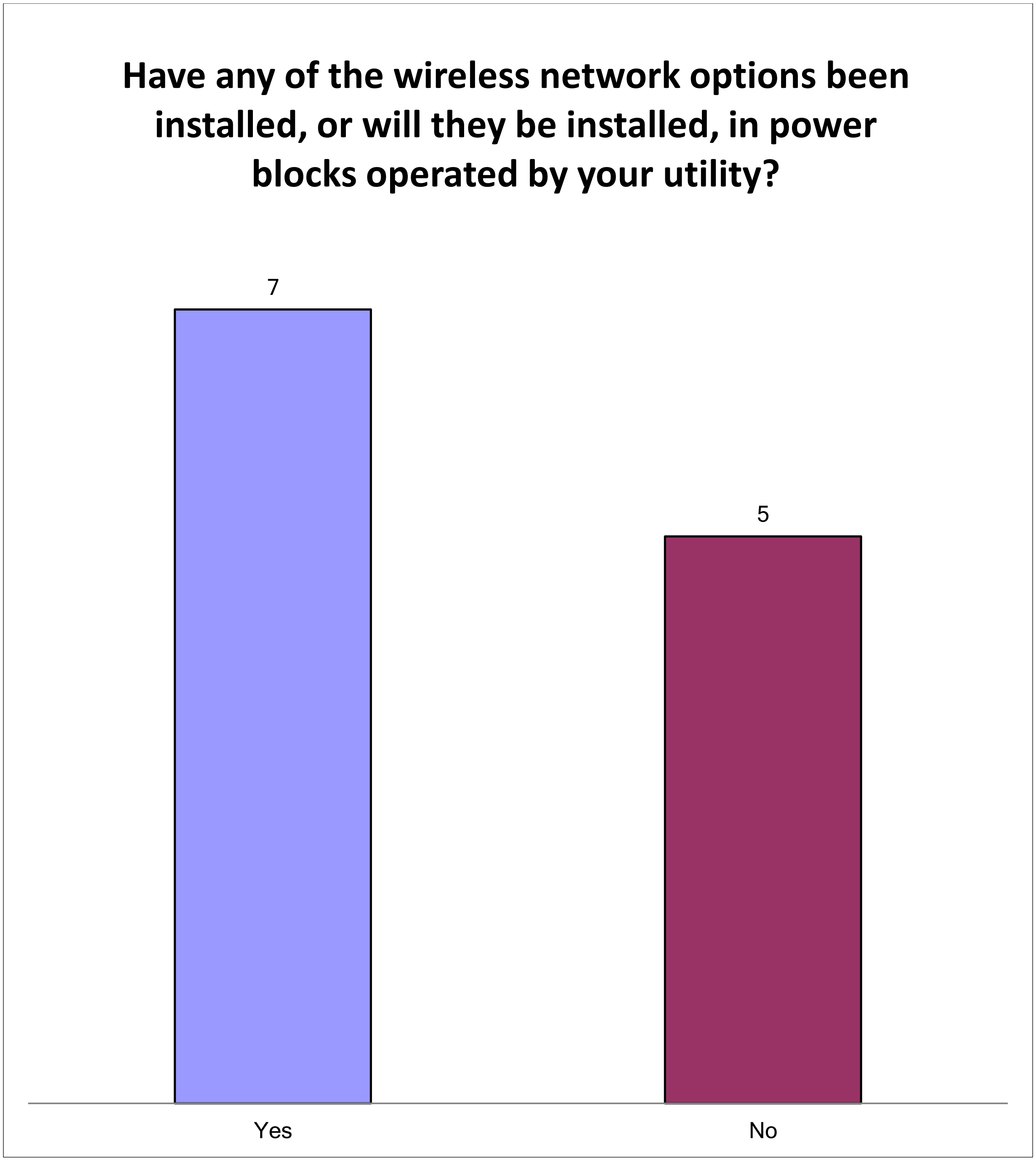
Thank you for taking the time to participate in the survey!
The INL researchers truly appreciate your input.

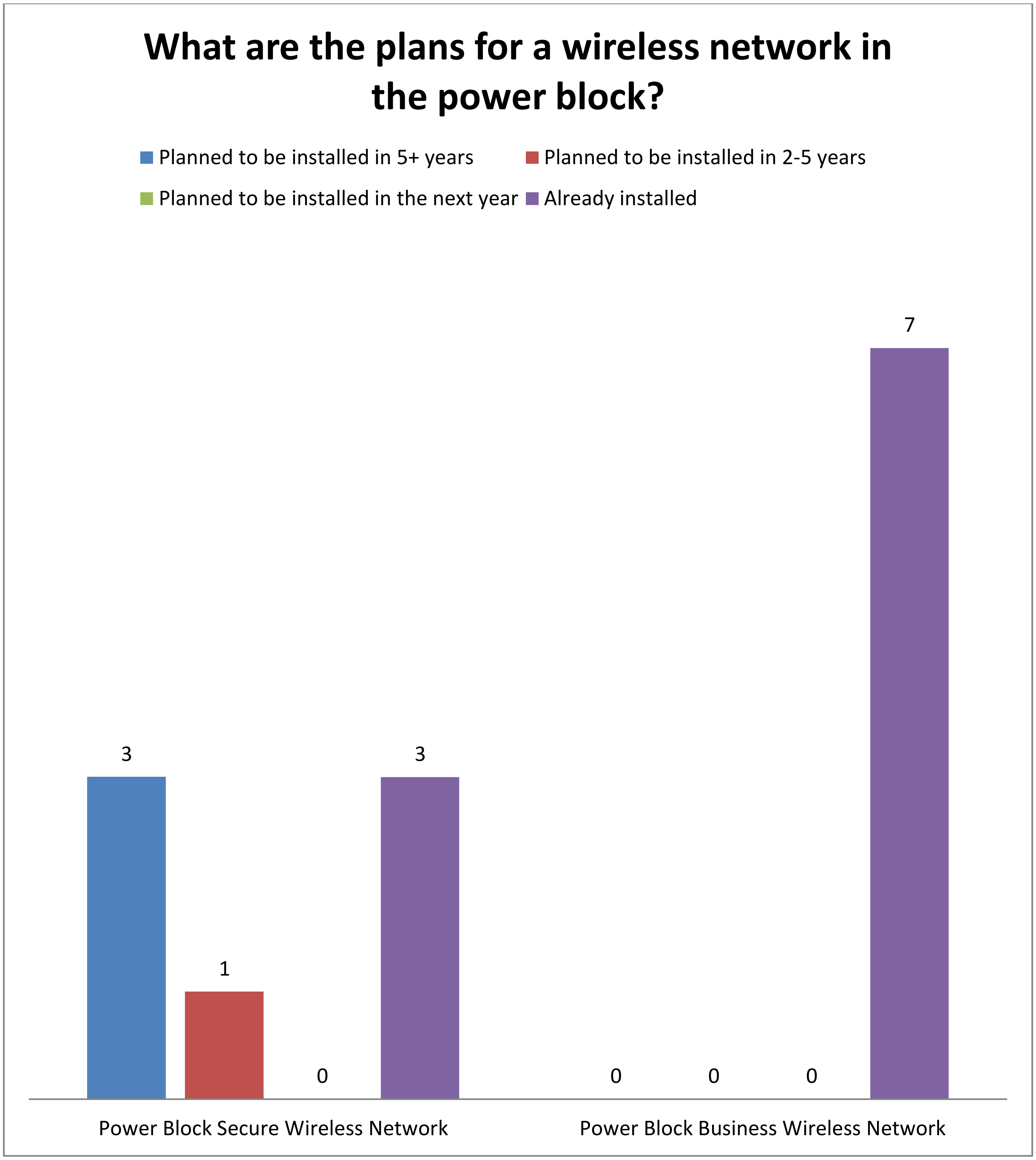
Have a great day!

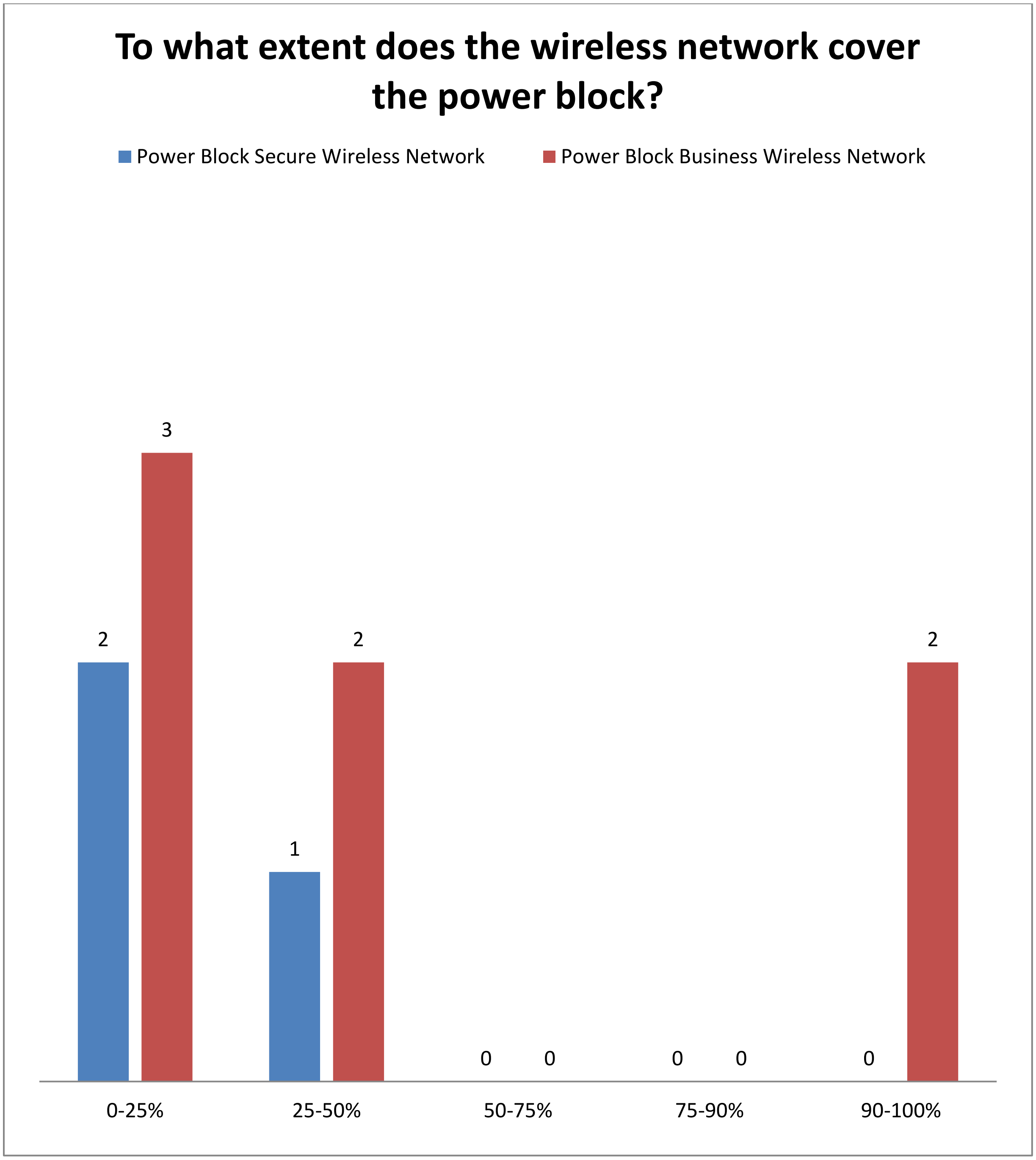
Appendix B
Survey Results

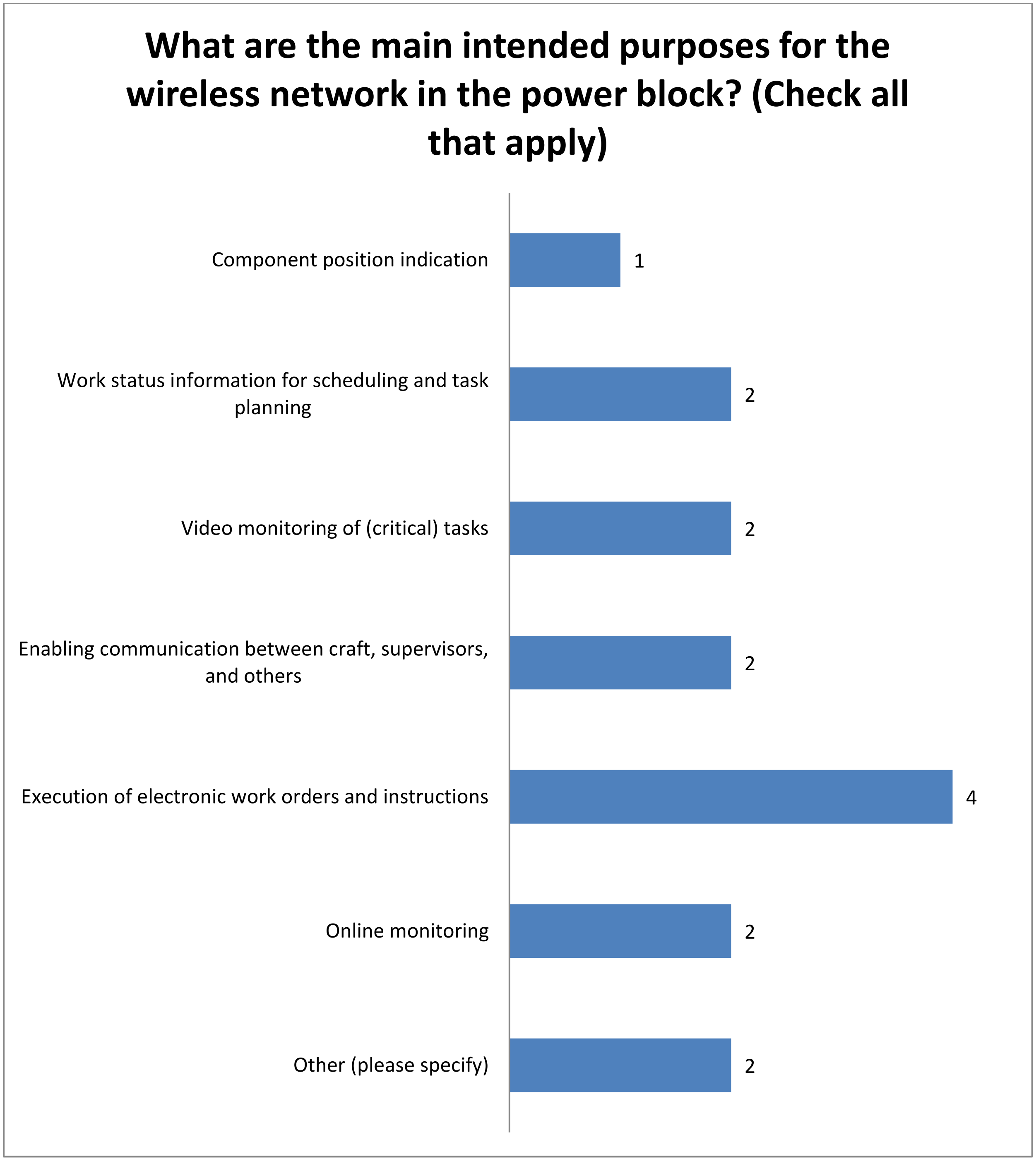
Results from the data analysis of all 13 participants is presented in this appendix. For the result of the data analysis of utility representatives only, see Appendix C.

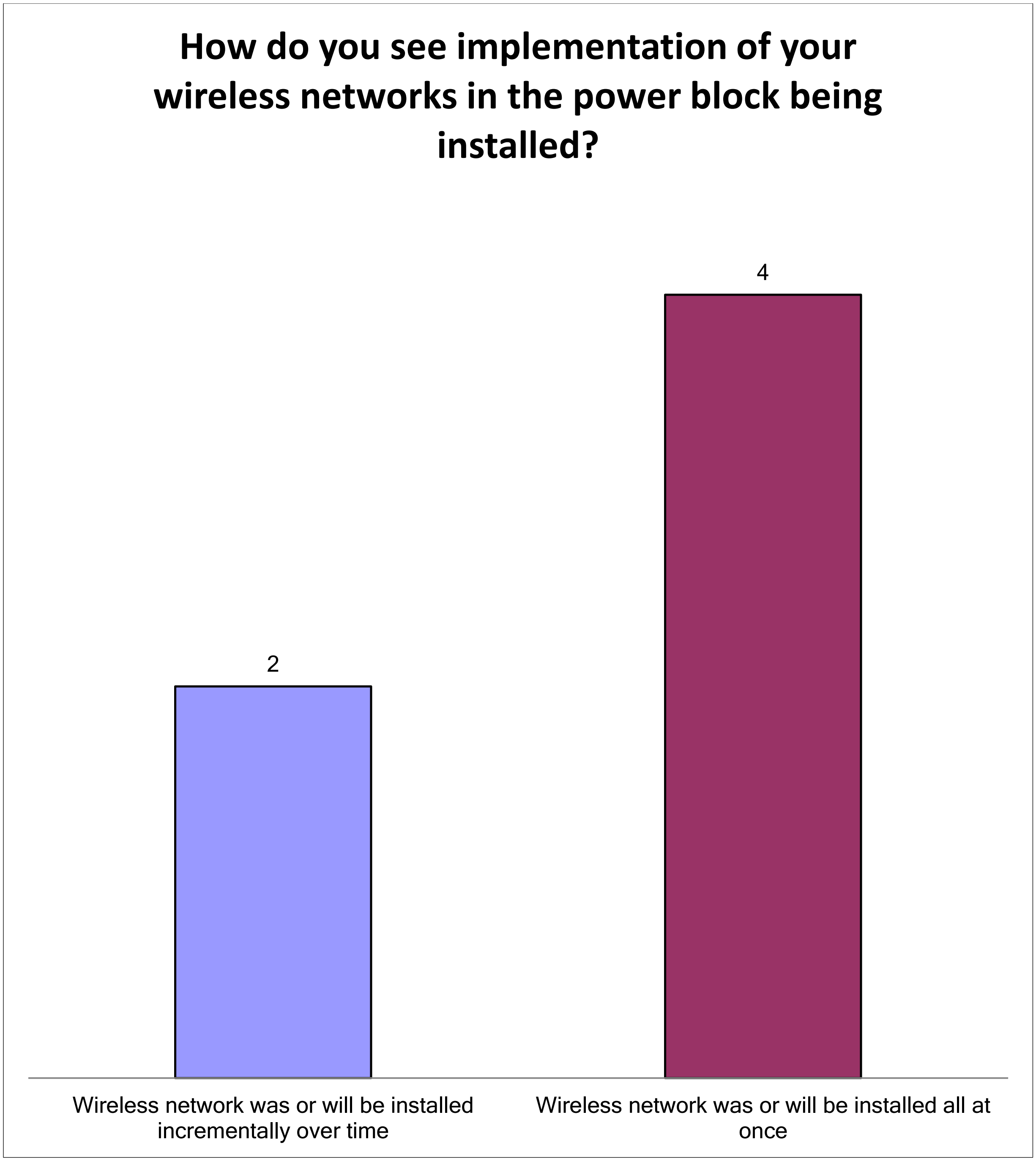


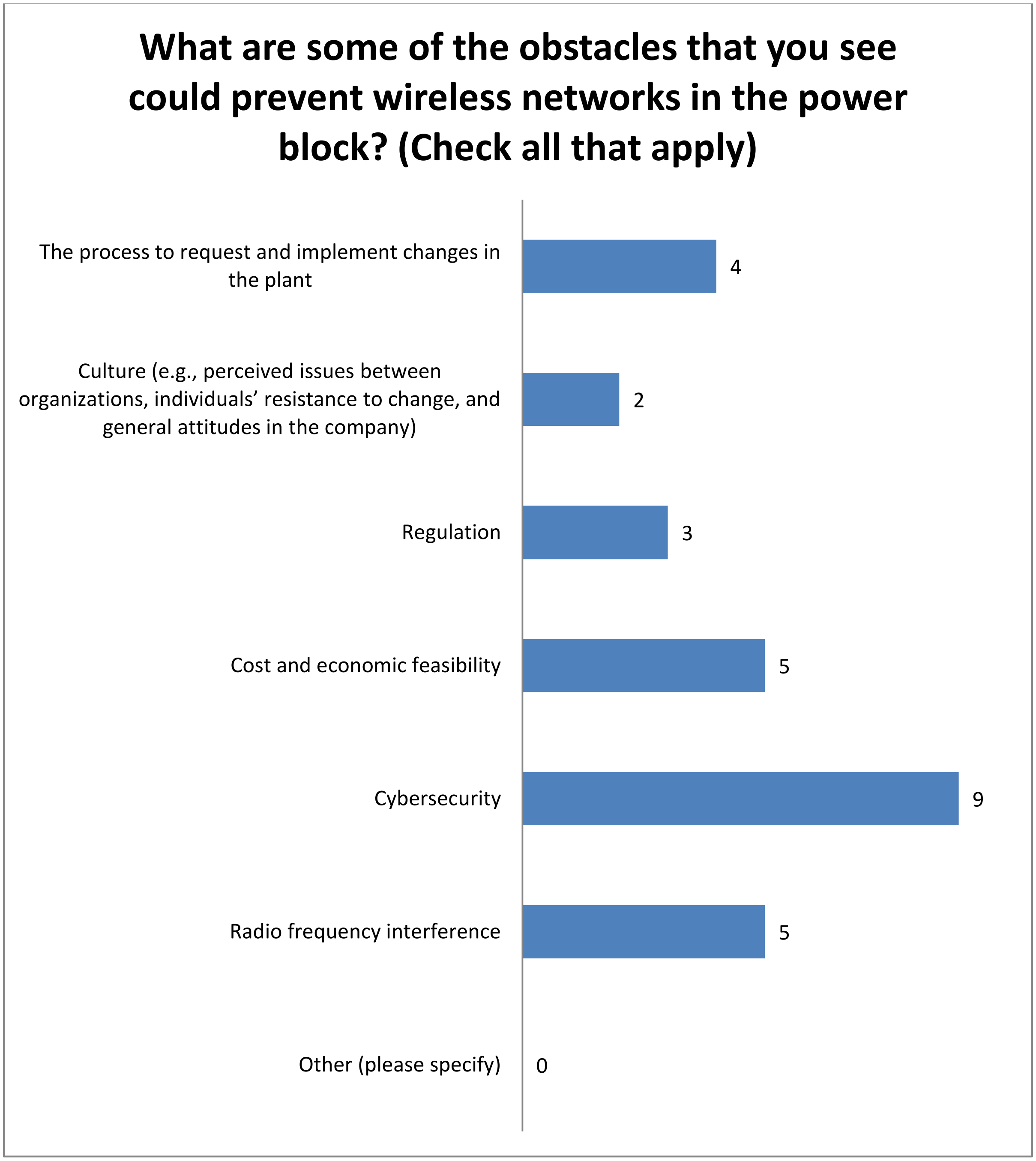

Have any of the wireless network options been installed, or will they be installed, in power blocks operated by your utility?
7
5
Yes
No

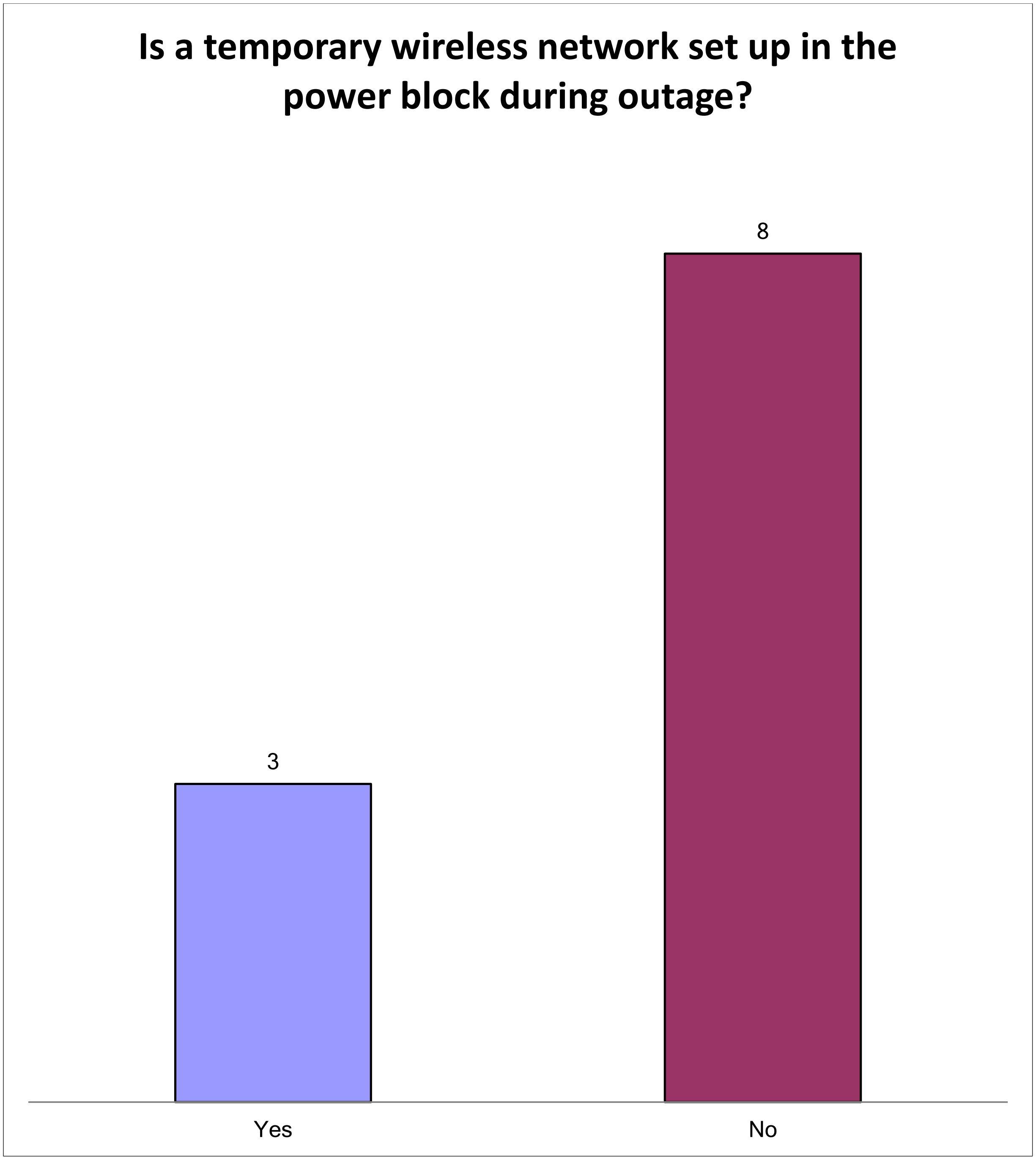

What are the plans for a wireless network in the power block?
Planned to be installed in 5+ years
Planned to be installed in 2-5 years
Planned to be installed in the next year
Already installed
7
3
3
1
0
0
0
0
Power Block Secure Wireless Network
Power Block Business Wireless Network


To what extent does the wireless network cover the power block?
Power Block Secure Wireless Network
Power Block Business Wireless Network
3
2
2
1
2
0
0
0
0
0
0-25%
25-50%
50-75%
75-90%
90-100%

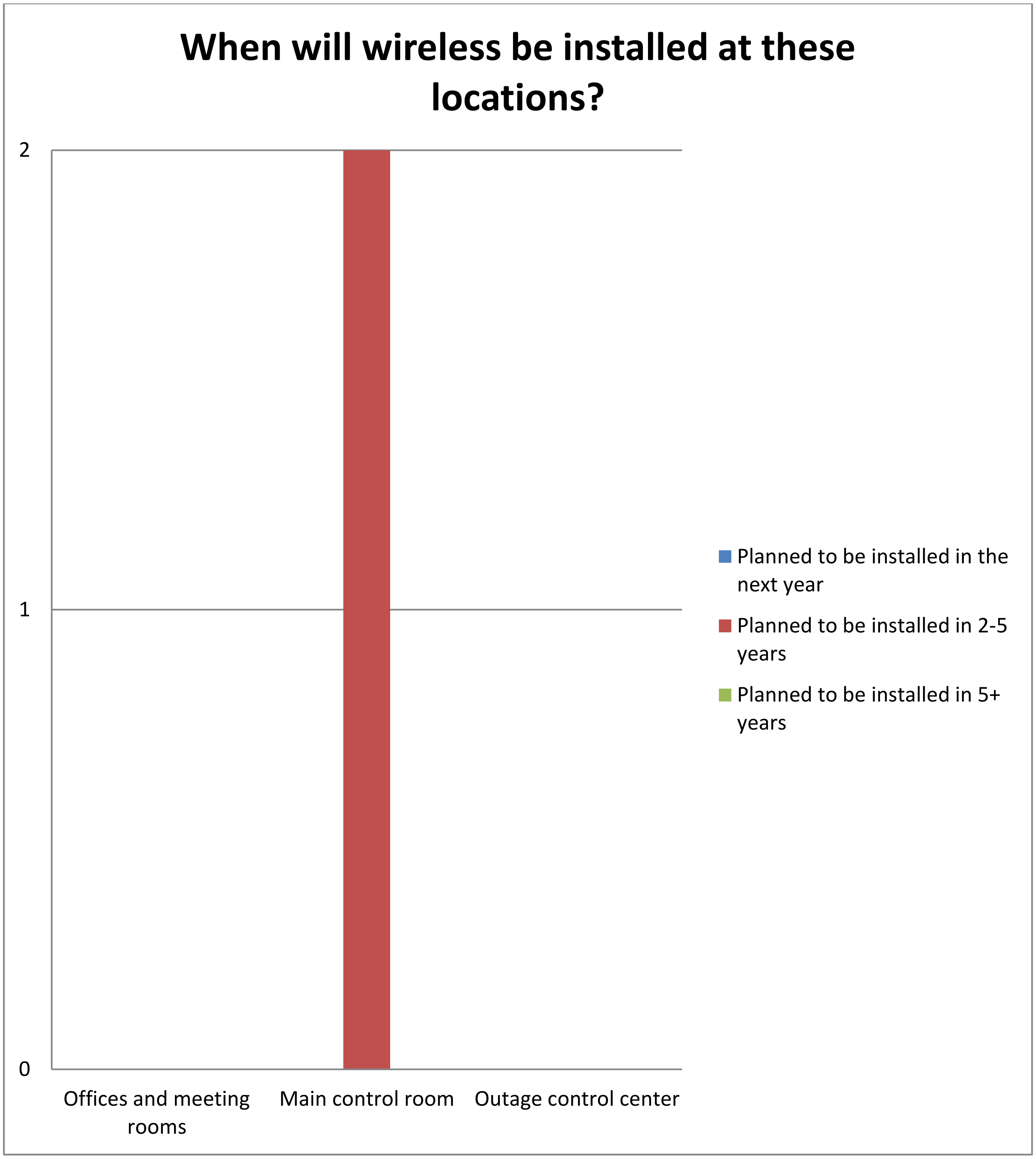

What are the main intended purposes for the wireless network in the power block? (Check all that apply)
Component position indication
1
Work status information for scheduling and task planning
2
Video monitoring of (critical) tasks
2
Enabling communication between craft, supervisors, and others
2
Execution of electronic work orders and instructions
4
Online monitoring
2
Other (please specify)
2


How do you see implementation of your wireless networks in the power block being installed?
2
4
Wireless network was or will be installed incrementally over time
Wireless network was or will be installed all at once

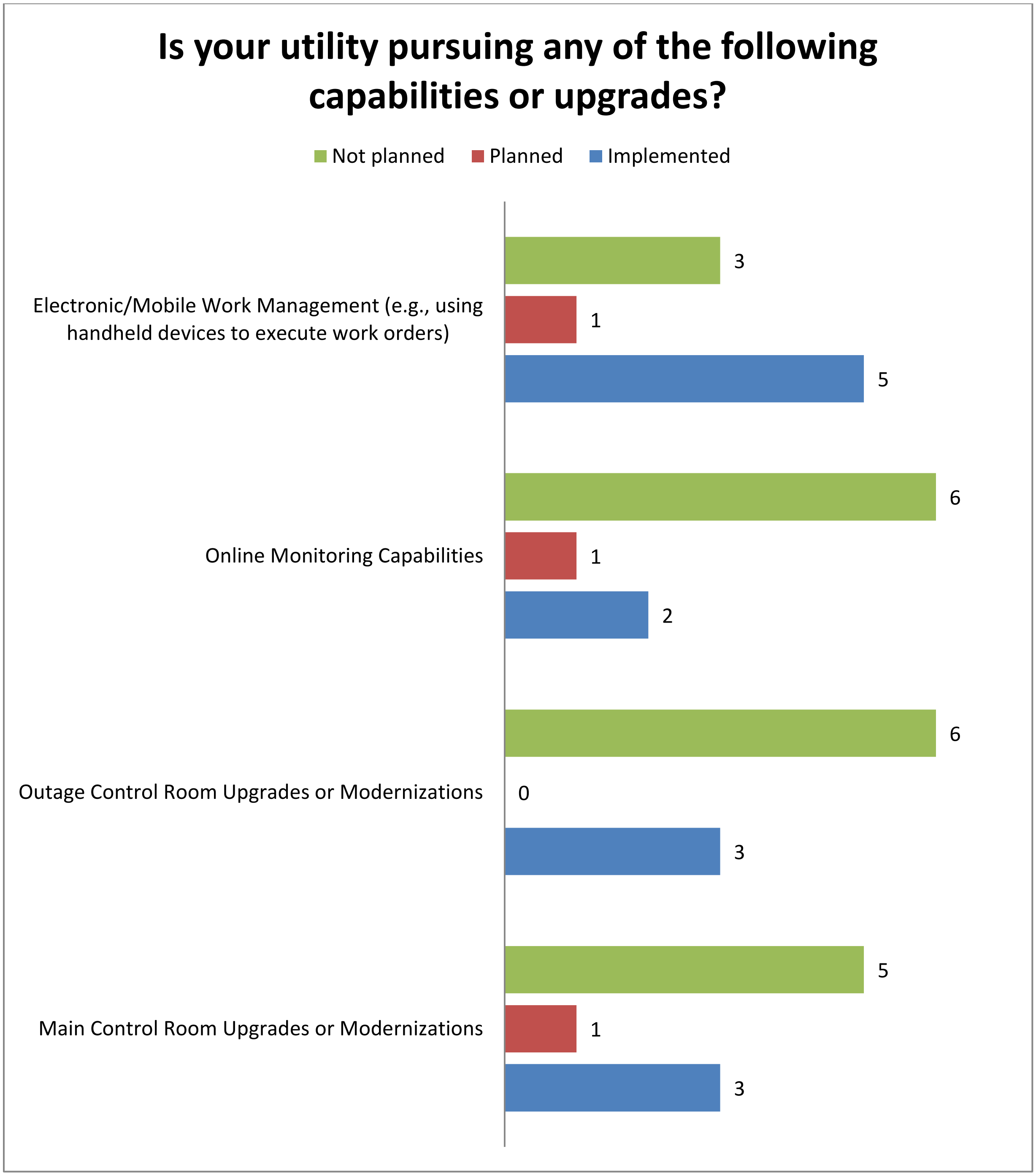

What are some of the obstacles that you see could prevent wireless networks in the power block? (Check all that apply)
The process to request and implement changes in the plant
4
Culture (e.g., perceived issues between organizations, individuals’ resistance to change, and general attitudes in the company)
2
Regulation
3
Cost and economic feasibility
5
Cybersecurity
9
Radio frequency interference
5
Other (please specify)
0

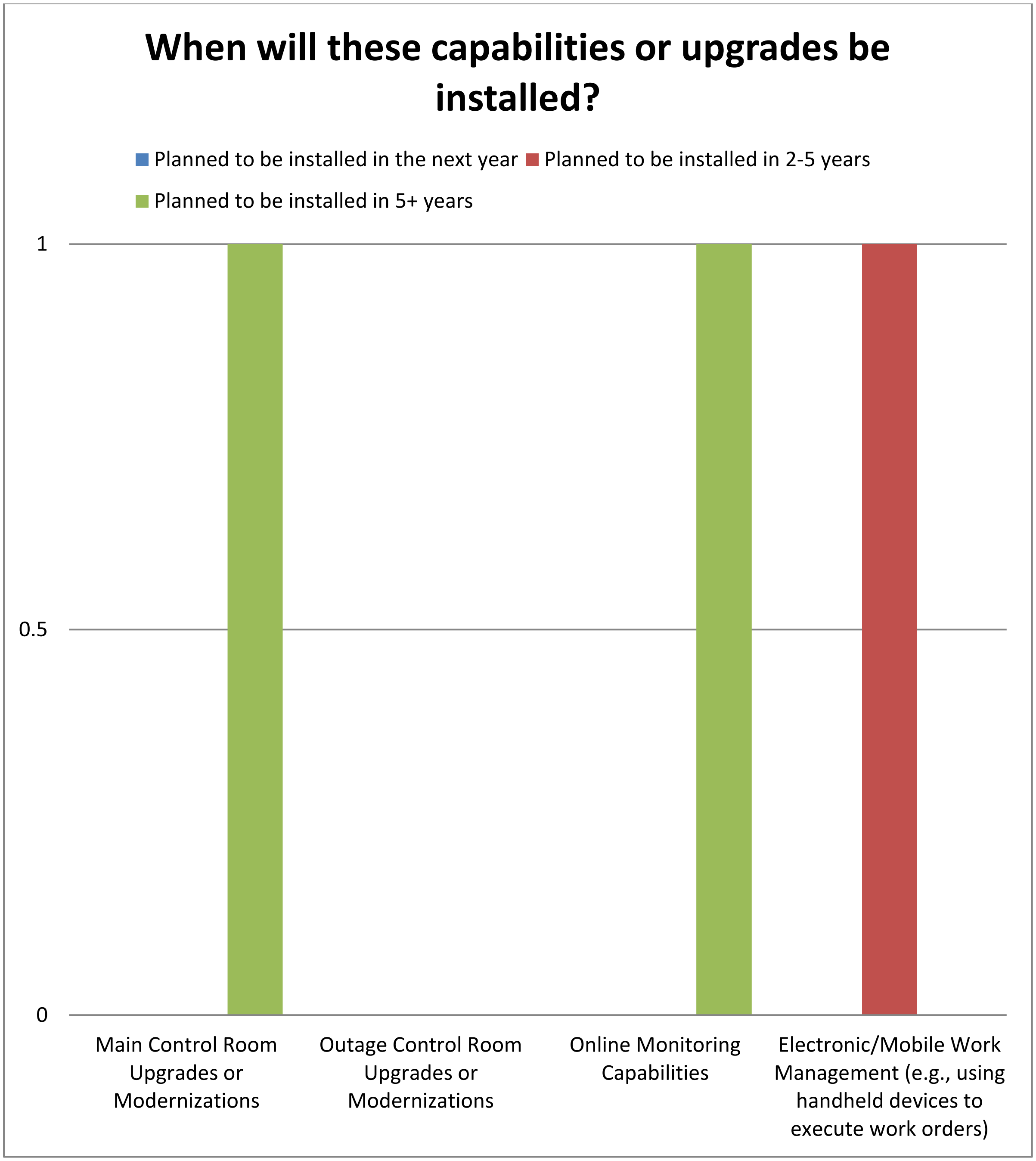

Is a temporary wireless network set up in the power block during outage?
8
3
Yes
No

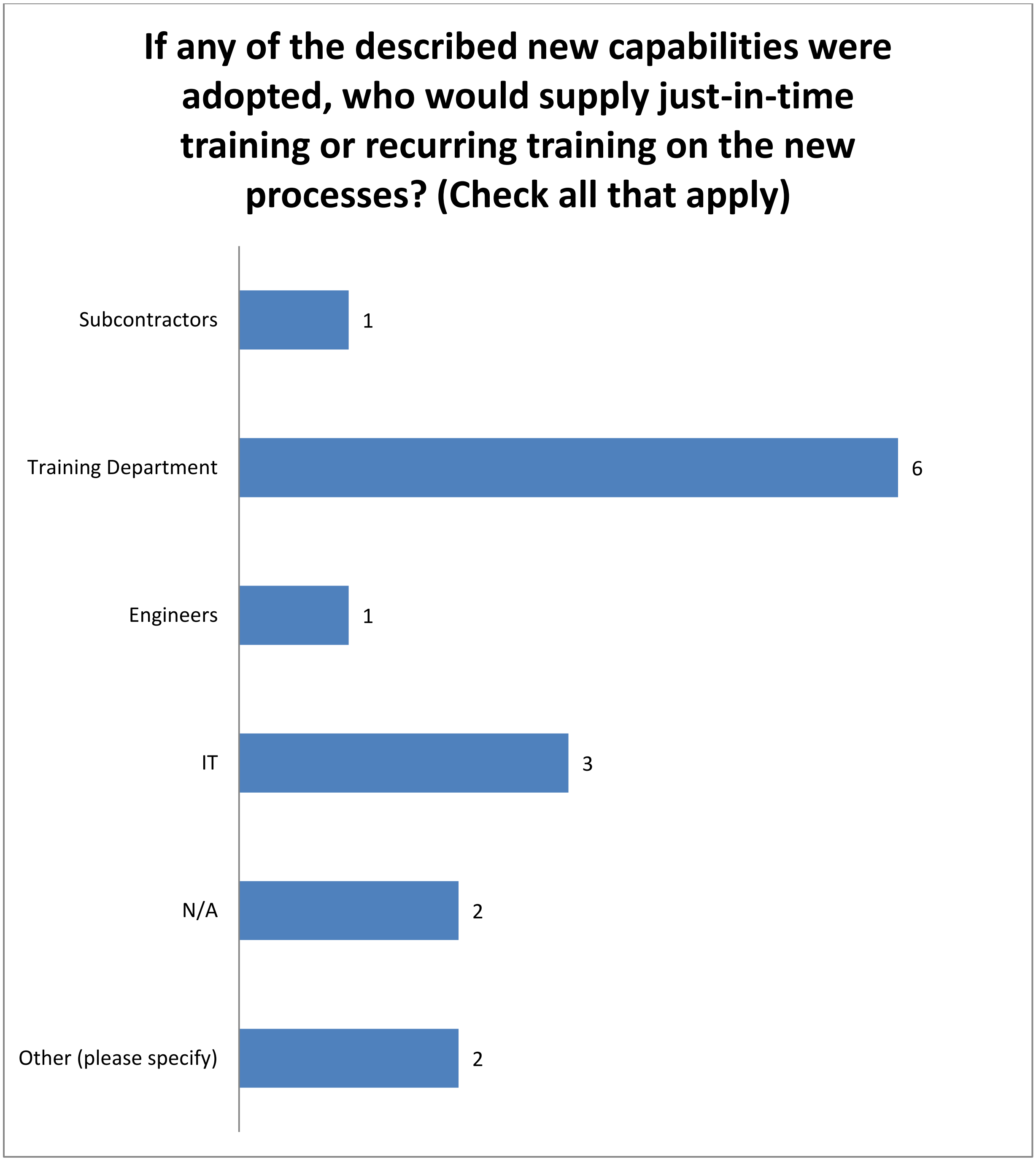

Do you have wireless network in any of the following locations?
Not planned
Planned
Implemented
Outage control center
2
0
7
Main control room
4
2
3
Offices and meeting rooms
2
0
7

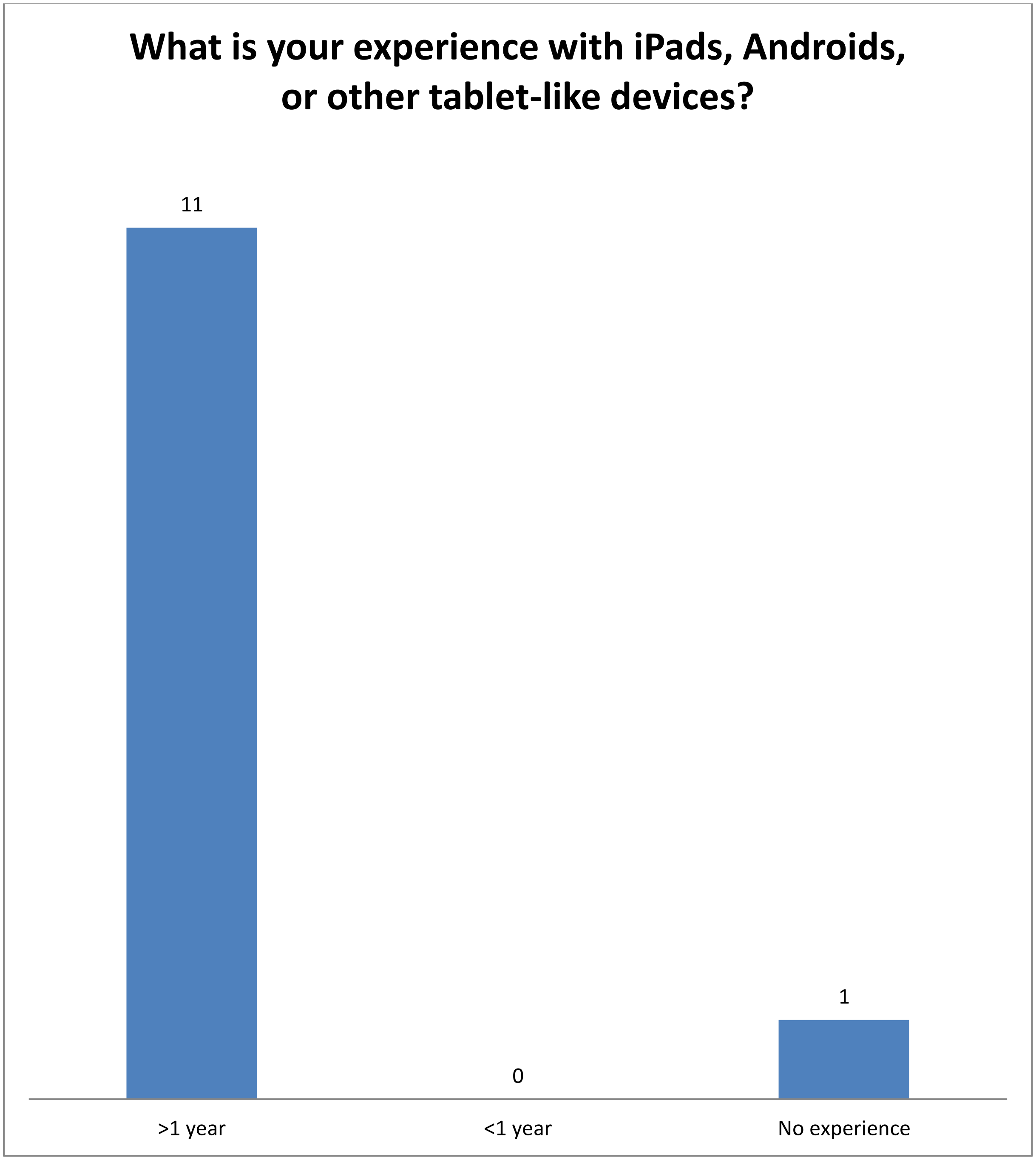


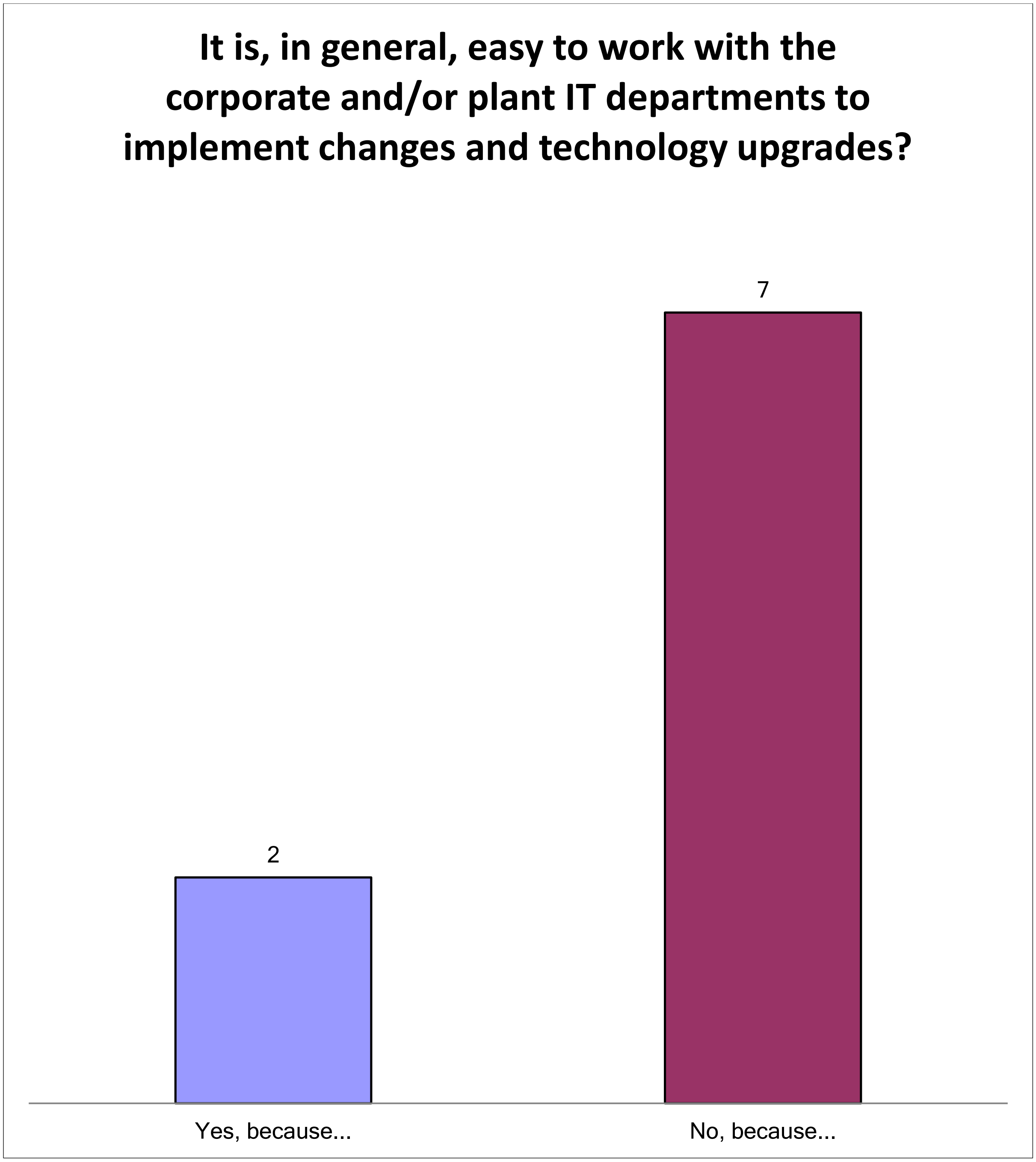
When will wireless be installed at these locations?
2
1
0
Offices and meeting rooms
Main control room
Outage control center
Planned to be installed in the next year
Planned to be installed in 2-5 years
Planned to be installed in 5+ years


Is your utility pursuing any of the following capabilities or upgrades?
Not planned
Planned
Implemented
Electronic/Mobile Work Management (e.g., using handheld devices to execute work orders)
3
1
5
Online Monitoring Capabilities
6
1
2
Outage Control Room Upgrades or Modernizations
6
0
3
Main Control Room Upgrades or Modernizations
5
1
3


When will these capabilities or upgrades be installed?
Planned to be installed in the next year
Planned to be installed in 2-5 years
Planned to be installed in 5+ years
1
0.5
0
Main Control Room Upgrades or Modernizations
Outage Control Room Upgrades or Modernizations
Online Monitoring Capabilities
Electronic/Mobile Work Management (e.g., using handheld devices to execute work orders)


If any of the described new capabilities were adopted, who would supply just-in-time training or recurring training on the new processes? (Check all that apply)
Subcontractors
1
Training Department
6
Engineers
1
IT
3
N/A
2
Other (please specify)
2

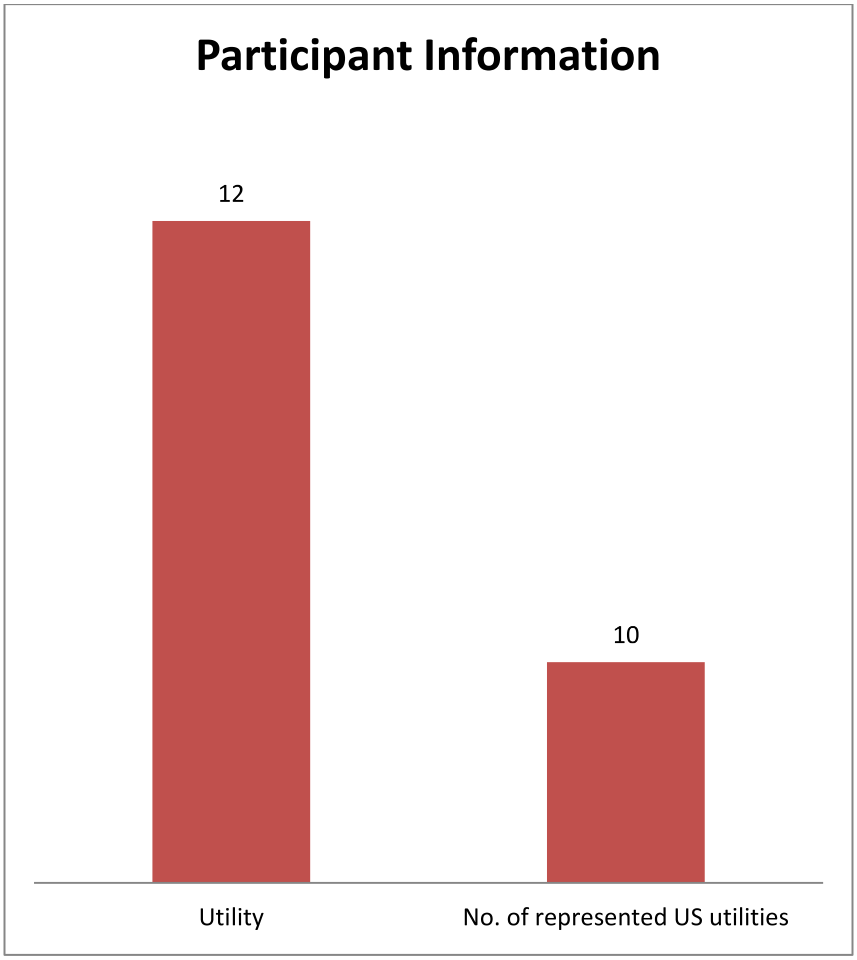

What is your experience with iPads, Androids, or other tablet-like devices?
11
0
1
>1 year
<1 year
No experience

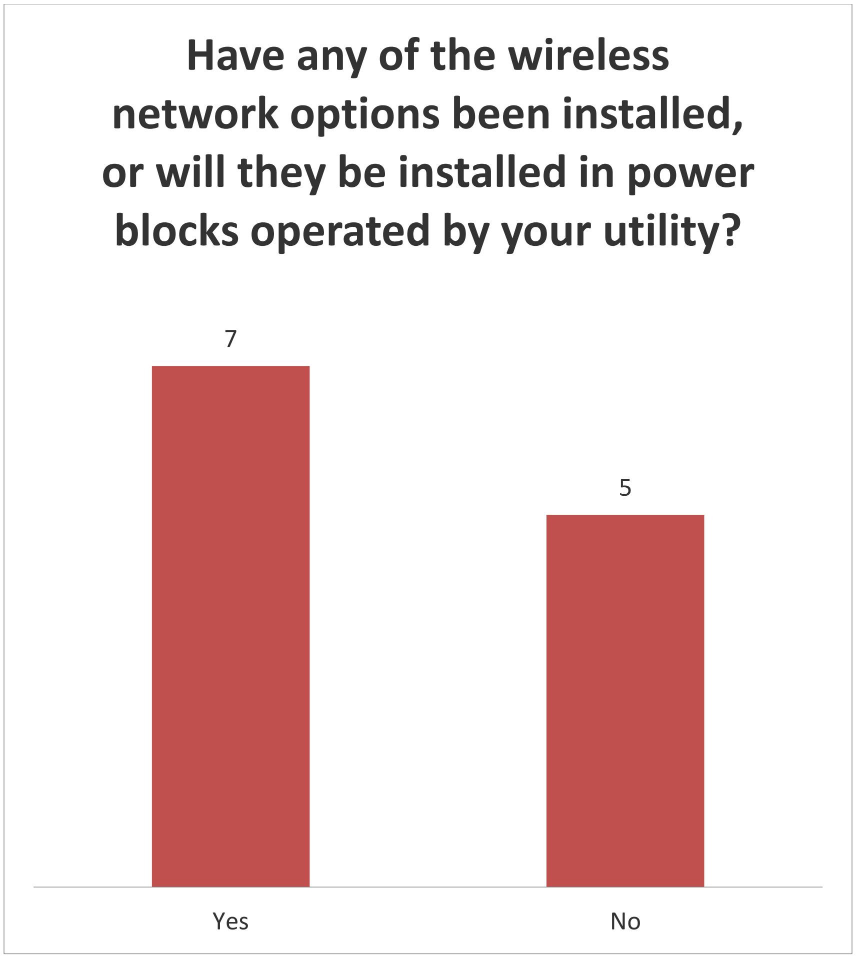

It is, in general, easy to work with the corporate and/or plant IT departments to implement changes and technology upgrades?
2
7
Yes, because...
No, because...

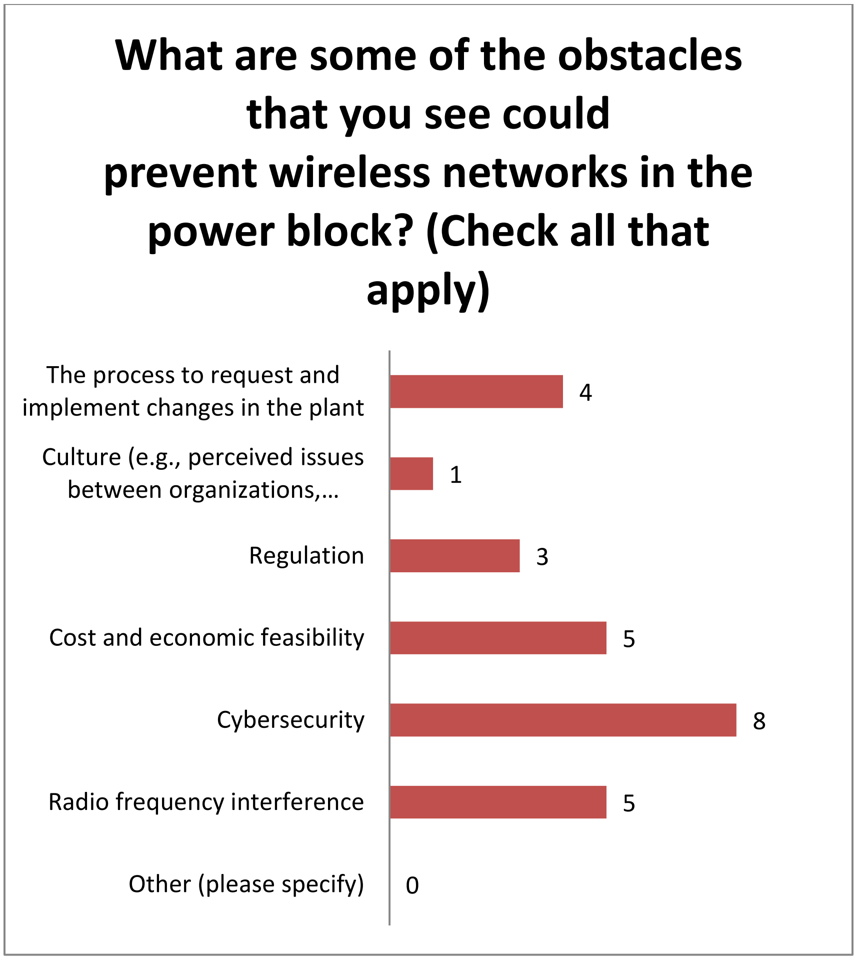
- Yes because..
  - if your request fits their regulatory and security requirements
  - They are knowledgeable and like technology
- No because...
  - It is always work to implement new technologies. Semi-rigorous processes to enable changes including concerns over support.
  - I don't have experience in that area.
  - Cyber security issues
  - review process cumbersome
  - regulations, they cite and/or they generally do not understand what is needed
  - IT department far behind times; generally lacks understanding of their impact on business.
  - they don't care if the project succeeds. They only care about security and feel it is the only thing that matters.

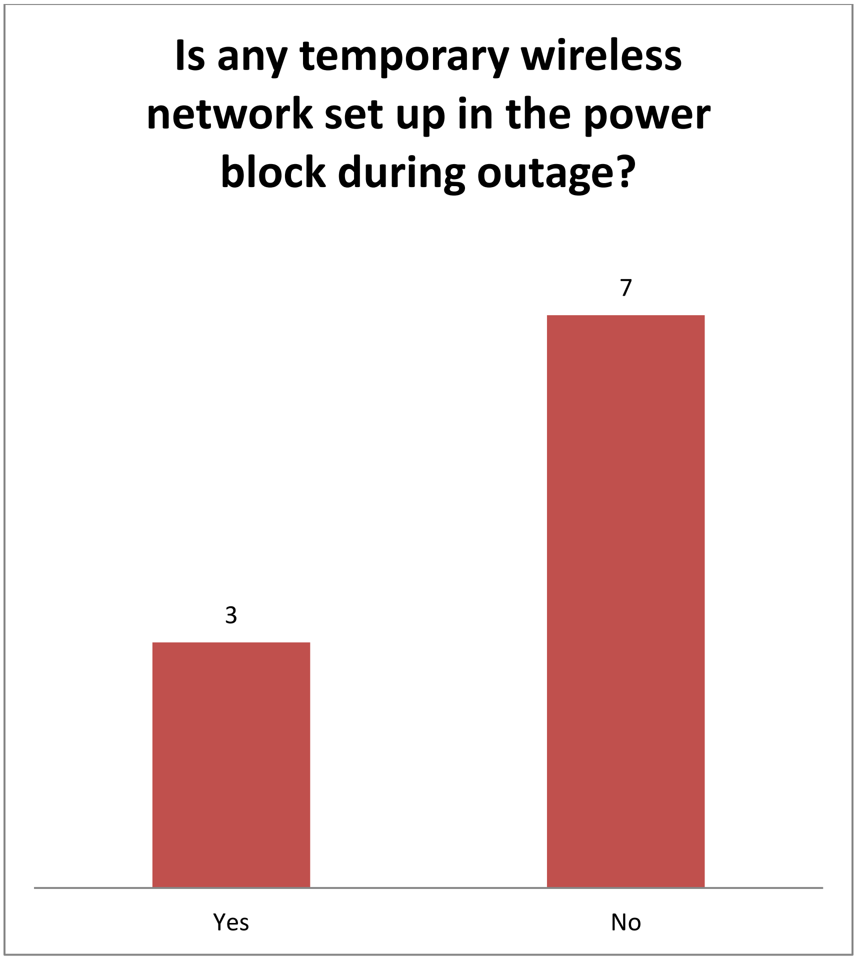
Appendix C
Survey Results for Utility Participants Only

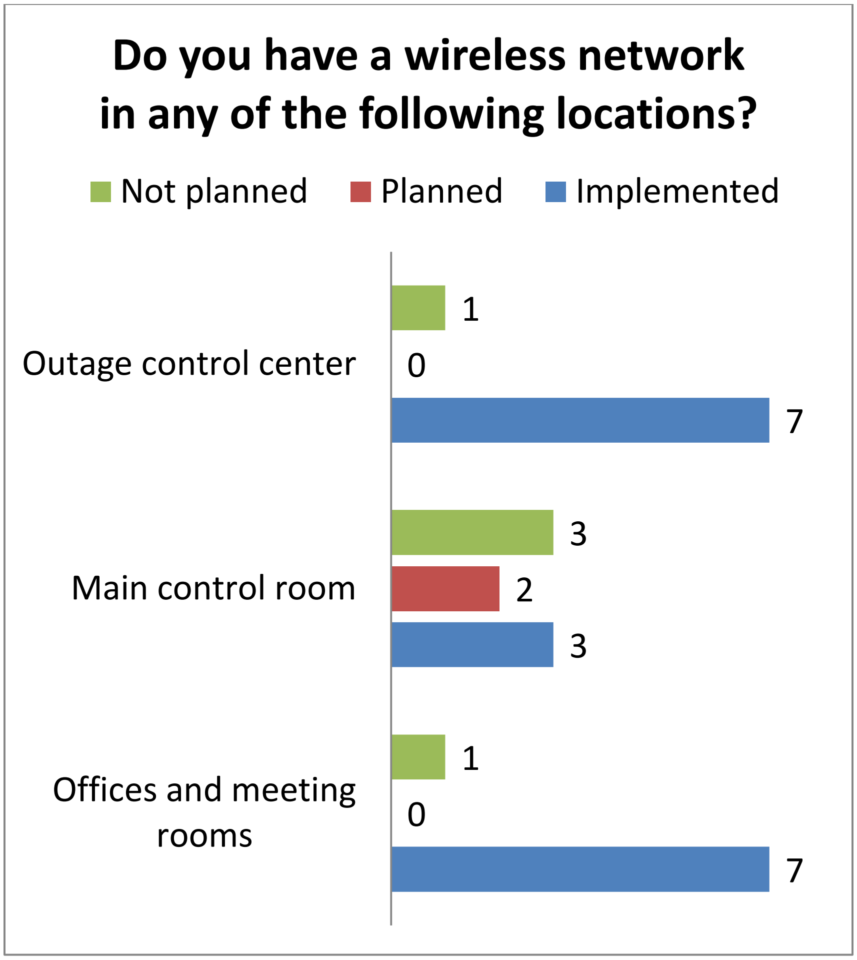
Only charts where the result changed when the vendor was removed are included in this appendix.

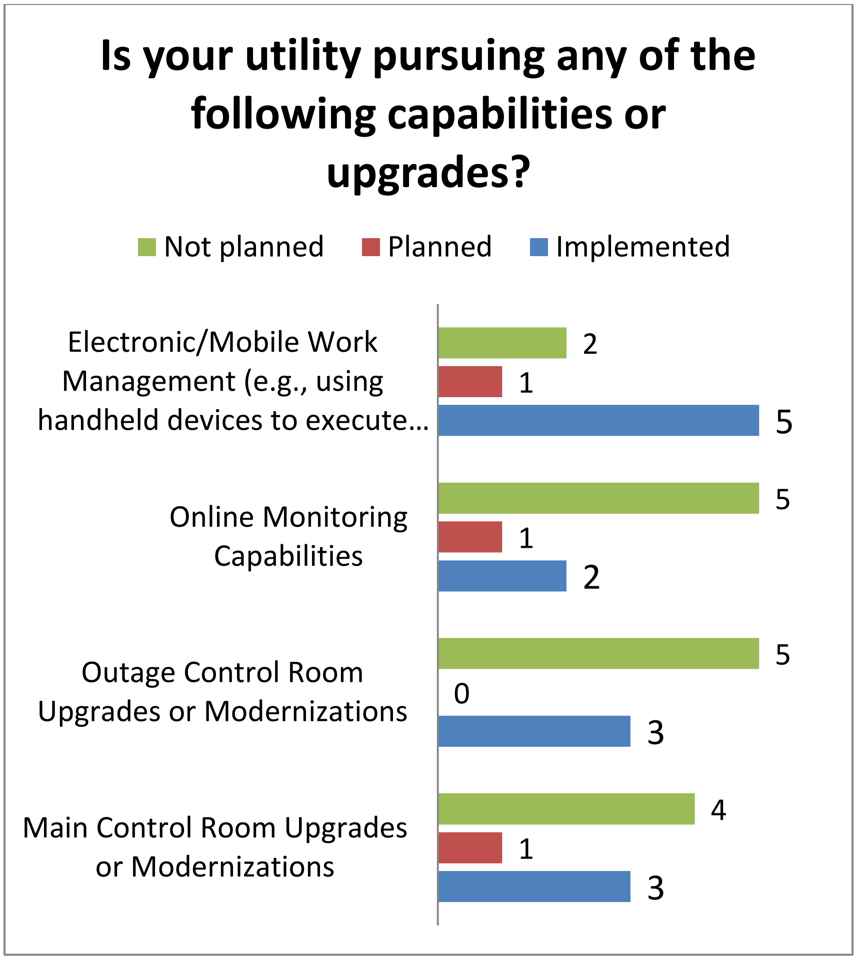


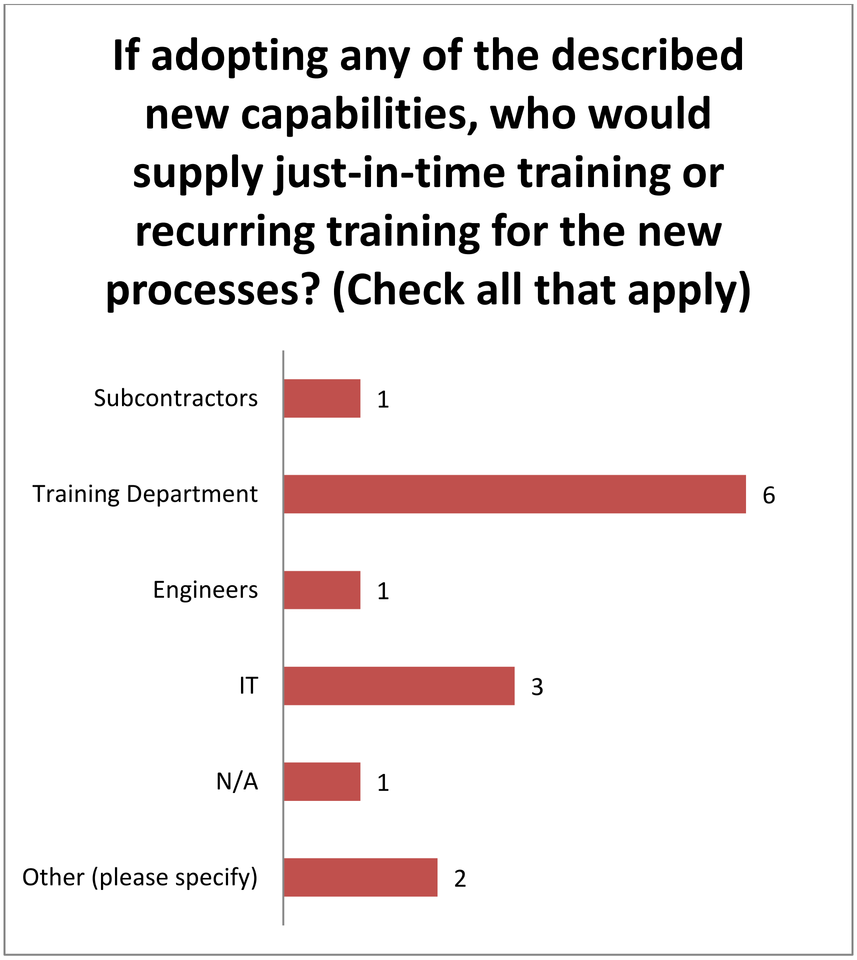

Have any of the wireless network options been installed, or will they be installed in power blocks operated by your utility?
7
5
Yes
No


What are some of the obstacles that you see could prevent wireless networks in the power block? (Check all that apply)
The process to request and implement changes in the plant
4
Culture (e.g., perceived issues between organizations,...
1
Regulation
3
Cost and economic feasibility
5
Cybersecurity
8
Radio frequency interference
5
Other (please specify)
0


Is any temporary wireless network set up in the power block during outage?
7
3
Yes
No

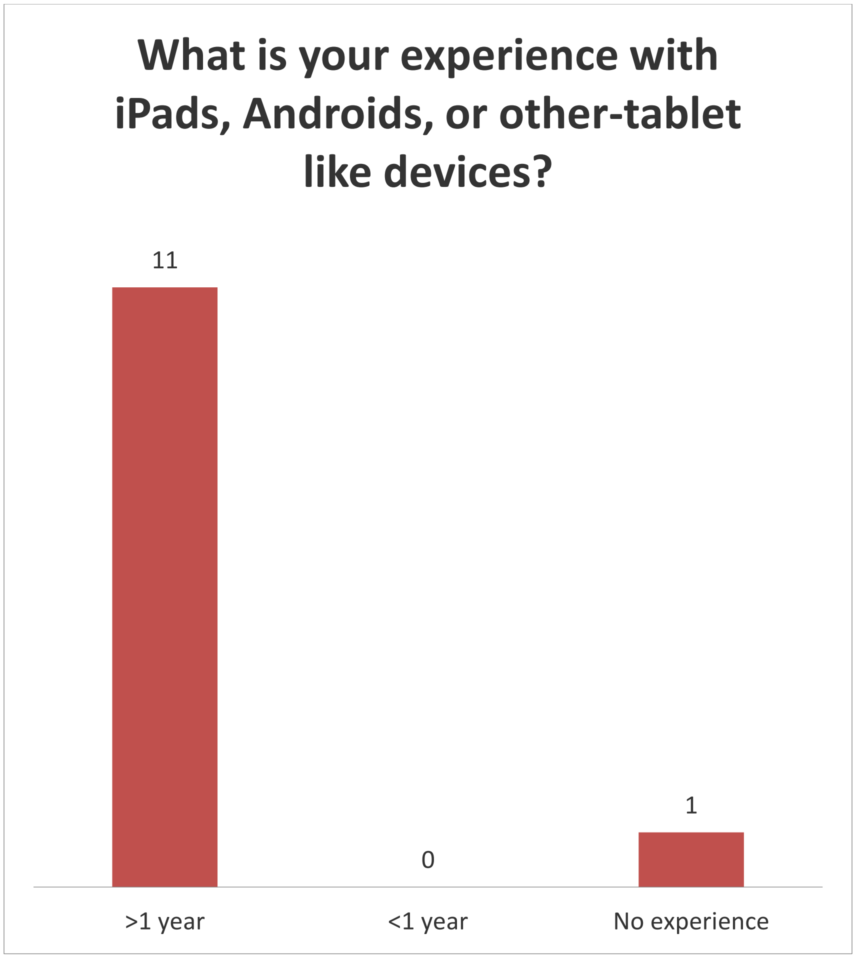

Do you have a wireless network
in any of the following locations?
Not planned
Planned
Implemented
Outage control center
1
0
7
Main control room
3
2
3
Offices and meeting rooms
1
0
7

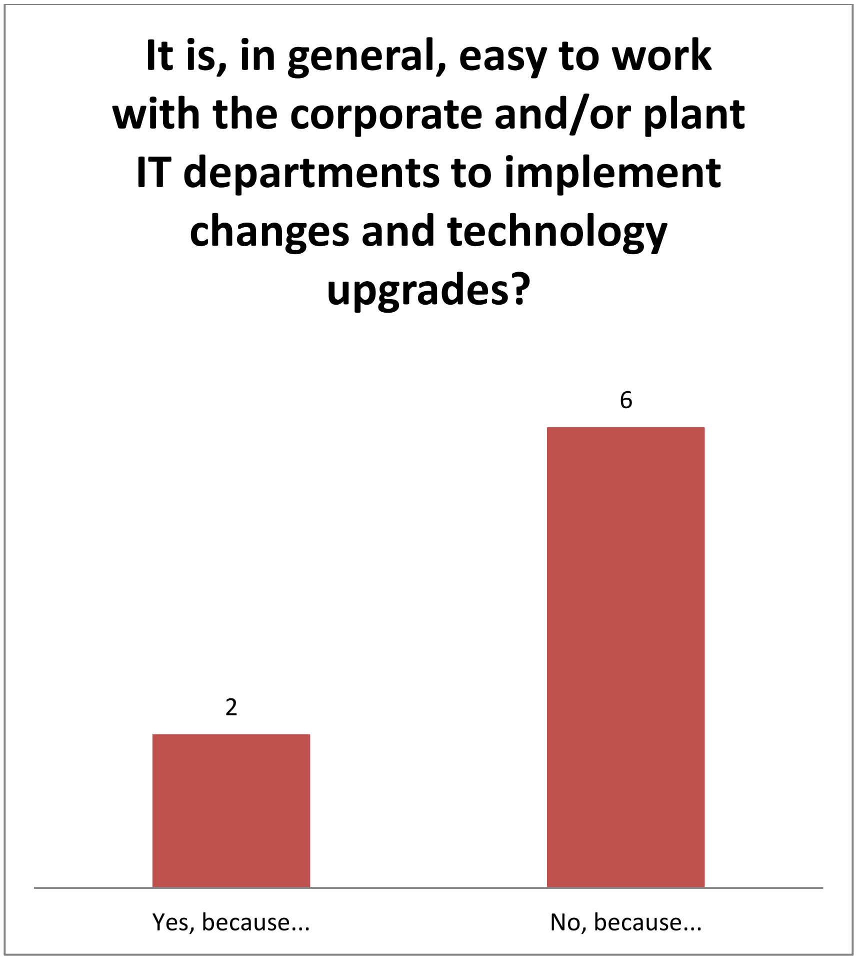

Is your utility pursuing any of the following capabilities or upgrades?
Not planned
Planned
Implemented
Electronic/Mobile Work Management (e.g., using handheld devices to execute...
2
1
5
Online Monitoring Capabilities
5
1
2
Outage Control Room Upgrades or Modernizations
5
0
3
Main Control Room Upgrades or Modernizations
4
1
3



Other:

- Maintenance for electronic work packages
- Note this would probably not be considered formal capital-T training.


What is your experience with iPads, Androids, or other-tablet like devices?
11
0
1
>1 year
<1 year
No experience


It is, in general, easy to work with the corporate and/or plant IT departments to implement changes and technology upgrades?
6
2
Yes, because...
No, because...