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Navigating the Future Control Room: Trends, Challenges, and Opportunities

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ABSTRACT

The energy system is undergoing significant changes and is expected to continue to evolve. Energy demand is anticipated to increase, as is renewable energy capacity, and technical solutions are advancing. For electrical power, traditionally centralized production is increasingly complemented by distributed production, transforming fundamental system functionality. These developing factors will affect both the power generation and the electric power control systems, which are supervised and run by human operators with support from various technical systems. The purpose of this paper is to present trends in the nuclear power and electric power control room systems as well as possible effects on the human technology organization (HTO) system. Semi-structured interviews were performed with 16 people having various types of expertise linked to process control. The results indicated that in the future there are many possible new technologies and support systems that would affect nuclear power plant - and transmission grid operators in their daily work and the organizations they belong to. With a digitalized control room with higher level of automation, remote operations were pointed out as a path forward. However, cyber-security issues were raised as a challenge. Furthermore, small modular reactors were mentioned to be safer and more efficient but raised many questions regarding organizational changes and operator activity levels. An increasing amount of weather dependent power was predicted to make balancing tasks more complex for transmission grid operators, also affecting the nuclear power plant organizations. To conclude, this study underscores the need for a comprehensive HTO perspective to address evolving roles, safety concerns, and protocols for operator intervention during system failures, necessitating further research in these areas.

Keywords: HTO system, Future, Electric power control systems, Nuclear power control systems

INTRODUCTION

Electricity consumption is projected to grow globally, as indicated by the International Energy Agency (IEA, 2023). This upward trajectory is anticipated to be mirrored in Sweden, driven by the imperative to achieve climate goals and a consequential shift from fossil fuels to electricity. According to an analysis made by the Swedish Energy Agency (2021, 2023), the energy production and need is increasing. The surge in electricity demand is driven by the escalating digitalization of society, the establishment of more data centres, and an impending growth in the transport sector. Moreover, the amount of non-dispatchable solar and wind power is expected to grow (European

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Commission, 2023), increasing the necessity and complexity of balancing the energy system. These changing factors are anticipated to affect the power generation and the electric power control systems respectively that are supervised and run by human operators with support from various technical systems.

Rollenhagen (1997, p. 10) defines Human Technology Organization (HTO) as follows: "Overall, the HTO area can be tentatively defined as a perspective on safety whose purpose is to study how people's physical, psychological and social conditions interacts with different technologies and organizational forms and act based on this knowledge for increased safety." Furthermore, Rollenhagen (1997, p. 14) applies a systems perspective on HTO and states that it is in the interaction between the sub-systems' human-technology-organization factors that are crucial for safety are found. "The interest is mainly in relations between the subsystems human, technology and organization rather than on the subsystems themselves". Furthermore, Karltun et al. (2017) suggests that the HTO concept can facilitate non-ergonomists in understanding how the human in the system affects and is affected by interaction with the technology and organization in a work system. They underline that a focus on the interaction between the HTO subsystems elicits the fact that the whole system becomes more than the sum of its parts.

Many industries, for example oil and gas (Andersen & Johnson, 2006) and drilling (Lauche et al., 2009), have transformed into centralized, remote-control centres, and with increasing levels of automation. As described by Bainbridge (1983), undesirable automation irones risk to occur when introducing automation in a human-machine system, such as out of the loop problems, loss of operator skills, and automation distrust- or over. trust. Transmission System Operators (TSOs) bear the responsibility of overseeing and managing high-voltage electricity transmission infrastructure within a given geographic area or region. Their primary functions encompass ensuring secure, reliable, and efficient operation of the electrical grid. They are thus responsible for transmitting the energy produced by different energy producers, such as nuclear power plants. The operational control centres of nuclear power facilities and transmission system operations exhibit a certain degree of operational autonomy; however, they are subject to mutual influence and external variables. Notably, control rooms within nuclear power plants display varying degrees of digitalization, with a notable prevalence of analogue components. In contrast, the control rooms of TSOs have undergone a comprehensive process of digitalization. The hierarchical configurations of roles within these control rooms are meticulously defined, and operational teams operate in a rotational shift pattern. A profound comprehension of both the facility and energy processes is widely acknowledged as crucial within this operational context. As renewable energy capacity and technical solutions are advancing and the system complexity increases, it is of great importance that the future HTO system within energy production and transmission is understood, and accordingly that the control room operators have sufficient levels of situational awareness. The present study investigates and describes the future challenges and opportunities on a holistic HTO system level as described by domain experts. The purpose of this paper is thus to present visons and trends in the nuclear power and electric power control room systems and their effects on the HTO system, according to researchers, human factors specialists, suppliers, and operators.

METHOD

A semi-structured interview study was conducted with 16 people from academia, industry, and operation working in the Nordic countries, such as human factors researchers, human factors specialists, suppliers, and operators (Table 1). Their expertise was linked to process control in nuclear power plants and electrical power systems respectively. Apart from one participant, all interviewees had ten or more years of experience. Four of the interviewees had more than 20 years of experience. Seven of the interviewees had practical experience working as operators. To form a diverse participant group for the interview study, a snowballing effect was initiated through the utilization of established contacts. Furthermore, interviews were conducted with individuals suggested to contact, resulting in a varied participant group. The interviews were performed online and took about one hour. The questions asked concerned the interviewees perspectives on the future control room systems, including what technical trends they predicted regarding the future, and their effects on the human, and the organization. The interviews were transcribed, and thematically analysed. Statements and reflections about control room trends, visions, challenges, and opportunities, as well as effects on the humans and the organizations in the whole HTO system were included in the analysis.

Table 1. The interviewees' roles, domain, years of experience, country of work and whether they had experience of working as an operator.

Role / Domain	Years of Experience	Previously Operator	Country
Human Factors Specialist / NPP	18 years		Sweden
Human Factors Specialist / NPP	10 years		Sweden
Human Factors Specialist / NPP	1 year		Sweden
Human Factors Specialist / NPP	15 years		Finland
Human Factors Specialist / NPP	10 years		Finland
Human Factors Specialist / Mixed	10 years		Sweden
Human Factors Researcher / NPP	18 years		Finland
Human Factors Researcher / NPP	25 years		Norway
Simulator Instructor / NPP	14 years	x	Sweden
Operational Manager / NPP	28 years	x	Sweden
Engineer on Duty / TSO	12 years	x	Sweden
Organizational Developer / NPP	34 years	x	Sweden
Strategic Advisor / TSO	25 years	x	Sweden
Customer Experience / Mixed	10 years		Sweden
Shift Technical Advisor / NPP	17 years	x	Sweden
Power System Analyst / TSO	10 years	x	Sweden

RESULTS

The findings from the interviews suggested numerous potential advancements in the HTO system including nuclear power plants and transmission grids, but also challenges and opportunities. The interviewees primarily originated their discussions from technology trends, and reviewed how the projected technological developments could or should affect the human and/or the organization, and the result is categorized accordingly.

Table 2. Primary themes and their corresponding sub systems within the HTO system, as identified by the insights shared by the interviewees.

Theme	Technology	Human	Organization
Automation	Artificial intelligence	IT & facility skills	Simultaneous processes
	Decision supports	Decision making timeframe	Remote operations
	Optimization		Maintenance role
	Error identification	Activity Level	Centralization
	Small Modular Reactors	System trust	Decision making whereabouts
Digitalization	Back-up System	Interpretation	Data maintenance
	'Digitalized' knowledge	Decision making	Workplace attractiveness
	Data & visualizations	IT & facility skills	Control room teamwork
Balancing & Regulating power	Techn. limitations	Observability	Maintenance role
	Support systems	Operator tasks	Inter-organizational teamwork

Theme 1: Automation

This theme explores the impact of automation, machine learning, and artificial intelligence in nuclear power and transmission grid domains. The professionals discussed challenges such as heightened complexity and centralization, along with divergent views on the adaptability of AI. The shift from active to passive operator roles is said to be executed for partly economic reasons, raising questions about skill retention and increased importance of IT proficiency. Centralization trends were highlighted, predicting a control centre model with experts monitoring various processes. Also, the role of maintenance gains prominence in a system leaning heavily on automation, amplifying the responsibility of technology.

Automation in Transmission Grid Operations

One of the principal technological advancements highlighted by the professionals in both the nuclear power and transmission grid domains pertained the integration of automation, machine learning, and artificial intelligence. Automation within the transmission grid was identified as a tough challenge, contingent upon heightened complexity, centralization, and the proliferation of data. One interviewee working with transmission grid operations expressed scepticism regarding the feasibility of artificial intelligence comprehending the intricate energy system, attributing this scepticism to the inherent complexity and the unpredictable trajectory of future developments. Conversely, another interviewee working for a supplier organization, with a mixed domain presented a more optimistic approach, postulating that the forthcoming energy landscape could evolve into a fully autonomous system seamlessly interwoven with production, transaction, consumption, and market dynamics. Two interviewees working within transmission grid operations, brought up that more and more tasks had become automated, such as balancing tasks, and anticipated that this trend would persist in that trajectory. These two had positive attitudes toward automation, seeing a need to get better tools in a system becoming more complex and less predictable. They also revealed that the operators often individually analyse incoming data, and when the operators have different views on the situation, they have short meetings, discussing with each other to find the best decision. In the future, interviewees hoped for more decision support tools, removing the insecurity and risk of different views. However, out of the loop issues were also raised, in a future with a higher level of automation, and the need for strategies to take over the control when needed.

Automation in Nuclear Power Plant Operations

One of the most frequently discussed technological advancements by interviewees working in the nuclear power domain was the advent of Small Modular Reactors (SMRs). This was identified by ten interviewees as a pivotal component of future energy production. SMRs are designed with an emphasis on enhanced safety features and reduced operator interventions. Speculations abound regarding the profound impact SMRs could have, particularly at the organizational level and in reshaping human tasks. Should SMRs become reality, the envisaged trajectory involves the implementation of multi-unit control rooms, where a single operator oversees multiple simultaneous processes. Concerns were raised regarding how many units one operator can monitor, especially during disturbances. Within the nuclear power domain, characterized by its critical emphasis on safety, the discourse centred around the integration of passive nuclear safety measures. Passive safety systems, reliant on inherent physical phenomena such as gravity, natural circulation, or intrinsic material properties, obviate the necessity for active intervention or electronic feedback, thereby assigning tasks to automated processes rather than to human operators.

Artificial Intelligence

In the context of an envisioned future system predominantly grounded in artificial intelligence, interviewees contended that the decision support mechanisms could be enhanced. Another perspective suggested that the primary role of artificial intelligence in the power system lies not in decision support, but rather in the validation of signal faults and the optimization of facility operations.

Five of the interviewees with human factors background working within the nuclear domain specifically mentioned artificial intelligence and machine learning to be part of the future control room system within nuclear power. Another interviewee, with experience from a mixture of domains, thought and hoped that nuclear power would be the last domain to use artificial intelligence as support systems, due to its safety critical nature. One interviewee within transmission system operations was highly negative to artificial intelligence and automation, due to the system complexity, and could not imagine how an AI could manage the complex tasks.

Automation Turning a Shift Towards Simultaneous Processes

Anticipating the increasing energy demand and higher level of automation, five interviewees within different domains and with different roles, suggested a future scenario wherein diverse energy processes, including nuclear, hydropower, and coal plants, would be centrally controlled. This centralization was perceived as a consequence of the escalating levels of automation.

Human Affected by Automation-Activity Level and Skills

The development of automation was stated to partly be due to economic considerations, prompting a shift in the operator's role from active engagement to a more passive observational stance. This transformation was said to influence the degree of operator activity, with reduced engagement, potentially extending the time required for the operator to comprehend situations necessitating intervention or decisions imposed by the system. Eleven interviewees in diverse roles and domains, reflected that a heightened automation level could make the human into an observer rather than the active operator. The interviewees raised challenges such as how to solve tough and stressed situations, when being a passive observer most of the time. In practice it could mean that the operator must monitor the automation and then determine if the automation is faulty or not. Nevertheless, advocates of heightened automation contend that advanced safety systems afford operators additional time to assess situations before acting or making decisions. Also, potential trust issues were raised; the operators must consider whether they trust the automated system. If the facility experiences power outage, the organization must have continuity to go back to the manual tasks. Thus, it was stressed by several interviewees that there will be situations when the system does not work.

Concerns were raised by six interviewees about potential challenges to the preservation of skills and knowledge in a system reliant on automation. This underscores the necessity for operators to in the future cultivate their skills in comprehending IT systems, enhance analytical capabilities, and optimize operational processes. It was also stated that operators must enhance their training for scenarios where the automation malfunctions, requiring the operator to assume control. Notably, one interviewee emphasized the imperative for 'digitalizing knowledge', drawing parallels with similar practices in other control room domains, such as oil and gas, from which they had prior experience. The interviewee elaborated that digitalized knowledge could be better tools or instructions in digitalized environments, rather than paper-based instructions and knowledge about the facility. Furthermore, if the operator must monitor several different processes, it is not reasonable for one operator to have all the knowledge needed for every single process, thereby pressing the need for more support systems, in contrast to today's operators extensive understanding of the complete facility they control. Also, today in nuclear power plants, most operators ascend through the ranks, from technicians at the facility to operators in the control room. One dominant effect on automation, explored by five interviewees within the nuclear power domain, could be in what way the operators gain their knowledge, and what knowledge they might have difficulties gaining. If having to monitor many processes, their role could change to monitoring the IT system rather than the actual process.

Organization Affected by Automation-Centralization

To centralize the control of different processes has become the natural consequence of a higher level of automation in domains such as pulp and paper and mining, due to remote monitoring and control. If the energy system could have a higher level of automation, centralization was mentioned by eight interviewees as a likely consequence. The interviewees described that if the operator becomes more passive and rarely make decisions, the decisions could be moved to an expert control centre, in which the more intricate decisions will be made. One interviewee speculated that if the power generating companies are highly automated and remote, the control of the power generation could be sold to the power grid owner. The consequence would be that the grid owner controls all power production, which would change the whole energy market.

Organization Affected by Automation-the Maintenance Role

Five interviewees speculated that in a system where more responsibility is laid on the automation, the reliance on the technology will increase, which in turn will make the relative importance of maintenance larger. It was also mentioned that in an automated system, operators and maintenance personnel can be provided with information in advance if a component might break, i.e. before it happens.

Theme 2: Digitalization and Data Providing Tools

The imminent future of nuclear power control rooms is anticipated to witness a transition towards digitalized systems with display-based interfaces. Modern control rooms exhibit a greater prevalence of digital interfaces compared to their older counterparts. Despite this, the retention of analogue backup systems is deemed necessary to address potential power outages, demanding a fallback to conventional systems. In the context of the conservative and safety-critical nature of the nuclear power industry, interviewees underscored that the primary attributes facilitating adoption are not aesthetically appealing interfaces but rather licensure and operational efficacy. This contributes to the gradual pace of technological advancement.

The control room of the transmission grid was reported to be more digitally oriented already. Two interviewees within transmission grid operations stated that new tools are introduced rather often and fast, making it difficult to accommodate these technological changes in routines and other parts of the HTO system. As the amount of non-dispatchable energy increases, it was mentioned that the energy loads are expected to be less predictable, and more flexible towards energy consumption. More tools helping operators to understand what is to happen in the next hour or even minutes will therefore be needed for TSOs.

The biggest challenge to overcome would however be cyber security – how to keep the power grid and nuclear power plant free from intruders. Being safety critical domains, this issue is currently yet to be overcome.

Human Affected by Digitalization

With a digital interface, seven interviewees within nuclear power declared that much more information could be provided to the operator. Interviewees in different domains also declared that more data could be helpful in decision making, since there would be more information to ground decisions on. However, interviewees raised issues regarding potential information overload. In scenarios involving small modular reactors with extensive passive safety systems and digital interfaces, the emphasis shifts from detailed information to the operational status of safety systems, interviewees said. The advent of future digital control systems necessitates an elevation in IT skills among operators.

Two interviewees mentioned 'gaming skills' to potentially be beneficial in the future. Additionally, the appeal of digital control rooms was posited to be higher for younger operators, who are more adept at computer-based work, as opposed to their older counterparts accustomed to legacy systems.

Organization Affected by Digitalization

One Human Factors specialist explored on that a shift to digital control sometimes diminishes the ease of common overviews, compared to analogue counterparts, potentially compromising the overall situational awareness. In shutdown scenarios, it was suggested that senior operators may find it more unproblematic to revert to traditional backup systems due to their familiarity, whereas junior operators lacking experience with legacy systems may encounter challenges in doing so.

Theme 3: Balancing and Regulating Power

Due to a higher penetration of solar and wind power, greater complexity, and necessity of balancing the power system was mentioned to influence primarily transmission grid organizations, but also nuclear power plant organizations. Eight interviewees stated that balancing, or power regulating tasks, already have been affected, and probably will continue to develop, as solar and wind power increases.

Human Affected by More Balancing Tasks

It was discussed by three interviewees that the balancing tasks are becoming more complex for TSOs, and already have been more automated, and it was anticipated that it will continue to evolve.

In Sweden, nuclear power has traditionally served as the primary source of base load power, complemented by using hydropower to fine-tune the balance between power supply and demand. However, six interviewees mentioned there has been instances where nuclear power plants have taken on the role of regulating power output. This emerging trend was anticipated to undergo further developments. According to the interviewees, this shift is not expected to significantly impact operator tasks; instead, it is likely to alter the relative importance of maintenance activities. Operators will need to acquire the necessary skills to safely regulate power downward, since the facilities are not often originally designed for such regulatory functions.

Organization Affected by Balancing Tasks-Teamwork and Maintenance

A less predictable energy system compels greater flexibility. The heightened demand for balancing tasks within the transmission grid places an increased emphasis on inter-organizational collaboration. This necessitates enhanced teamwork among various TSOs and fosters a closer connection between TSOs and regional transmission operator organizations. Five interviewees discussed that historically, the maintenance has been and is scheduled regularly on a timely base, since the power plants have been run in a more predictable way. But as the energy production and distribution might be operated more flexibly in the future, i.e., in a way that is not optimal for the facility, the timely schedules may not be applicable. Planning and managing maintenance tasks may have to be reconsidered, as the maintenance's relationship to organization together with operation is predicted to change due to dynamic management of operations and production.

DISCUSSION

The HTO framework within complex systems, notably within the energy sector, manifests a high degree of intricacy. Interactions among its subsystems - comprising humans, technology, and organizational structures - are multifaceted and further complicated by external influences such as political, social, and economic factors. This study presents how experts within the process control system domains nuclear and electric power describe and reason about the future and its challenges, seen from a HTO perspective.

Advancements in technology, exemplified by innovations like SMRs, digitalization and data visualizations, coupled with increasing energy demand and production, herald a potential for automation and the use of artificial intelligence. However, the challenges accompanying automation echo concerns articulated as early as Bainbridge's seminal work in 1983, cautioning about negative side-effects of automation. Nonetheless, such benefits center upon the presumption that the presented information is not only pertinent but also comprehensible and accessible. Conversely, an overwhelming amount of information hampers overview and might obscure relevant cues. Too much data competing about space in the operator's working memory could contribute to worsened operator situational awareness. Some of the interviewees expressed the need for better decision support systems to understand the possible increase of data. This pinpoints future needs of not more information per se, but rather technical supports that do not require the operators to interpret data. Hence, the interpretation can be different among the operators, and it is of great importance that all individuals in the control room team are comfortable enough to raise their opinion or interpretation. Having a support system that all trust benefits team dynamics.

The course toward heightened automation signifies a shift towards centralized control centers, driven by economic imperatives, with effects extending across organizational structures, operational dynamics, skill requirements, and workforce composition. Many of the interviewees seem to believe that a higher level of automation is the future. Nevertheless, opposing voices persist. Notably, individuals closely associated with, or operating within, control room environments exhibit skepticism towards fully automated systems, perhaps due to hesitations concerning system complexity, and fears of labor displacement. Regardless of disciplinary domain or occupational role, the interviewees converge on the observation that the energy sector, particularly the control room domain, embodies a conservative ethos prioritizing safety above all else. Consequently, while divergent attitudes and strategies may prevail concerning the attainment of a secure energy infrastructure, a unanimous acknowledgment of safety's paramount importance unites stakeholders. Given the march of technological progress and escalating energy production imperatives, a holistic understanding of the evolving HTO system becomes imperative to ensure the fulfilment of future energy needs in a manner that upholds safety standards.

CONCLUSION

In conclusion, the exploration of the automation's impact on nuclear power and transmission grid domains reveals a dynamic landscape shaped by technological advancements and evolving industry paradigms. The integration of automation, machine learning, and artificial intelligence emerges as a pivotal force, driving changes in operational roles, system centralization, and the overall human-machine interface. In transmission grid operations, the challenges posed by increased complexity and scepticism about AI's ability to comprehend intricate energy systems are contrasted by optimistic views envisioning a seamlessly interconnected autonomous energy landscape. The transformation of operators into passive observers prompts considerations about trust issues, and the ability to revert to manual tasks during system failures. Centralization emerges as a natural consequence of higher automation levels, with experts envisioning expert control centres making critical decisions.

The interview data indicated probable changes in parts of the HTO system and underscored the importance of analysing and understanding the development with a holistic approach, for instance, through the adoption of an HTO perspective and consideration of system aspects. This can be carried out at various levels, e.g., individual facility, energy system, as well as the broader society of which the energy system is a crucial part. This is necessary for effectively addressing both efficiency aspects and safety and security concerns.

Consistent with this, it would be valuable to conduct further research on what information is possible and relevant to have in a future remote control-centre. Additionally, contextualized enquiries into how operators' system understanding is shaped by education and experience, and how it interacts with the information that operators demand, are needed in this evolving domain. Also, further investigations are needed to elicit how safety aspects are affected given the presented changes, with help from existing theories on for example HTO, risk and safety, situation awareness and human cognition and decision making. Finally, more research is required to understand when and how the operators must reclaim the control when the automated system fails.

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