Thesis for The Degree of Licentiate of Engineering

Being in Control

Exploring the Impact of Electric Power System Changes on Control Room Operator Work

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Gothenburg, Sweden, 2025

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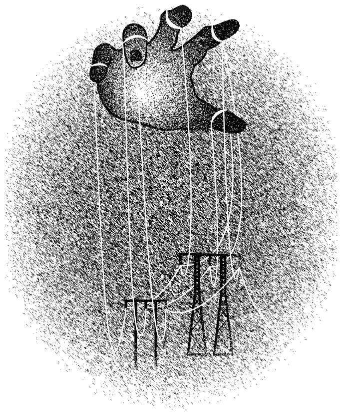

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Cover:
Illustration of a human hand with power lines wrapped around its fingers, resembling the strings of a marionette. The hand appears to control the power lines, as if directing them like a puppet on strings. This illustration and the illustrations in this thesis, are made by Signe Svensson.

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Abstract

Electricity demand is projected to increase globally, affecting both the power generation and the electric power control systems, which are supervised and run by operators with support from various technical systems. This licentiate holistically explores and describes how the work of control room operators is affected by electric power system changes anticipated by domain experts, with a particular focus on the transmission system operator domain. The research employs semi-structured interview and questionnaire studies and uses the Socio-Technical framework of Leavitt's system model as an analytical tool. Results indicate that the volatile system has shifted tasks from monitoring to action, yet automation is expected to make operator tasks more passive, leading to challenges during system failures. Higher degrees of automation align with the expressed needs among operators working in the transmission system operator domain, due to the electric power system's complexity, but historical tool introduction and the industry's conservative mind-set creates uncertainty about new systems' effectiveness. Operators must maintain facility knowledge and understand automated systems to make informed decisions, despite potential skill shifts towards bug fixing and algorithm understanding. Recurrent training is necessary to handle system failures and maintain manual operation capabilities, with increased IT competence required due to rising disturbances. As manual tasks decrease, new roles may emerge, and organisational structures must evolve to support these changes, including developing new IT departments and tailored training programs. This licentiate thesis advocates for a comprehensive design of the entire control room system to ensure stability and safety, and calls for an investigation into the transparency of automated systems. The thesis explores the potential future roles of operators working in control room systems, focusing on how they can continue **being in control** while interacting with automation in dynamic environments. To conclude, as automation and digitalisation increase, the roles of control room system operators must be redefined to match the system development. This involves confidence in their ability to intervene, continuous training, and effective human-machine collaboration. Organisations need to adapt by developing new IT departments, tailored training programs, and support systems to ensure operators' psychological well-being and adaptability.

Keywords

Socio-Technical System, Control Room System, Automation, Human Factors

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper A**] **S. Svensson**, A-L. Osvalder, J. Borell, *Navigating the Future Control Room: Trends, Challenges, and Opportunities*
In: Tareq Ahram (eds) Human Factors in Software and Systems Engineering. AHFE (2024) International Conference.(July 2024), vol 140.

[**Paper B**] **S. Svensson**, J. Borell, A-L. Osvalder, *Anticipated Impacts of Current Electric Power System Trends on Operator Conditions and Roles. Manuscript submitted to a scientific journal.*

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Other publications

The following publications were published during my PhD studies. However, they are not appended to this thesis, due to contents overlapping that of appended publications or contents not related to the thesis.

[**a**] **S. Svensson**, A-L. Osvalder, J. Borell, *Teamwork in the Future Control Room*
Poster in: Annual Meeting of Human Factors and Ergonomics Society (HFES). Europe Chapter (April 2024).

[**b**] **S. Svensson**, A-L. Osvalder, J. Borell, *Future scenarios for power control room systems*
Poster in: Annual Meeting of Human Factors and Ergonomics Society (HFES). Europe Chapter (April 2025).

Author Contributions

- **Paper A** SS and ALO designed the study. SS collected the data. SS analysed the data. SS wrote the original drafts. All authors reviewed, edited, and approved the final version of the manuscript.
- **Paper B** SS, JB and ALO designed the study. SS collected the data. JB and SS analysed the data. SS wrote the original drafts. All authors reviewed, edited, and approved the final version of the manuscript.

Abbreviations and Definitions

- **EPS:** Electric Power System
  An EPS is a network designed to generate, transmit, and distribute electrical energy from power sources to consumers and incorporates various components such as power plants that convert primary energy sources into electricity.

- **CRS:** Control Room System
  CRSs are Socio-Technical Systems and operates as open entities interacting with their environment, where mutually interdependent elements, the technological subsystems, the personnel and the organisational subsystems, interact with one another and the external environment to jointly transform inputs into outputs

- **TSO:** Transmission System Operator
  The TSO is an ***organisation*** *responsible for ensuring grid stability by overseeing and managing high-voltage electricity grids within a specific geographic area (often a whole country). In the TSO's control room, human operators are responsible for real-time control, planning, and maintenance of the high-voltage grid.*

- **DSO:** Distribution System Operator
  The DSO is typically an ***organisation*** *responsible for operating and maintaining the medium- and low-voltage electricity grids within a specific geographic area. In the DSO's control room, human operators are responsible for real-time control, planning, and maintenance of the medium- and low-voltage grids.*

- **HPP:** Hydro Power Plant

- **NPP:** Nuclear Power Plant

- **SMR:** Small Modular Reactor

- **HTO:** Human-Technology-Organisation
  HTO is an approach where the purpose is to study how people's physical, psychological and social conditions interact with different technologies and organisational forms and act based on this knowledge for increased safety.

Preface

This work was carried out at Division Design & Human Factors, Department of Industrial & Materials Science, Chalmers University of Technology between August 2023 and May 2025. The research was conducted within the project *The Future Control Room for Sustainable Power Systems (No: P2022-00177)*, funded by The Swedish Energy Agency.

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Firstly, I would like to thank my main supervisor, Professor Anna-Lisa Osvalder, for your guidance, support, and insights throughout the research process. I am truly thankful for the opportunity to learn under your mentorship and for all the enriching experiences we have shared through writing sessions, conferences, and various other events. Furthermore, I'd like to thank my co-supervisor, PhD Jonas Borell, for your engagement, curiosity, and valuable feedback throughout this work. I always feel encouraged and inspired after our meetings. I would also like to thank my examiner, Professor MariAnne Karlsson, for providing important perspectives to the research and comments to this thesis.

Many thanks go to my project partners at The Royal Institute of Technology (KTH) for valuable discussions throughout the project. I especially want to thank Professor Lars Nordström for your guidance in reviewing and describing the power system engineering content, particularly during the writing of this thesis. I would like to express my gratitude to both of my research schools: Human-Technology-Design and Graduate School in Energy Systems. These two academic environments have offered valuable and complementary perspectives that have enriched my PhD journey. To my fellow PhD students in the Graduate School in Energy Systems, spread across Sweden: thank you for the engaging discussions, diverse viewpoints, and the memorable travels we have shared. Furthermore, I want to extend my appreciation to my colleagues at Chalmers, for the enjoyable times both in and outside the office. Special thanks to my 'roommate', unofficial mentor, travel companion, and discussion partner, Melina Makris. Without your support, insights, and sense of humour, this journey would have been only half as fun.

This research would not have been possible without the valuable contributions of its participants. I extend my heartfelt thanks to everyone I interviewed and to those who completed the questionnaire. Your time, insights, and engagement are deeply appreciated.

I am also grateful to my friends and family for your support and love. Last but not least, Olof, thank you for your encouragement. With you, I get to experience an exciting life (beyond the university), which keeps me grounded, safe, and reminds me of what is important in life.

Gothenburg, May 2025
Signe Svensson

Contents

Chapter 1

Introduction

The Electric Power System (EPS) is in change. Electricity consumption is projected to grow globally, the number of power producers is increasing, and renewable energy sources such as solar and wind power are accelerating to meet the new demand and reduce dependence on fossil fuels [1].

An EPS is a network designed to generate, transmit, and distribute electrical energy from power sources to consumers. This system incorporates various components such as power plants that convert primary energy sources into electricity. The transmission network carries electricity from major producers to regional distribution networks, often spanning entire countries and connecting with other grids. The Transmission System Operator (TSO) is an organisation responsible for overseeing and managing high-voltage electricity transmission infrastructure within a specific geographic area or region. Their primary duties include ensuring the secure, reliable, and efficient operation of the electrical grid. TSOs are tasked with transmitting energy produced by various sources, e.g., Nuclear Power Plants (NPPs) and Hydro Power Plants (HPPs). TSOs are thus responsible for the grid and transmitting the power, but have no influence on- or responsibility over power producers or power consumers [2]. These different organisations (i.e., power producers and TSOs) have different roles in the EPS, but as parts of the same system, changes in one part affect the other [3].

Furthermore, behind the processes of producing, regulating, and transmitting power to consumers are operators, working in their respective Control Rooms. These Control Rooms are in this licentiate referred to as Control Room Systems (CRSs), since they can be defined as Socio-Technical **systems** [4] that operate as open entities, interact with their environment, and the mutually interdependent elements - the technology, the personnel, and the organisational subsystems - interact with one another as well as with the external environment. Changes to one element will cause domino effects in the EPS due to the interactions between these elements within the system and the environment. Therefore, single elements cannot be considered in isolation when designing successful Socio-Technical Systems [5]. Humans, technology, and organisations within each CRS interact and influence each other and their environment.

Consequently, human work and roles are shaped by these interactions and the surrounding context.

The Nordic TSOs are implementing significant changes to improve the efficiency and reliability of the EPS. For instance, the trading and settlement period is changing from 60 to 15 minutes to harmonise the electricity market and provide better conditions for managing variations in the EPS, especially with the increasing amount of weather-dependent electricity production [6]. An example of adjustment to handle the shift to 15-minute settlement and trading periods, is that the manual Frequency Restoration Market (mFRR) is automated, which helps TSOs balance the EPS more effectively and align with European standards [7]. Today, the Nordic TSOs trade the support service mFRR via the Nordic market, often called the balancing power market, and activation is mainly done via telephone. However, with the automation of mFRR, the system can automatically activate reserves when needed to balance the electricity grid. Also, a new calculation method called Flow-Based [8] improves the determination of available transmission capacity in power grids by using a mathematical model to simulate and assess feasible electricity flows in advance. This method allows for a more accurate estimation of which flows can be permitted in the grid. By replacing traditional rule-of-thumb approaches with advanced algorithms and data models, it enables more efficient use of the grid's capacity, helps avoid overloads, and supports the reduction of price differences between electricity areas. This transition is mandated by EU law and affects all market participants.

The EPS is thus a dynamic environment [9], and becoming increasingly so. The rising volatility makes it more difficult to evaluate the future state of the system and prognosis tools must develop to handle this complexity. The higher demand for electricity is expected to be met primarily through the expansion of land-based wind power and solar power, as well as capacity enhancements in hydropower, combined heat and power, and existing nuclear power [1]. With automation being introduced to address this dynamic environment, the work of operators in the TSO domain also becomes more complex, since they need not only to understand the EPS, but also understand and predict how the automated systems will behave under various conditions, leading to a potential difficulty to anticipate the outcomes of automated actions, especially when multiple automated processes interact. Additionally, a more volatile EPS means that conditions can change rapidly and unpredictably. The operators must anticipate these changes and prepare for them. For example, sudden fluctuations in renewable energy sources like wind and solar can create instability, making it challenging to predict their impacts on the grid. Moreover, with higher levels of automation, there is less direct human intervention and operators in the TSO domain must rely on automated systems to handle routine tasks, yet they still need to anticipate potential failures or unexpected events that the automation might not effectively manage. This requires a deep understanding of both the automated systems and the underlying processes. When unexpected events occur, understanding their causes and effects becomes difficult due to the multiple interactions within the system. Operators in the TSO domain need to quickly establish a mental model of the situation to make informed decisions. For instance, if there is a sudden drop in power generation, operators must determine whether it is due to a technical failure, a sudden weather change, or some other cause. In addition, with higher levels of automation, the operators in the TSO domain will have less access to the working field, and will have to create a mental model of the process they are controlling, with even less information available in an automatic system, than when controlling the processes manually. This may lead to a lack of system transparency for operators, making it difficult to comprehend the system states [9].

The EPS changes along with technical developments significantly impact CRS operations. To ensure the system remains safe, stable, and progresses towards a sustainable and resilient EPS, it is crucial to examine the operational effects of these developments. However, much research on operations within TSO often has a technical focus (e.g., [10], [11]) and does not consider how new technology implementations affect the operator work, or investigate the operational implication of trends or technologies in single CRS domains (e.g., [12], [13], [14], [15]).

With the argument that humans, technology, and organisations within each CRS interact and influence each other and their environment, this research adopts a holistic Socio-Technical System perspective, exploring the implications of EPS changes and technical development, across different CRS domains within the same EPS. Furthermore, the individuals with the most profound insights into the current CRS, its evolution, and future expectations are believed to be within the CRS and other domain experts involved in its design. The knowledge and experience of the operators is invaluable in understanding the developments they have experienced, expected to further experience, and their needs. Other domain experts, such as Human Factors specialists, can provide insights into the ergonomic and cognitive aspects of system design, while stakeholders such as control room suppliers contribute their technical expertise and innovation perspectives.

This licentiate thesis therefore investigates how these experts in power production and transmission expect their CRS to develop in the future, and how those trends might influence operators and their organisation across various CRS domains within the EPS, with a particular emphasis on the Socio-Technical System of the TSO domain.

1.1 Aim and Research Questions

This licentiate thesis aims to holistically explore and describe how the work of control room operators is affected by EPS changes anticipated by domain experts, with a particular focus on the TSO domain. Furthermore, directions for future research are suggested. The aim is addressed through the overarching research question: **How is the work of control room operators affected by changes in the EPS predicted by domain experts?**

This overarching question was divided into five research questions, with two different focus. The first two questions are posed with a broad perspective, exploring different future CRS systems in the EPS.

RQ1a: How do CRS experts perceive current trends in CRSs within the EPS domain, and what implications might these trends have for the HTO system? (Paper A)

RQ1b: How do current CRS trends impact the conditions and roles of operators in the future CRS? (Paper B)

After the questions with a broad perspective had been asked, explored, and answered, the focus was narrowed down to focus on the TSO domain, and the following three RQs were posed. The focus on the operator's experience of change, in RQ2a-c, was developed because it was made clear after answering RQ1a-b that interviewees often described the future in terms of the changes they have experienced or are experiencing currently.

RQ2a: How do operators in the TSO domain report their tasks to have changed in the last five years, and how are the tasks expected to continue to develop?

RQ2b: What are the attitudes of operators in the TSO domain towards current tools, the introduction of new tools, and higher levels of automation?

RQ2c: How do operators in the TSO domain perceive the impact of new tools and automation on their tasks, efficiency, and the overall safety and reliability of operations?

1.2 Thesis Outline

This thesis is organised with the following chapters and content:

1. **Introduction** Provides an introduction to the topic, as well as the aim and research questions to be answered.
2. **Frame of References** Presents the frame of reference upon which the research in this thesis is based.
3. **Methodology** Describes the research approach and methodology used to answer the research questions.
4. **Findings** Presents the main empirical results obtained and provides brief answers to each of the research questions.
5. **Synthesis** Concludes and discusses the results and their implications in the format of Leavitt's system model.
6. **Discussion** Discusses empirical considerations and brings forward methodological considerations encountered during the project.
7. **Conclusion** Presents the conclusions.
8. **Future Work** Future Research suggestions are presented.

Chapter 2

Frame of Reference

The introduction emphasised the critical need to comprehend future challenges due to system changes. Consequently, the frame of reference is devoted to describing theories and models related to Socio-Technical System Theory and the interplay between humans and machines in dynamic systems such as the EPS.

2.1 Socio-Technical System Theory

A system is in the simplest of terms defined as a *"regularly interacting or interdependent group of items forming a unified whole"* [16]. The delineation of a system involves establishing its boundaries, entailing determination of which entities are included within the system and which are considered part of the EPS environment [3].

For the public, ecosystems may perhaps be one of the most well-known kinds of systems and is an example of a natural system. Natural systems may not have an apparent objective but their behaviour can be interpreted as purposeful by an observer. Furthermore, there are also so called man-made (or designed) systems, which are designed or constructed with various purposes, achieved by some action performed by or with the system. The parts of a system must be related, otherwise they would be two or more distinct systems [17]. Examples of man-made systems are EPSs and CRSs. In this thesis the CRS can be viewed as a Socio-Technical System [4] comprising people, structures, tasks, and technology, part of the EPS.

Socio-Technical Systems Theory [4] is a branch of General Systems Theory [3] used to examine complex organisational activities, problem-solving, and change. Socio-Technical Systems integrate technical components with human actors, working collaboratively to achieve overarching goals. Because they include people—who are self-aware, capable of decision-making, and influenced by social dynamics— Socio-Technical Systems are inherently complex. Moreover, the dynamic nature of human behaviour means that changes in one part of the system often trigger ripple effects throughout. This interdependence requires that any modification within the system be approached holistically, considering the interactions among all sub-systems and their environment. Ignoring these relationships can jeopardise the success of change initiatives. Therefore, effective design and transformation of Socio-Technical System must account for the system as a whole, rather than isolating individual elements. When a system perspective is neglected, organisations risk falling into the trap of sub-optimisation - a scenario where improvements in one area inadvertently degrade performance in another. Sub-optimisation can result in a deficiency in technical skills required for new tasks, fostering mistrust, negativity, and resistance among personnel. It may also cause discrepancies in routines and rules when new technology is implemented.

2.2 Leavitt's System Model

There are many different Socio-Technical System models, all of which comprise technology, humans, and organisations in different variants. This research utilises Leavitt's System Model [18], sometimes called Leavitt's diamond. It was developed in the 1960's and focuses on system changes, and how system changes affect these related factors.

This particular system model was selected for several reasons. Firstly, the model emphasises change, which aligns with the focus of this licentiate on future CRS and the exploration of system changes and their impacts on other system components. Secondly, the model provides a structured approach to examining the relationships between various factors within the system. Thirdly, the abstraction level and components of the model were deemed appropriate based on the findings of this licentiate.

Furthermore, Leavitt's system model, depicted in Figure 2.1, contains four factors related to each other; technology, people, tasks, and structure. The double-headed arrows indicate that the four factors are interdependent, and changes in each factor, affect the other. **The Structure** of an organisation serves as its foundational framework, encompassing various elements such as hierarchies and departments, and their interactions. It also includes the communication styles among different hierarchical levels and departments. Consequently, for any organisational change to be effective, the structure must be adjusted and evolved to meet the new requirements. **The People**, for example, the employees are the backbone of an organisation, with organisational functions and goals heavily dependent on their skills, knowledge, and performance. Changes in the workforce impact all other organisational elements, necessitating adjustments across the board. **The Tasks** refer to the activities performed by employees, encompassing both routine actions and broader organisational goals. Tasks define who performs specific functions and the overarching objectives pursued by the organisation. Finally, **Technology** enhances employees' ability to perform tasks efficiently. It includes a range of tools from computers and machines to software and mobile devices. It also includes buildings, or refurbishments of premises. The four components make up the organisation. The model has been used to study organisational change [19], but it has also been developed to more clearly involve the environment as a component, e.g., [20] [21] . Given the assumption in this thesis, that the environment also affects the system (i.e., changes to the electric power system in terms of e.g., more volatile power affect operator work), the environment is also illustrated as part of the model in this thesis.

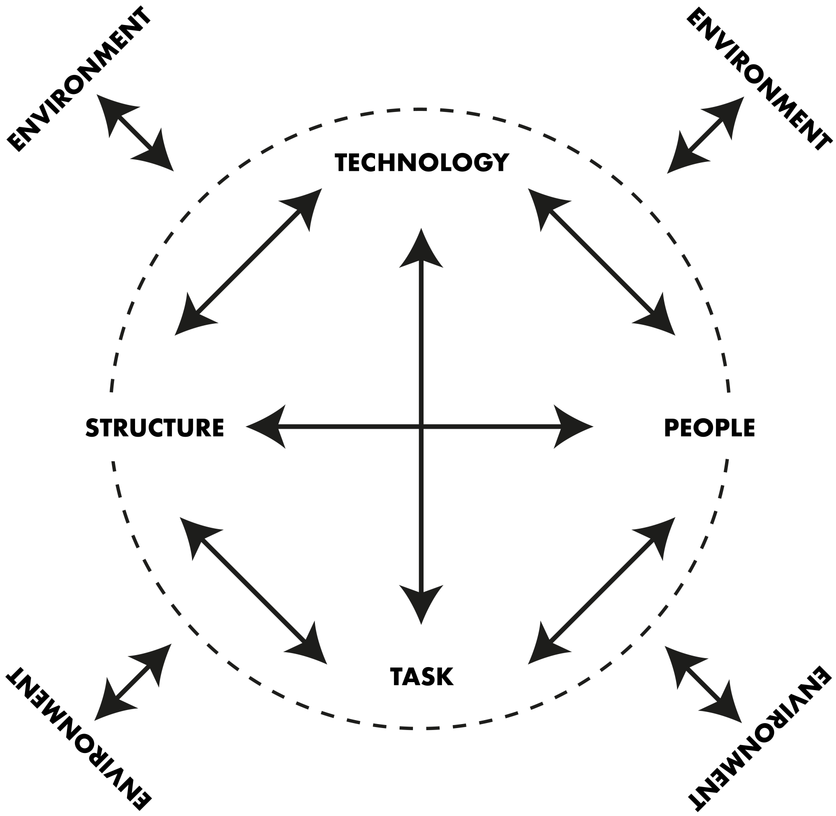

Figure 2.1: The first author's interpretation of Leavitt's System Model.

Relationships Between Technology, People, Tasks and Structure

The following section generally describes the relationship between each of the factors in Leavitt's system model [18].

Relationships between Technology and People

The introduction of new technology in an organisation also affects the people component, requiring training and additional skills to adapt. In some cases, new technology necessitates the hiring of personnel with the expertise to manage it. Technology must align with the needs of the organisation's employees. The skills and expertise of employees determine the level of technology utilised within the organisation.

Relationships between Technology and Tasks

Task changes often lead to technological adjustments. For example, an organisation aiming to make a certain task more efficient, might implement a certain technology. Consequently, technological changes lead to modifications in the tasks performed by people. Employees must adapt to new technologies by altering their methods of task execution, often resulting in a reduction of manual tasks.

Relationship between Technology and Structure

New technology brings changes in the organisational structure, e.g., higher levels of automation causes changes in structure like a reduced number of employees, stronger technological infrastructure etc. Likewise, a new set up or department may also demand shift in new technology. Also, technology provides solutions when an organisation alters its structure. For instance, reducing costs and increasing productivity may be achieved through automation.

Relationship between Tasks and People

The introduction of new tasks impacts people, provides people with new experiences and opportunities and/or necessitates them to enhance their expertise. Also, when tasks change, people must adapt their methods of task execution. Proper training enables employees to adjust to new tasks effectively.

Relationship between Structure and Tasks

Modifications in organisational structure affect the tasks performed by its employees. For instance, the establishment of a specialised department necessitates the reallocation of tasks among existing employees to align with the new structure. Additionally, the establishment of new departments or hierarchical layers within an organisation necessitates changes in employee tasks and functions. Structural changes also affect workflow and processes, requiring adjustments to align with the new organisational framework.

Relationship between Structure and People

Changes in organisational structure require its people to adapt to new roles and responsibilities. Employees are often the first to adjust to new structural setups or departmental changes.

Human-Technology-Organisation

Another framework within the Socio-Technical Systems approach is the Human Technology Organisation (HTO) framework. HTO can be defined as an approach where the purpose is to study how people's physical, psychological and social conditions interact with different technologies and organisational forms and act based on this knowledge for increased safety. Furthermore, it is the interaction between the sub-systems human-technology-organisation that are crucial for safety are found, rather than the subsystems themselves [22]. HTO underline that a focus on the interaction between the HTO sub-systems elicits the fact that the whole system becomes more than the sum of its parts [23].

2.3 Electric Power Systems

An EPS generates, transmits, and distributes electrical energy from power sources to consumers and is a kind of supra-system [3] that encompasses various components, including generation facilities like power plants, that produce electricity from primary energy sources. A transmission network transports electricity from the major electricity producers to the regional distribution networks and often runs through entire countries and connects to other grids. Electricity is generated from various sources and transported via high-voltage power lines to regional networks. It is then transferred via medium-voltage power lines to local networks and finally distributed via low-voltage power lines to end-users.

The TSO (often one organisation per country, e.g., Svenska Kraftnät in Sweden, Statnett in Norway, etc.) bear the responsibility of overseeing and managing high-voltage electricity transmission infrastructure within a given geographic area or region. The TSO's primary functions encompass ensuring a secure, reliable, and efficient operation of the electrical grid. They are thus responsible for transmitting the energy produced by different energy producers, such as NPPs and HPPs. Furthermore, other organisations vital in the EPS are the Distribution System Operators (DSO) (as an example, approximately 170 organisations in Sweden), who manages the electric distribution system and works closely with the TSO. The operational control centres of TSO, NPP, and HPP facilities exhibit a degree of operational autonomy; however, they are subject to mutual influence and external variables [24]. The TSO and power producers cooperate, as the TSO issues dispatch orders to producers—for example, to regulate power output in response to system needs. In the Nordic countries, HPPs play a crucial role in power regulation due to their relatively high flexibility and ease of adjustment, especially when compared to NPPs[25]. With a Socio-Technical System Approach, it is possible to zoom in and out of the EPS. If 'zooming' in to, and focusing on the CRS, it has an internal environment consisting of organisational structure and culture, machines, humans, etc. The external environment consists of other CRSs, weather conditions, political decisions, etc. The CRS have no control over these external factors, but are highly affected by them [3].

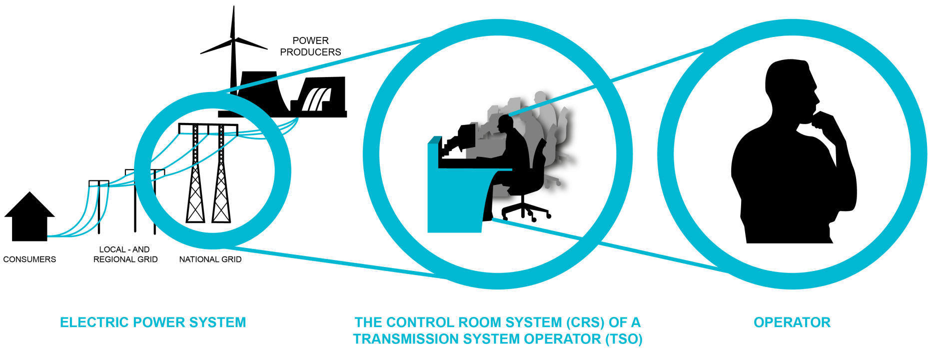

Figure 2.2: Schematic figure depicting the structure of an electric power system from generation to end-use, with emphasis on the roles of the Transmission System Operator (TSO) and the Control Room System (CRS) in overseeing and managing the flow of electricity. Adopting a systems approach allows for zooming in and out of different levels of the system to understand interactions and dependencies.

2.4 Control Room Systems

CRSs are Socio-Technical Systems and operates as open entities interacting with their environment, where mutually interdependent elements, the technological subsystems, the personnel and the organisational subsystems, interact with one another and the external environment to jointly transform inputs into outputs [5]. The CRSs being part of the same EPS are interdependent. Furthermore, each CRS has an internal environment, including organisational structure, culture, procedures, machines, and humans. The external environment consists of other CRS, events in the EPS, and political decisions, such as changes in power production methods. While CRS cannot control these external factors, they are significantly affected by them. Humans, technology, and organisations within each CRS interact and influence each other and their environment. Consequently, human roles and work are shaped by these interactions and the surrounding context. The CRS in the EPS are non-decomposable in that sense that they depend on - or affect - each other. More weather-dependent power sources affect Nuclear Power producers in that sense that they might have to regulate their power load, as a contrast to their current main task of being base load power. CRSs thus are dynamic environments [9], in which operators interact with each other, technology, and other CRS.

Both the supra-system (i.e., the EPS) and each constituent system (i.e., the CRSs) can be considered complex. This complexity arises from several interrelated characteristics. Each CRS comprises a large number of components, such as organisational structures, technical systems (e.g., control rooms, turbines), procedures, and operators. These elements interact in dynamic and often unpredictable ways. For example, changes in weather conditions can affect renewable energy production, which in turn influences how nuclear power plants adjust their output—shifting from base load to load-following operations.

The attributes of these components are not fixed; human roles, technologies, and procedures evolve in response to internal developments and external pressures. Interactions between elements are loosely organised—coordination between CRSs, such as between a NPP and the TSO, often depends on real-time decisions. The system evolves over time due to technological innovation, regulatory changes, and shifts in energy policy (e.g., increased reliance on renewables). Subsystems are purposeful and generate their own goals—such as a DSO aiming to maintain local grid stability, which may not always align with national-level objectives. In addition, CRSs are subject to behavioural influences: operator decisions, organisational culture, and inter-actor trust all shape system performance. Finally, the systems are open to their environment. A CRS cannot control external factors like political decisions or market fluctuations, but it is significantly affected by them—highlighting the interdependence and non-decomposability of the EPS as a whole.

The Operator

The operator plays a central role in Socio-Technical Systems in general, and in CRS in particular and several key aspects of human cognition are directly related to the operator's conditions and responsibilities within CRS. Wickens' model of human information processing [26] is a framework with various interrelated psychological processes and systems involved in human information processing, used for analysing the human interaction with the environment, e.g. control room systems. The model is centred around the flow of information as a human performs tasks (Figure 2.3).

Sensation is the initial step, where environmental stimuli are processed by human senses (sight, touch, hearing, etc.) and briefly held in the short-term sensory store. Following this, perception takes place, where sensory information is interpreted to derive meaning. This process is influenced by past experiences stored in long-term memory, i.e., transforming raw data into meaningful information. Based on this perception, an immediate response selection is made from a range of possibilities. The chosen response is then carried out in the response execution stage, involving both brain control and muscle action. Additionally, information may be temporarily retained in working memory for further processing, such as scanning for additional information or pondering a fact. Executed responses can change the environment, thus creating new sensory information, which provides feedback that may direct a revised response. Throughout these stages, attention plays a crucial role, both by acting as a filter to select certain elements for further processing and as a resource provider for various stages of information processing. Based on this perception, an immediate response selection is made from a range of possibilities. The chosen response is then carried out in the response execution stage, involving both muscle action and brain control. Additionally, information may be temporarily retained in working memory for further processing, such as scanning for additional information or pondering a fact. This stage involves cognition, where sensed material is interpreted and thought about. Executed responses can change the environment, thus creating new sensory information, which provides feedback that may direct a revised response. Throughout these stages, attention plays a crucial role, both by acting as a filter to select certain elements for further processing and as a resource provider for various stages of information processing.

Guided by the holistic overview represented by Wickens' model of human information processing, central aspects of human cognition can be related to operators' conditions in CRSs. The primary task of operators is decision-making. Specifically, they engage in dynamic decision making [27], which involves making decisions in complex, time-pressured, and constantly evolving environments where system feedback is often delayed. Dynamic decision making demands continuous adaptation, rapid responses, and the ability to act without extensive deliberation. A critical component of effective decision making in safety-critical systems is Situation Awareness [28]. Situation Awareness (SA) encompasses three levels: the perception of relevant elements in the environment, the comprehension of their meaning, and the projection of their future status. Both SA and knowledge-based decision making rely on internal representations of the environment, known as mental models [29], which are developed through experience. As EPS develops and automation increases, ironies of automation [30] risk occurring. Automation intended to simplify tasks can lead to increased cognitive load and skill degradation among operators, requiring constant monitoring and preparedness for emergencies. Automation can also shift the nature of work, increasing task complexity and introducing new types of errors. Ashby's Law of Requisite Variety [31] states that a system's internal complexity must match the external complexity to maintain control. As systems become more complex, operators' knowledge and adaptability must increase accordingly.

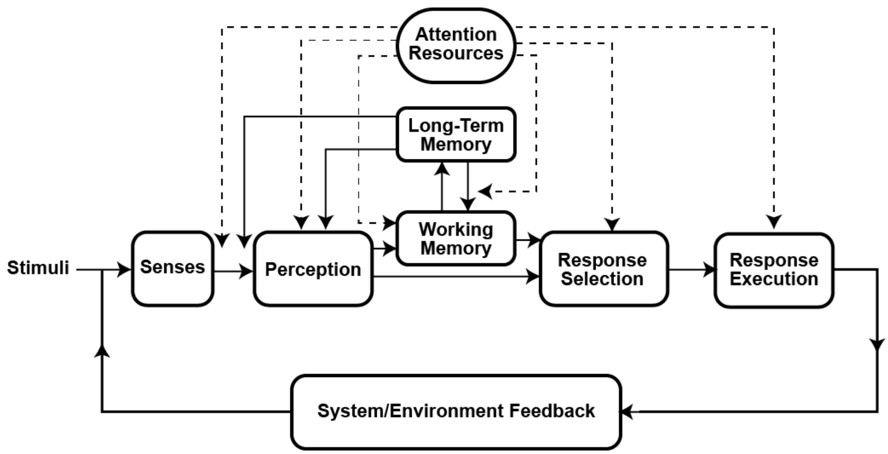

Figure 2.3: Wickens' Model of Human Information Processing.

2.5 Summary of Frame of Reference

This bullet point list summarises the frame of reference of this licentiate thesis and are central for the rest of the thesis.

- Electricity demand is projected to rise and the development of renewable energy sources aims to reduce dependence on fossil fuels. Additionally, technology is introduced to handle these EPS developments. This shift introduces operational challenges in the CRS.
- With a systems approach, changes in one part of the system affects other parts of the system, which is why a systems approach is needed in times of change and/or when designing successful Socio-Technical Systems.
- The CRS can be viewed as a dynamic Socio-Technical System comprising people, structures, tasks, and technology.
- Operators are central in Socio-Technical Systems in general, and CRS in particular, and a number of interrelated aspects of human cognition can be related to operators' conditions and roles in the CRS, such as Dynamic Decision Making, SA, Mental Model, Ironies of Automation, and Ashby's Law of Requisite Variety
- CRSs are part of the same EPS and are thus affected by, and affect, each other.
- As the EPS changes and CRS technology develops, CRS organisations and operations are also affected.
- Leavitt's system model conceptualises organisational dynamics through the interaction of four interdependent components: technology, people, tasks, and structure. This framework serves as a tool for analysing and guiding systemic change. In its extended variants, the model also incorporates the external environment as a critical contextual factor, which is likewise acknowledged in the present thesis.

Chapter 3

Methodology

This chapter describes the methodology used to address the RQ of this thesis. Two studies (Study I and Study II) were conducted. Study I comprised a semi-structured interview study with the objective to explore the future CRS operation within energy production- and transmission and identify future trends, challenges, and opportunities from an operator's perspective (RQ1a, RQ1b). Study II comprised a questionnaire study with the objective to provide insight into the future role of operators in the TSO domain in response to technological advancements and shifts within EPS (RQ2a, RQ2b, RQ2c). The connection between the studies and RQs are presented in figure 3.1.

3.1 Research Approach

The research methodology was predominantly exploratory [32] and user-centred [33], involving empirical, exploratory, semi-structured interview and questionnaire studies.

The exploratory character of this study is evident in the use of semi-structured interviews with a diverse range of experts and operators from various sectors within the EPS. This methodological choice provided the flexibility to engage with participants' individual experiences and perspectives, rather than confining the discussion to predetermined themes. Crucially, the research did not begin with a fixed hypothesis; instead, it embraced an open-ended inquiry into the concept of the 'future control room'. Moreover, this approach not only encouraged the emergence of novel insights but also ensured that the findings were firmly rooted in practical expertise and attuned to the inherent complexity and uncertainty of future-oriented challenges. Furthermore, the user-centred dimension of the study is underscored by the inclusion of operators in both Study I and Study II, highlighting a consistent commitment to incorporating end-user perspectives throughout the research process.

The research approach is here conceptualised using the metaphor of a funnel (figure 3.2) which illustrates that Study I used a broad system perspective and gradually narrowed down the focus through Study II. Doing studies with users and other experts is aligned with a user-centred approach [33]. When designing for users (in this case operators), it is of importance to understand who the users are, what tasks they need to perform, and the context they are situated in. Empirical methods, such as interviews and questionnaires, are suitable to gather data on user interactions and needs.

In Study I, a holistic perspective was adopted by conducting interviews across diverse domains and roles to develop a broad understanding of the EPS, its challenges, and potential opportunities. The assumption was that different people have different experiences and educational background, and thus bring different perspectives. The study employed an inductive approach, beginning with the analysis of empirical data and progressing toward broader generalisations or theoretical insights. This method is particularly suitable for exploratory research [32]. Exploratory studies can for example be conducted to explore a topic that is little known, or develop hypotheses or ideas, or to plan a dissertation, and to find further research questions [34]. This exploratory approach was therefore considered appropriate, since the aim was to explore the domain experts' view of the future CRS. As the research progressed, the scope was systematically refined, mirroring the funnel-like approach. In addition, the findings from Study I raised new questions regarding the tasks, roles, and tools of operators in the TSO domain—both in the present and looking toward the future—as well as their attitudes toward these developments. Therefore, the focus narrowed down to questions regarding these topics.

Research Questions	Study I	Study II
RQ1a: How do CRS experts perceive current trends in CRSs within the EPS domain, and what implications might these trends have for the HTO system? (Paper A)	X	
RQ1b: How do current CRS trends impact the conditions and roles of CRS operators in the future EPS? (Paper B)	X	
RQ2a: How do operators in the TSO domain report their tasks to have changed in the last five years, and how are the tasks expected to continue to develop?		X
RQ2b: What are the attitudes of operators in the TSO domain towards current tools, the introduction of new tools, and higher levels of automation?		X
RQ2c: How do operators in the TSO domain perceive the impact of new tools and automation on their tasks, efficiency, and the overall safety and reliability of operations?		X

Figure 3.1: This licentiate's research questions in connection to respective study.

3.2 Study I: Interview Study

A semi-structured interview study was conducted investigating the future CRS, and the potential implication of EPS trends described by domain experts on operators' conditions and roles in future CRS. The interview study explored the future CRS within energy production and transmission, according to domain experts. To form a participant group for the interview study, a convenience sampling with snowballing effect was employed through the utilisation of established contacts, resulting in 18 individuals[1] from academia, industry, and operation in the Nordic countries. The participants consisted of six human factors specialists, two human factors researchers, nine working in or close to operation and one working for a supplier. The participants' domain expertise was linked to process control in TSO, HPP and NPP respectively. Two interviewees had experience from a mixture of domains, both within the energy sector (TSO, NPP, and HPP) as well as other domains (e.g., pulp and paper), one as working for a supplier company and the other as a human factors specialist from several CRS domains. All interviewees, except two, had ten or more years of experience within the CRS domain and four of the interviewees had more than 20 years of experience. Nine of the interviewees had prior or current experience working as operators.

Data Collection

The interviews were performed and recorded online via Microsoft Teams and lasted about one hour each. All interviews were performed by the first author, and the same semi-structured interview template (Appendix A) was used for all interviews. The interviews were transcribed verbatim by the first author through careful listening to the audio recordings and documenting each spoken word. Following transcription, the data were subjected to thematic analysis to identify recurring patterns and key themes.

Study I Analyses

The interview data were analysed using two complementary approaches. The first analysis (Paper A) employed a socio-technical perspective, utilising the HTO framework to explore systemic interactions. The second analysis (Paper B) zoomed in to the human component of the system, examining the evolving conditions and roles of operators within future CRSs. This analysis investigated how emerging trends in the EPS may influence operator roles and working conditions, drawing on established theories and models relevant to understanding the implications of such trends as described by domain experts.

Analysis I: Future HTO system

Analysis 1 (Paper A) examined how domain experts conceptualise the future Control Room System (CRS) from a HTO perspective. Thematic analysis was conducted using data from 16 participants in the interview study. The data reflected participants' perspectives on the future CRS, including anticipated technological trends and their implications for humans and organizational structures. The analysis encompassed statements and reflections on CRS-related trends, visions, challenges, and opportunities, as well as their potential

[1]For Analysis I, 16 individuals were interviewed. For Analysis II, an additional 2 individuals were interviewed, bringing the total to 18 individuals.

impacts across the human, technological, and organisational dimensions of the HTO system. Statements and reflections about control room trends, visions, challenges, and opportunities, as well as effects on the humans and the organisations in the whole HTO system were included in the analysis. In Findings, quotations, all originally in Swedish, are used to support the claims made. Each quote is attributed using a respondent identifier, where ‘I’ denotes interviewee and the accompanying number indicates their unique ID.

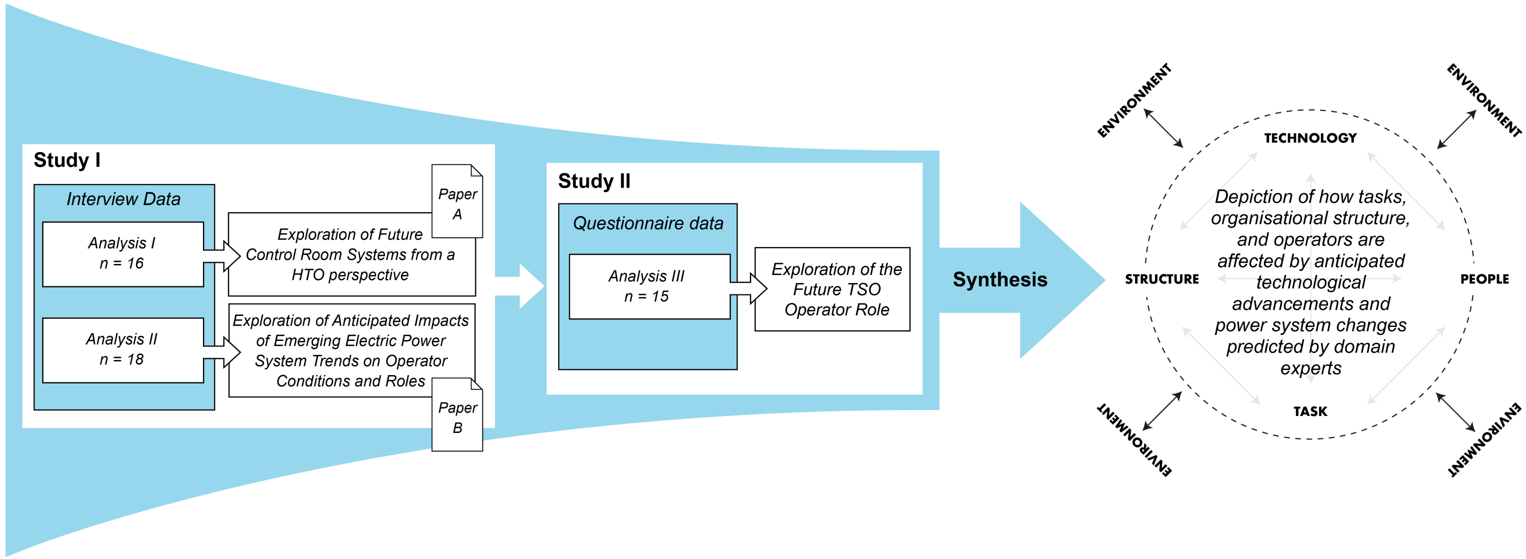

Figure 3.2: An overview of the research approach. The interview study (Study I) explored projected CRS challenges and opportunities on a systems level (paper A). Additionally, anticipated impacts on operator work and roles were explored (paper B). Together with the questionnaire study (Study II) exploring operator roles, tasks and technology attitudes in the TSO domain, a synthesis of findings from Study I and II was conducted (chapter 5).

Analysis II: Future Control Room Operations

Analysis II (Paper B) investigated the potential implications of EPS trends described by domain experts on the conditions and roles of operators in future CRSs. The data in analysis II were coded, categorised and subsequently analysed using Dynamic Decision making [27], SRK Model [35], SA [28], Mental Models [29], Ironies of Automation [30], and The Law of Requisite Variety [31]. These interrelated and complementary models and theories were chosen due to their relevance in understanding the potential implications of trends described by domain experts on the conditions and roles of operators in the future. Grounded in the understanding that the human component is a critical element in all socio-technical system theories—including both HTO framework and Leavitt's System Model—it becomes imperative to examine system changes through the lens of the above mentioned interrelated models and theories. CRS, as complex socio-technical environments, are shaped not only by technological advancements but also by the evolving roles, behaviours, and cognitive demands placed on operators. By employing these complementary theoretical models and theories, the analysis is better equipped to capture the interplay between human and other system elements, thereby offering a comprehensive understanding of how future CRS must adapt to support effective human performance. For instance, the SRK Model and Mental Models provide insight into cognitive processes and behavioural patterns, while SA and Dynamic Decision Making address the temporal and perceptual demands placed on operators. Bainbridge's Ironies of Automation and Ashby's Law of Requisite Variety further contextualise the systemic and organisational challenges posed by increasing automation and complexity.

3.3 Study II: Questionnaire Study

Previous research has shown that emotional responses to technology are crucial for acceptance and can significantly contribute to safety and performance [36]. Implicit attitudes toward automation can affect trust in specific automated systems and influence reliance behaviour, impacting safety and performance outcomes [37]. Therefore, a questionnaire study was conducted to examine operators in the TSO domain current and future tasks and tools and operators' attitudes toward changes in tasks, tools, and implementation of higher degrees of automation.

The questionnaire (Appendix B) consisted of seven sections with a total of 20 questions and covered open-ended questions on how operator tasks have changed during the last five years, how tasks are anticipated to change, and how they want tasks to change. The questionnaire also included questions about attitudes towards the introduction of new tools and higher levels of automation, using a five-graded Likert scale. This section aimed to understand the attitudes of operators in the TSO domain towards new tools and automation, and gather views on the effectiveness and challenges of current and future tools.

Data Collection

To form the participant group, a digital questionnaire in English was distributed to Nordic TSOs via email. A designated reference person within each TSO was contacted to facilitate the distribution of the questionnaire. However, not all reference persons responded, making it challenging to determine the exact number of recipients. Additionally, due to confidentiality concerns, the TSOs do not disclose the total number of operators working in their control room.

A total of 15 respondents completed the questionnaire. The digital tool LimeSurvey was employed to gather data. The questionnaire respondents had varying operator roles; Balancing Engineers, Switching Engineers, Power System Analysts and Engineers on duty. Balancing Engineers monitors the grid frequency and adjust the grid frequency to stay within acceptable limits. Switching engineers are responsible for execution of planned or emergency switching to reconfigure the grid for re-routing power due to maintenance or during the restoration phase after larger disturbances. Power System Analysts monitor the system security limits in real-time and recalculate transfer limits given the current and upcoming system state(s). The Engineer on duty oversees the overall operation and are responsible for the overall delivery.

Analysis III

All answers in the open-ended questions were categorised and summarised into the following themes: (1) the changes in tasks over the past five years as perceived by respondents, (2) the anticipated changes in tasks according to respondents, (3) the desired changes in tasks from the respondents' perspective, and (4) respondents' attitudes towards tools and higher levels of automation. These categories were derived from the different sections of the questionnaire. In Findings, quotations, all originally in English, are used to support the claims made. Each quote is attributed using a respondent identifier, where 'R' denotes the respondent and the accompanying number indicates their unique ID.

3.4 Cross-Study Synthesis

The findings from Studies I and II were synthesised using Leavitt's System Model to highlight the impacts on tasks, organisational structure, and personnel, in light of anticipated technological advancements and changes in the external environment. Leavitt's System Model was introduced later in the project as an analytical tool to structure and interpret the findings.

Given the thesis' particular focus on the work of operators in the TSO domain, this became the central theme of the synthesis. The data were categorised accordingly and summarised. Responding operators in the TSO domain described similar developments within the system, along with their perceived benefits and drawbacks. As a result, few conflicting views required reconciliation. Nonetheless, most participants discussed both positive and negative aspects of these developments, all of which were incorporated into the analysis. The double-headed arrows in Figure 2.1 illustrate that changes in one factor influence the others bidirectionally. Consequently, the cross-study synthesis explored the interrelations among these factors—namely, Technology ↔ People, Technology ↔ Tasks, Technology ↔ Structure, Tasks ↔ People, Structure ↔ Tasks, and Structure ↔ People.

As previously noted, this synthesis also acknowledges the environmental dimension as a significant influence on the system. This is particularly relevant given that participants from both the HPP and NPP domains in Studies I and II highlighted the increasing integration of renewable energy sources, which is reshaping the nature of operator work.

Chapter 4

Findings

This chapter provides the main findings from Study I and II. In Study I, the system boundary encompassed the entire EPS, including diverse power producers (HPP and NPP) and the TSO. In Study II and the synthesis, the system boundary was limited to the TSO control room.

4.1 Study I

Study I explored future CRS trends, opportunities, challenges, and operations across EPS domains from a Socio-Technical Systems perspective, aiming to answer the following RQs:

RQ1a: How do CRS experts perceive current trends in CRSs within the EPS domain, and what implications might these trends have for the HTO system? (Paper A)

RQ1b: How do current EPS trends impact the conditions and roles of operators in the future EPS? (Paper B)

The findings from analysis I (presented in Paper A) suggested numerous potential CRS trends, and their effects on human and organisational factors. 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 organisation, and the result is categorised accordingly. Furthermore, the findings from analysis II (presented in Paper B) were structured according to Wickens' model of human information processing [26].

Identified Trends

The main trends as identified through analysis I, and presented in paper A were Balancing and Regulating Power, Automation, and Digitalisation.

Balancing and Regulating Power

While this theme operates primarily at the level of the EPS, it has significant implications for CRS operations. Interviewees from the TSO domain reported increasingly dynamic roles in balancing and regulating power, largely due to the growing share of weather-dependent energy sources. Interviewees from the NPP sector described that NPP operators are also experiencing a potential shift, with more frequent adjustments to power output.

One interviewee from the HPP domain emphasised the impact of increased system volatility over the past ten to twenty years on operational tasks, particularly in terms of their more active involvement: *"The network needs to be balanced in some way. Support services and markets have exploded in recent years. So, we have probably shifted from less monitoring to more action" (IP18).*

From an organisational perspective, one interviewee from the NPP domain and another from a supplier company mentioned that the maintenance role needs to adapt to the unpredictable nature of energy production, requiring dynamic maintenance strategies. Meaning, there is a growing emphasis on collaboration between operators and maintenance staff. Advanced tools for scenario simulation and forecasting could play a crucial role.

Automation

Automation was described by some interviewees in the TSO domain as a solution to the dynamic power landscape, and mentioned as main trend and solution in the the HPP and TSO domains. However, there were divergent views on the feasibility of automation in managing power systems. While many new tools were expected to be introduced, which could improve decision making processes and reduce operator stress, there were concerns about how to handle disturbances and IT challenges in an automated future. In the NPP sector, the emergence of Small Modular Reactors (SMRs) with passive safety systems could drive higher levels of automation. Interestingly SMRs are more frequently mentioned by human factors specialists and researchers than by the interviewees closer to operations. The shift to an increase of automation could impact operator roles and decision-making processes, potentially transforming operators into passive observers. Maintaining facility and technical skills in such an environment could be challenging, emphasising the need for IT and scenario training. One interviewee in the TSO domain noted: *"A challenge then is that when we move towards more automation and data-driven processes, we might have a more withdrawn role in everyday tasks, so to speak. But then I think it will be an even bigger challenge when something goes wrong and we have to step in, and then we don't have any support while at the same time we might not be comfortable in our roles. I think that can be a bit difficult, and above all, there will be a lot of uncertainties" (IP16).* Organisationally, one potential trend presented by the interviewees in the HPP domain was that of centralised control centres, where multiple plants could be controlled from one main centre. Also, the interviewee from a supplier company and human factors specialist from the NPP domain mentioned one organisational consequence of higher levels of automation, and simultaneous processes might lead to the establishment of expert centres where operators control diverse energy processes simultaneously.

Digitalisation

The transition to digital CRS and interfaces was described as a trend mainly by interviewees with operator roles within the NPP domain, though the level of digitalisation varies between different CRS and domains. It was described that digitalisation could offer the potential for more information to be available to operators, which can enhance decision-making. However, this also brings the risk of information overload, where the sheer volume of data can become difficult to overview and sort. IT and system disturbances, along with cybersecurity, are notable challenges in the digitalisation process. Ensuring the security and reliability of digital systems is crucial, as any disruptions can have significant impacts on operations. As such, future IT skills will be essential for operators to effectively manage and utilise these digital systems. From a human operational perspective, there is a need to balance detailed information with the overall operational status. It was discussed by interviewees in the NPP domain that junior operators might tend to prefer digital systems, finding them more intuitive and aligned with their technological expectations. It was also expressed by interviewees from the NPP domain, that NPP must be operated with hardwired systems and others mentioned if they would transfer to digital systems, it would be important to maintain analogue backup systems to ensure continuity in case of digital system failures. One interviewed operator from the NPP domain mentioned *"I think operators will control it (Ed. future NPPs) from a screen-based control room with a diversified hardwired system. I think so. I think that will be the solution that they have to choose." (IP6)* and that completely digital systems is too unsafe from a cybersecurity point of view. Regular recurrent training was described in all three domains to be necessary to keep operators prepared for any incidents.

Exploration of Anticipated Impacts of Emerging Electric Power System Trends on Operator Conditions and Roles

The following findings (from analysis II, presented in paper B) illustrate the anticipated impact on the operator conditions and roles, given trends identified by interviewees, structured using the elements of Wickens' Model of Information Processing [26].

Perception

The dynamic energy landscape, with less predictable energy flows, increases the volume of information operators working in the TSO and HPP domains must manage [38].Tasks have already begun to be implemented in the TSO and HPP domains. Furthermore, digitalisation and SMRs in the NPP domain may change the nature of information presented to operators, enhancing detail and visualisation possibilities.

The interviewees from both TSO and NPP domain noted that if operators are not actively engaged in controlling the system, it may take longer to perceive issues presented by it, which can be interpreted as that, the sense-making of sensory information is influenced by past experiences [26]. As presented in previous research [13], automation might risk making operators less situationally aware since the information flowing from field crews (described as the eyes and ears of the operators) might be reduced and thus affect the perception of the operators.

Working Memory

The increasingly dynamic energy landscape has compelled operators in the TSO and HPP domains to more actively manage, sense, and interpret a growing volume of information. The increased information load can strain operators' working memory [26], making it challenging to form SA, which is crucial for appropriate decision-making [28].

As described, automation was by the interviewees in the TSO and HPP domains considered a potential solution to the increasing complexity, as it reduces the need for operators to retain excessive information in their working memory. However, the mixed views on automation's adaptability highlights the need for a balanced approach that supports operators without overwhelming their cognitive capacities.

The interviewees from the TSO and HPP domains also discussed that because of the increasingly dynamic energy landscape and volumes of information, new tools would be needed to present relevant information to operators. There is a fine balance though, since, an excessive amount of data presented to operators' risks causing cognitive overload, particularly if the information is not delivered in a clear, recognisable manner at the appropriate time. Cognitive processing using working memory can easily be disrupted by new incoming information, especially under stress, and excessive cognitive load reduces the problem-solving capacity [26].

Long-Term Memory

Many interviewees across different domains expressed concerns that higher automation levels could make operators passive observers, leading to skill loss and stress during disturbances. One interviewee with Human Factors competence, from the NPP domain noted: *"We can not automate everything anyway, because then we may get more operators out of the loop. Then we may not maintain this 'plant knowledge' that I said was so important, over time as well. I think we should be a little careful there" (IP1).* Similarly, one interviewee from the TSO domain mentioned: *"I also think that training will be very important. Now we have a large part of training during work, so to speak, because we still do work and decisions and we kind of run the system. But it* *will be more difficult. Then maybe this computer will make all the decisions and then I think it will be important to do more training"(IP16).* Opinions varied among the interviewees on whether operators would need the same technical knowledge in a highly automated future. Future digital control systems will require elevated IT skills, possibly including analytical skills and IT skills. Recurrent training is crucial for recovering from system failures. Furthermore, suppliers might be consulted during disturbances, with expert centres handling difficult decisions, would require operators to communicate and trust experts. If operators are required to manually run the facility when automation fails, there is a risk that they may have limited skills and knowledge about the facility stored in their long-term memory due to fewer experiences to draw upon in case of an incident [30].

Response Selection and Response Execution

The interviewees across different domains highlighted that the operators' main task of today is to make decision and foresee the consequence of said decision. It was discussed though, that in the TSO and HPP domain decisions are made closer to the operating hour due to the volatility, necessitating faster and more accurate decisions informed by models, forecasts, and Decision Support Systems. This shift requires improved forecasting. One interviewee in the TSO domain said: *"Upcoming automations make it more important to make decisions about, for example, input data to the calculation algorithms, i.e. earlier decisions, compared to decisions today which are normally made closer to the operating hour" (IP17).* AI-based decision support tools may alter decision-making, raising concerns about stress during disturbances and potential system failures. Better support systems could warn of component failures beforehand. This shift from data-based decision-making to decisions informed by models, forecasts, and Decision Support Systems, underscored the importance of improved and trust-worthy forecasting and requiring operators to have sufficient variety or flexibility in their responses to match the variety of the environment [31].

Feedback

The interviewees across different domains concurred that one of the primary responsibilities of operators today is to anticipate the consequences of their decisions, making feedback crucial. Each decision carries consequences that must be carefully evaluated. In the context of higher levels of automation, feedback remains essential but must be adapted to meet the new operational situation. Automation feedback must be adapted to the new operational situation, as deficient feedback can leave operators unaware of the automation's state. Operators need to understand the facility to grasp the consequences of various alternatives and why automation behaves as it does.

According to literature [26], automation feedback can be deficient in several ways: it may be completely absent ("silent"), insufficiently noticeable, ambiguous, or inflexible and lacking in detail. Without proper and transparent feedback, operators can be left unaware of the automation's state. Additionally, humans have difficulty detecting subtle environmental changes due to limitations in signal detection and vigilance. Even when feedback is provided, it may be too low in saliency to capture the operator's attention, especially if they are focused on other tasks.

Attentional Resources

Many interviewees across domains expressed concerns that operators might become passive observers, leading to skill loss and stress during disturbances if automation is implemented without caution. This aligns with the risk of skill degradation due to increased automation [30]. Passive observation could strain attentional resources, making it hard to maintain focus over low-activity periods. With SMRs, operators may need to monitor multiple processes simultaneously, raising questions about the number of units one operator can effectively oversee. Digital interfaces could provide more data, aiding decision-making but also risking information overload.

Summary and conclusions from Study I

RQ1a to RQ1b are shortly answered in the concluding bullet points below.

- **Volatile EPS**
  The volatile power landscape has increased the volume of information that TSO and HPP operators must manage.

- **Varying trends**
  The EPS faces various trends affecting the HTO system. Similarities and Differences exists between domains. While automation is expected to grow in HPP and TSO domains, it is not anticipated to increase significantly in the NPP domain—except potentially for future SMRs.

- **Deskilling**
  Higher levels of automation may lead to operators becoming passive observers, increasing the risk of deskilling, especially affecting operations during disturbances, where active engagement and expertise are critical.

- **Decision Making**
  Decision-making is expected to be increasingly focused on planning and optimisation in automated CRSs, with operators primarily intervening during disruptions. These situations can be particularly stressful due to their high-stakes and time-sensitive nature.

- **Training**
  Continuous training is essential to maintain operator competence. Future operators will need a mixture of technical, analytical, and IT skills to effectively manage automated systems and complex information environments.

- **System Feedback**
  Effective feedback from systems is crucial for operators to understand the state of automation. Without it, maintaining focus during low-activity periods becomes difficult, and the risk of stress and errors increases.

4.2 Study II

Study II examined the current and future tasks and tools of operators in the TSO domain, and operators attitudes toward changes in tasks, tools, and implementation of higher degrees of automation, aiming to answer the following RQs:

RQ2a: How do operators in the TSO domain report their tasks to have changed in the last five years, and how are the tasks expected to continue to develop?

RQ2b: What are the attitudes of operators in the TSO domain towards current tools, the introduction of new tools, and higher levels of automation?

RQ2c: How do operators in the TSO domain perceive the impact of new tools and automation on their tasks, efficiency, and the overall safety and reliability of operations?

Task Development

Most questionnaire respondents reported that the EPS is becoming less predictable, primarily due to the increase in renewable energy production. The questionnaire respondents described that wind power, which is not always predictable, can cause significant imbalances. This affects Load Balancing tasks, i.e., the maintaining of grid stability by matching electricity production with consumption in real-time and management and deployment of reserve power sources to handle unexpected consumption spikes or production drops. One Balancing Engineer noted: *"It is becoming more difficult to balance production and consumption because of renewable energy sources like wind power. This requires more monitoring and has become more stressful. Also, a lot of new tools have come." (R3).* Another Balancing Engineer highlighted that there are *"less reserves available" (R2).* The task of monitoring and adjusting the grid frequency to stay within acceptable limits was reported to have changed due to introduction of a new automated mFRR model, and the task of managing and deploying reserve power sources to handle unexpected consumption spikes or production drops has changed due to a lack of reserves but does not expand on how the task has changed.

One Engineer on duty commented: *"The work is increasingly data-driven, and the tools are usually not fully tested and developed when put into production. Training is sometimes equal to learning by doing" (R8).* The same respondent also commented that *"There is more interest from the outer world, especially regarding electricity prices. Five years ago, we seldom talked about prices, but now it's part of the daily operation".* Two Engineers on duty also observed that reporting in the logbook is more systematic and is now followed up with daily meetings between the TSOs. Another Engineer on duty added, *"We are better trained for documenting during stress." (R7)* and another noted that there are *"More events and more things to report" (R11).*

In addition, Power System Analysts stated that their tasks including preparation of the trading capacities for the electricity market and overseeing grid modelling and system analysis has been affected by the introduction of the new flow-based capacity calculation method. One operator remarked that: *"With the new capacity calculation method 'Flow-based,' the whole capacity calculation process has changed completely with new tasks, new tools, new sub-processes, more international cooperation, and new daily meetings" (R15).* Additionally, positive wordings regarding task changes were reported. Both Engineers on duty and Power System Analysts commented that the task to monitor the system security limits in real-time and recalculate transfer limits given the current and upcoming system state(s) has become easier thanks to better tools and observability. In addition, it was noted that a dedicated 24/7 person for recalculating limits has made the process more efficient. Responding switching engineers reported no changes in their tasks.

Expected Future Task Development

The questionnaire respondents expected their tasks to change significantly with the introduction of higher levels of automation and anticipated new roles, better tools, and more complex calculations, along with challenges from the green transition and the need for improved training and system integration.

In addition, 73 percent of the questionnaire respondents agreed or strongly agreed to the statement: *"I believe my tasks will change as support tools with higher levels of automation are being introduced"*. The rest answered Neither disagree nor agree. Balancing operators reported that balancing tasks will be mostly automated. These results are supported by the results from the statement: *"I believe that support tools with higher levels of automation will become increasingly common"*, in which all questionnaire respondents responded that they agree or strongly agree to.

Furthermore, one operator mentioned that: *"The new balancing model starting this year will change almost everything" (R3).* Tools and systems are becoming more autonomous, and operators' roles are to take over when these systems fail to deliver. The questionnaire respondents mentioned that this requires more training for rare events. With the introduction of automatic balancing, much more is required in the pre-balancing timeframe, such as solving local congestions and handling fluctuations with very short look-ahead capability. New processes for balancing the system and further development of capacity allocation processes will affect the work. One Power System Analyst commented that: *"new processes for balancing the system and further development of capacity allocation processes will affect the work. More or less stressful? We'll see" (R14).* Some questionnaire respondents also thought that new reserve products will be available, such as batteries.

Moreover, the questionnaire respondents anticipated that the green transition would introduce new challenges and effects on the organisation. One Engineer on duty mentioned: *"The green transition will introduce new challenges. We will probably have more operators, with new roles, to supervise. The SCADA and other tools and system is more autonomous, and our role is to take over when it fails to deliver. That requires more training for rare events" (R7).* Another Engineer on duty noted: *"More positions in the control centre.*

More complex calculations and analysis" (R12).

Regarding reporting, questionnaire respondents observed that the initial reporting will always start in the control centre, but they expect better support in the back office. One operator commented that: *"Status reporting will probably be identified by the system: The operator gets a notification of a possible incident/deviation to report on".* The questionnaire respondents also mentioned improvements such as a larger grid model, better visualisation, and better integrations between systems, making it easier to find the most optimal countermeasure for different events. The introduction of the 15-minute market was also noted. Power System Analysts will have a continuing development of the flow-based calculation method: *"We've introduced Flow-based on the Day-Ahead market. We will introduce it on both Intraday and for balancing in the future. This will definitely imply new tasks." (R15).*

One Engineer on duty mentioned: *"We will maybe have to prepare for disturbed operations while still in normal operation" (R9).* Another operator mentioned that: *"Better models and systems will enable faster and more accurate calculations, making it easier to find the most optimal countermeasure for different events. The system will propose proper actions" (R7).* The questionnaire respondents also reported better tools and new positions to reduce the workload.

Desired Task Development

The questionnaire respondents described that they are seeking to streamline and automate tasks to reduce manual checks and improve efficiency, especially with increasing automation levels. They emphasised the need for better tools, clearer guidelines, and improved alarm handling to manage future challenges and ensure operational security.

Additionally, one respondent with balancing tasks, reported that much of their time goes to checking and validating production and consumption forecasts and suggested that this issue would rise with increasing automation levels, implying that (s)he would want to streamline these tasks. Another operator, within system power analysis, wrote: *"We double-check everything. I'd like to slim down many processes and automate them rather than having operators double-check numbers. In a perfect world, we calculate and model once and trust the processes" (R15).*

In addition, the questionnaire respondents indicated that a new level of automation will be necessary to handle situations where the current balancing is not sufficient and that the alarm lists could be designed better. One respondent with balancing tasks commented: *"A number of manual tasks could be automated. The SCADA alarms could be better handled and presented – today we have the same priority for a large number of events, making it difficult for operators to know what to react to" (R7).* Additionally, operators emphasised the need for automation in the quarter market. One operator within balancing noted: *"Everything needs to be automated because we can't do the same things we are doing now manually every 15 minutes" (R3).* Also, operators highlighted the importance of having enough grid capacity in the future, as production and price changes will be weather-based. One operator saw that: *"a possible conflict of priorities between monitoring the real-time situation and preparing for day-ahead" (R14).*

Furthermore, the questionnaire respondents reported that required information should be better presented. One respondent mentioned that: *"Better observability and more tools to perform power system analysis are needed" (R12).*

Another respondent noted that the control centre design, which determines operator interaction, is more crucial during a disturbed system state and stated that: *"Communication is crucial. I would also like the same layout in the control centre for training as for production" (R7).* The operators are constantly working on providing themselves with better and clearer guidelines, tools, and instructions. One respondent commented that: *"The tasks remain the same (solve the issue related to the disturbed operation), but hopefully the task can get easier with better tools, instructions, etc. It's especially important to have clear instructions and good education as we have a lot of changes coming up in the future" (R15).*

Support Tool Attitudes

The questionnaire respondents reported that there are too many support tools and that these tools should be more reliable. One Power System Analyst mentioned that: *"Unfortunately, the systems are very old, and the new systems are often introduced without proper introduction to the operators" (R15).* Another operator expressed a desire for: *"more customisation and more reliability." (R11).* This is reflected in the statement: *"The support tools positively impact my overall job performance"* which 40 percent answered agree or strongly agree to, and 40 percent answered disagree or strongly disagree, and the rest neither agree nor disagree. It was also reflected in the result of the statement: *"I am satisfied with the current support tools provided to me"* in which 60 percent answered disagree or strongly disagree to, 27 percent agree or strongly agree and the rest (13 percent) neither nor.

One questionnaire respondent discussed operator attitudes, writing that: *"More automation often means more things can go wrong. If the reliability were higher, I think there would be more acceptance for more automation. There is a lot of frustration when complicated systems spit out the wrong answers or stop working when we rely on them" (R11).* Some questionnaire respondents described that automation tools used for balancing will burden them less as data quality and forecasting models improve in the future. However, there were also concern that there will be a lot of manual work and stress when the Nordic Balancing Model, requiring higher levels of automation, is implemented if the tools are not ready. In line with this, questionnaire respondents highlighted that one of the biggest problems in the CRS has always been the tools.

Moreover, one Balancing Engineer noted regarding tools that: *"They are not designed for the end user and have a lot of 'bugs.' When something happens, it takes too much time to fix them." (R3)* Another operator wrote, *"The development of such tools is slow and conservative. The actual users have* *little to say about the final product" (R7).* Some questionnaire respondents reported that the tools are never good enough and are often developed without considering what the user needs. One operator added, *"Support tools are generally designed for a different power system and lack good features for congestion management and reserve monitoring" (R9).*

The questionnaire respondents mainly reported optimism toward automation but also expressed scepticism. One Engineer on duty stated that: *"New is not necessarily better. Having too many different 'new tools' without considering how they should work together as a whole is problematic" (R11)* and adding that: *"The skills developed with more automation are bug fixing and learning exactly how the algorithms work to identify problems. I am not convinced that these are the types of skills operators want to learn".* There were also concerns that automation malfunction situations will challenge CRS operations, especially when more tasks are automated, and time dimensions are shorter (the imbalance settlement period being 15 minutes instead of 60 minutes). Sixty percent agreed or strongly agreed to: *"I am optimistic about the introduction of tools with higher levels of automation".* The rest were equally divided into neither nor and disagree or strongly disagree.

Despite the concerns, most questionnaire respondents described a need for automation due to the increasing volatility in the system with more renewables and other types of markets. One Power System Analyst commented: *"The manual operation is a thing of the past where flows were predictable, and the generation was easy to regulate (hydro). I see many challenges getting there, though. Will the automation work? Will we keep the manual fallback procedures fresh, or will we forget how to do it without automation?" (R14)* Another Power System Analyst was convinced that more automation is necessary, stating: *"This is a very conservative industry that is slowly adapting to the improved, digitalised, and automated future" (R15).* This is supported by the results from the question: *"I believe that support tools with higher levels of automation will make my tasks more efficient"*, in which 80 percent answered agree or strongly agree and the rest answered neither disagree nor agree.

One questionnaire respondent summarised the ongoing system changes with: *"Better tools improve the work, changing power system (renewables etc) makes it more challenging, new processes (flowbased capacity allocation) affects the work" (R15).*

Summary and conclusions from Study II

RQ2a to RQ2c are answered in the concluding bullet points below.

RQ2a: How do operators in the TSO domain report their tasks to have changed in the last five years, and how are the tasks expected to continue to develop?

- **New Tasks**
  The new mFRR model has automated certain balancing tasks, changing how grid frequency is monitored and adjusted. The flow-based capacity

calculation method has changed Power System Analysts' tasks and will continue to evolve, introducing new responsibilities. Similarly, automation in the CRS was expected to increase, reshaping operational roles. Meanwhile, real-time monitoring of system security limits has improved thanks to better tools and observability.

- **Operational Complexity**
  Overseeing overall grid operations has become more data-driven and complex, often relying on tools that are not fully tested when deployed. Managing reserve power sources is also more difficult due to a lack of available reserves.

RQ2b: What are the attitudes of operators in the TSO domain towards current tools, the introduction of new tools, and higher levels of automation?

- **Outdated tools and rapid tool introduction**
  The questionnaire respondents reported an overload of support tools, with some systems being outdated and new ones introduced without sufficient training.

- **Perceived Drawback of Automation**
  While 60 percent of the questionnaire respondents expressed optimism about increased automation, there is also scepticism. Concerns included the risk of more failures if reliability does not improve, and the potential for increased stress and manual work if automation is implemented before tools are ready.

- **Perceived Benefits of Automation**
  Some of the questionnaire respondents expressed that automation tools for balancing will reduce their burden as data quality and forecasting models improve.

RQ2c: How do operators in the TSO domain perceive the impact of new tools and automation on their tasks, efficiency, and the overall safety and reliability of operations?

- **Automation as a solution**
  Automation is by most of the questionnaire respondents described as necessary to manage the increasing system volatility. There is also a recognised need for automation to address situations where manual balancing is insufficient.

- **Perceived Benefits of Automation**
  A majority of the questionnaire respondents described that support tools with higher levels of automation will probably make their tasks more efficient. The introduction of new tools and automation was seen as a way to reduce workload and improve efficiency.

- **Implementation Challenges**
  Although better tools were expected to improve work, new processes and system changes can make tasks more challenging. Concerns remain about the readiness and reliability of these tools, and the potential for malfunctions in automated systems.

- **Reliability Expectations**
  The questionnaire respondents expected that better tools and systems might enable faster and more accurate calculations, ultimately improving operational safety and reliability.

Chapter 5

Technology, Structure, Tasks & People

This chapter presents a cross-study synthesis of the interview and questionnaire findings. It uses the relationships in Leavitt's system model [18] to categorise how experts in power production and transmission foresee the system's evolution and its future impact on the roles and working conditions of operators in the TSO domain, in the future EPS. Here, the system boundary is drawn around the TSO control room, with the environment defined as the EPS. By applying Leavitt's model, the synthesis illustrates the interconnections between changes in technology, structure, tasks, and people (figure 5.1).

The Environment

The key change discussed in Studies I and II regarding the CRS environment was the growing share of weather-dependent energy sources in the power mix. This shift has led to a reduction in the trading and settlement period—from 60 minutes to 15 minutes—to better align the electricity market and improve its responsiveness to variability [6]. Consequently, the role of operators in the TSO domain has been significantly affected. Tasks that previously managed over an hour must now be completed in only 15 minutes, requiring faster, more frequent, and more adaptive decision making. This evolving context intensifies the need for dynamic decision making [27], as operators must respond to rapidly changing conditions with limited time and often incomplete information. The increased variability introduced by renewables demands continuous monitoring and swift action to maintain system balance. The shift to more weather-dependent power, according to the HPP interviewee in Study I, also has implications for the HPP sector, which must now engage in more frequent regulation to balance the system. Furthermore, Study I highlighted that, in some instances, even NPPs have been called upon to regulate. However, since these facilities are not designed for such operational flexibility, such occurrences remain rare. This evolving context sets the stage for the subsequent analysis, which investigates how the components of Leavitt's system model - task, structure, technology, and people - interact and adapt in response to these dynamic conditions.

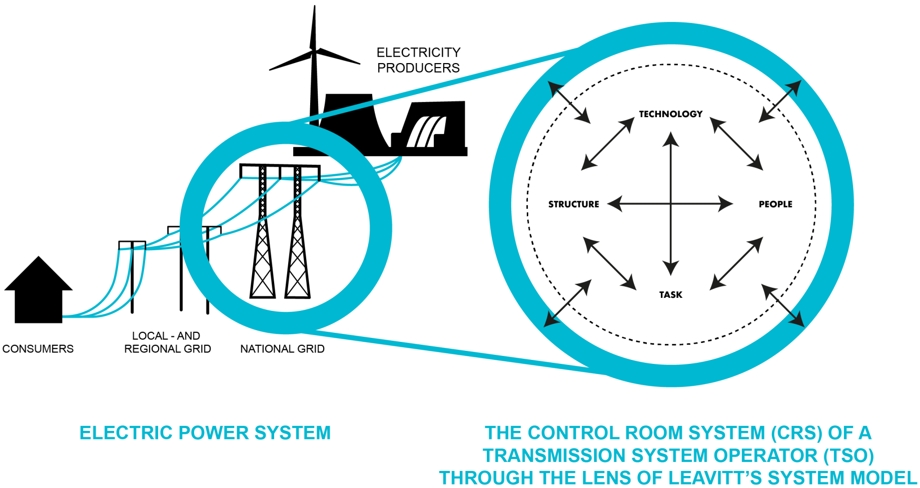

Figure 5.1: The synthesis concentrated on analysing the relationship between technology, structure, task, and people in the Transmission System Operator's (TSO's) Control Room System (CRS). The environment is the Electric Power System (EPS).

Relationship between Technology and People

The introduction of new technologies inevitably demands the acquisition of new skills and training. However, as emphasised by Leavitt [18], technological advancements must be aligned with human needs. In the context of the TSO domain, automation emerges as the technological component with significant impact on the human element. As demonstrated in Study II, there is a consensus within the TSO domain that automation will continue to expand in the coming years. The questionnaire respondents not only anticipated this growth but also expressed a clear need for it. A primary driver behind this sentiment is the increasing operational frequency—from hourly to every 15 minutes—which many operators described to not be possible without automation. Although the majority of the questionnaire respondents acknowledged the necessity of automation, several concerns were also raised. These included the risk of skill degradation and the potential for system failures. The operators voiced worry about the reliability of automated systems and whether manual procedures would be retained over time. These concerns resonate with established literature, such as that of Bainbridge [30] on the ironies of automation. Moreover, as described in Study I, knowledge-based decision making requires internal representations of the environment, known as mental models, which are developed through experience. With less experience, due to increased automation levels, operators may struggle to form mental models that align with those of the system [29].

Moreover, many questionnaire respondents in Study II reported that new tools are frequently introduced without sufficient consideration for user experience. These tools often lack proper training support and are plagued by bugs that delay resolution and hinder efficiency. A more critical perspective was offered in Study I by a former TSO operator, who questioned whether automation could truly manage the increasing complexity of future energy systems. This scepticism highlights the limitations of current AI and automation technologies in anticipating and adapting to rapidly evolving scenarios.

In summary, the implementation of higher degrees of automation seem to be aligned with the needs of the operators in the TSO domain. However, how tools have been introduced historically seem to create an uncertainty of how well the new systems will work in operation. The participants in Study I and II seem to be well aware of potential ironies of automation [30] such as deskilling and vigilance issues, creating an uncertainty among the operators regarding the effect of these introduction.

Relationship between Technology and Tasks

The literature indicated that in recent years, the EPS has become increasingly volatile, a trend that the interviewees report has made operator tasks in both the TSO and HPP domains more dynamic. As one HPP operator noted, the heightened volatility over the past ten to twenty years has transformed monitoring tasks into more active forms of work. However, with the anticipated rise in automation, the operator roles are expected to shift toward a more passive nature. As outlined in Study I, this growing passivity influences operator responsibilities in several ways. Classic automation-related challenges—such as deskilling, being out-of-the-loop, diminished vigilance, reduced situational awareness, and boredom—are among the key concerns [30]. Another factor highlighted in Study I is that future automation may shift critical decision-making from the operational hour to the planning stage. As one interviewee in Study I described, the use of forecasts is expected to increase, resulting in more monitoring during the operational hour.

To summarise, the increasingly volatile system has significantly impacted the tasks of the operators in the TSO domain, which has shifted from less monitoring to more action due to the explosion of support services and markets. However, with the anticipated rise in automation, operator tasks are expected to include more monitoring and less active work (Figure 5.2). Study participants from TSO domain has described anticipated challenges when they need to take over the control of the process during system failures, without adequate support, leading to uncertainties. Additionally, future automation might shift critical decision-making from the operating hour to the planning stage, particularly emphasising a need for proper prognosis tools and high-quality data.

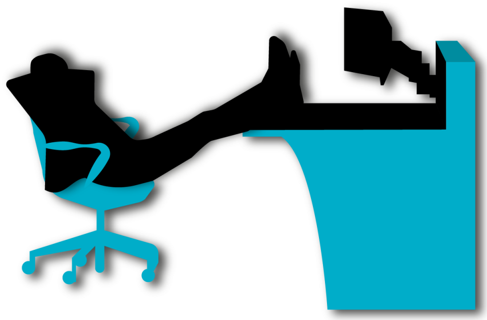

Figure 5.2: A symbolic illustration of a relaxed operator at a workstation. This image is not intended to imply a lack of responsibility or diligence among operators, but rather to represent a conceptual moment of reduced active work.

Relationship between Technology and Structure

Technology brings changes in the organisational structure and vice versa [18]. Interviewees working in the NPP domain mentioned in Study I that in a control room where more responsibility is laid on the technology (e.g., automation), the reliance on the technology will increase. Interviewees meant that this will make the relative importance of maintenance larger. Similarly, as highlighted by an interviewee from the TSO domain in Study I, the growing dependence on IT systems within this domain has necessitated the provision of continuous, round-the-clock IT support. Historically, such constant oversight was not required; however, the increasing integration and complexity of digital infrastructure have rendered continuous monitoring of the IT systems. This ensures that any issues arising during off-hours, including nighttime, can be promptly addressed by mobilising IT personnel or escalating the matter to appropriate specialists. The interviewee further projected that IT-related disruptions are likely to become more frequent in the future, thereby underscoring the critical importance of maintaining a high level of operational readiness.

These examples illustrate how technological advancements not only reshape operational practices but also influence organisational roles, responsibilities, and hierarchies. As technology assumes more decision-making and monitoring functions, traditional boundaries between departments—such as operations, maintenance, and IT—begin to blur. This necessitates new forms of coordination and communication.

In summary, increasing reliance on automation and IT systems could reshape organisational structures. As technology takes on more operational responsibilities, the importance of maintenance and continuous IT support grows. This shift is also fostering new collaborations between varying roles. Overall, technological integration is driving a transformation toward more adaptive and interconnected organisational models.

Relationship between Tasks and People

The emergence of new tasks necessitates the development of new skills to master them [18]. Interviewed operators and human factors specialists across domains in Study I emphasised that operators today possess extensive knowledge of their facilities, whether they are working within NPP, HPP, or TSO. Training, which is always conducted on-site, builds on their technical backgrounds. The participants in Study I and Study II generally did not anticipate a decrease in the technical knowledge required of operators. Additionally, the participants in both Study I and II describe that if the automation does not perform as expected, operators need to know what the system is attempting to do to address any issues effectively. However, many interviewees (also across domains) in Study I discussed that the loss of facility skills might be a consequence of higher levels of automation, which also aligns with the ironies of automation [30]. In a automated, digital future control rooms, operators will not only need to understand the facility but also have a grasp of the automated systems (Figure 5.3). Also, it was noted by questionnaire respondents that the skills operators must learn, has to do with solving IT issues. Furthermore, the interviewees from the TSO and HPP domains in Study I noted that decisions are currently made closer to the operating hour than historically, leaving less time for decision-making. Consequently, the interviewees described a probable shift in control-room tasks from data-based decision-making to decisions informed by models, forecasts, and Decision Support Systems, aiming to enable faster and more accurate decisions by the combined human-machine system. Consequently, interviewees from the TSO and HPP domains thought their work would shift from 'here and now' tasks to more preparatory ones. This shift underscored the importance of improved and trust-worthy forecasting and requiring operators to have sufficient variety or flexibility in their responses to match the variety of the environment [31].

In summary, in increasingly automated CRS within the TSO domain, operators must develop a comprehensive understanding of both the technical processes and the automated systems they supervise. Despite ongoing automation efforts, technical expertise remains essential, as operators must be able to interpret and validate the system's actions with confidence.

Relationship between Structure and Tasks

Study I highlighted that future operators—regardless of domain—will continue to require extensive facility-specific knowledge, while also needing to develop more advanced IT competencies. Although higher levels of automation are likely to reduce the amount of manual, day-to-day operational work, this may in turn lead to a decline in hands-on facility expertise. These concerns were reported in both Study I and Study II. Consequently, comprehensive and ongoing training will be essential. As more tasks are automated, it is critical to preserve the capacity for manual intervention in the event of system failures. This ensures that operators remain capable of managing the system effectively

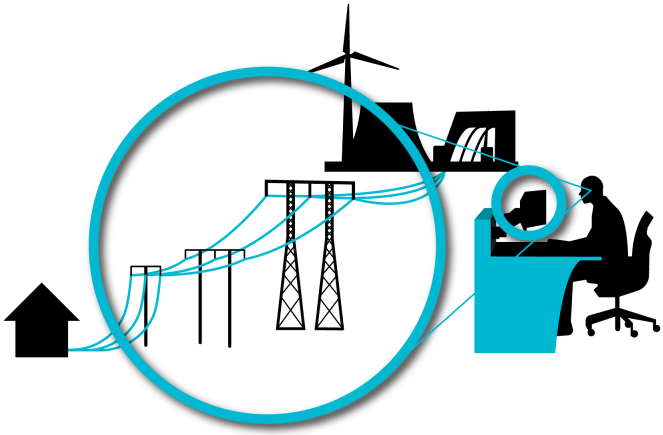

Figure 5.3: A conceptual overview of an operator in a CRS, monitoring the grid through computer interfaces. As systems grow more complex, operators must posses a deep understanding in both the processes they oversee and the automated system in place.

under both normal and abnormal conditions. As described in Studies I and II, new departments have already been established within the TSO domain to provide continuous IT support, which reflects the increasing frequency of system disturbances. With growing system complexity, IT-related disruptions are expected to become more prevalent, thereby necessitating a higher level of IT proficiency across organisations. Moreover, as automation reshapes routine tasks and decision-making processes, organisational structures must evolve to support emerging forms of work—such as system supervision, data analysis, and exception handling.

In summary, extensive training will be necessary to ensure that operators in the TSO domain can handle system failures and maintain manual operation capabilities. Additionally, the rise in IT disturbances with increased complexity will require more IT competence within organisations.

Relationship between Structure and People

The relationship between structure and people in an organisation undergoing automation is characterised by a need for adaptability and continuous learning. As the organisational structure evolves to integrate new technologies, the roles and responsibilities of individuals within the organisation must also transform [18]. Studies I and II emphasised the importance of training, skill development, and effective communication to support a smooth transition and sustain high levels of engagement. As manual tasks and calculations traditionally performed by operators are increasingly automated, their roles are undergoing significant transformation. This shift may also prompt changes in organisational structures.

New roles could emerge, or the existing ones may expand to include broader responsibilities—particularly if operator activity levels decline. For example, the establishment of new IT departments is already reshaping organisational setups. One interviewee in Study I highlighted the increasing reliance on IT systems and the corresponding organisational adaptations required to manage them effectively. (S)he noted that the role of IT-DC now operates on a 24/7 basis, reflecting the growing need for continuous system monitoring. Although improvements have been observed in recent years, the interviewee emphasised that incidents still occur during off-hours. As automation progresses, the organisation must adapt its training schedules to accommodate the need for continuous learning and skill enhancement. Training programs must be tailored to fit the evolving roles of operators, ensuring they are equipped to handle new technologies and processes effectively. Moreover, the organisation must foster a culture of adaptability, where employees are encouraged to embrace change and continuously improve their skills. This includes providing ongoing support and resources to help the operators navigate the transition and thrive in their new roles. By prioritising training, skill development, and effective communication, the organisation can ensure a successful integration of automation while maintaining a motivated and engaged workforce.

To summarise, automation in an organisation necessitates adaptability and continuous learning, transforming roles and responsibilities. This shift requires training to maintain technical knowledge, as well as new skills including IT knowledge. As manual tasks decrease, new roles may emerge, and organisational structures must evolve to support these changes, including the development of new IT roles and tailored training programs.

Chapter 6

Discussion

6.1 Empirical Considerations

This licentiate thesis has utilised interview and questionnaire studies, along with Leavitt's system model [18] to holistically explore and describe how the work of control room operators is affected by EPS changes anticipated by domain experts, with a particular focus on the TSO domain.

Study I - the interview study - addressed through RQ1a and RQ1b, explored future CRS trends, opportunities, challenges and operations from a Socio-Technical perspective. The findings indicated that the EPS is subject to a range of trends impacting the human–technology–organisation system. Both similarities and differences were observed across domains; while automation is anticipated to increase within HPP and TSO domains, it is not expected to grow significantly in the NPP domain—except potentially in the context of future SMRs.

Moreover, the domain experts contributed with diverse perspectives to the study, thus, suppliers and human factors experts offered more research-oriented perspectives, often referencing broader industry discussions, while the operators provided insights in relation to what change they have experienced. Furthermore, in the TSO domain, automation was generally welcomed, particularly in response to increased system volatility driven by a higher share of weather-dependent energy sources. However, concerns were also raised, including issues related to operator vigilance and the risk of deskilling. As a result, ongoing and recurrent training is regarded as essential. As EPSs grow more complex, automation is shifting the TSO operator tasks to more monitoring, with increased preparatory tasks. While automation was considered a solution to decrease the stress level in the dynamic power system, it also introduces uncertainty such as vigilance issues, deskilling, and need for new skills, such as IT comprehension. To ensure resilience, operators need recurrent training, strong IT competence, and recurrent training.

Given the identified developments in particularly the TSO domain, Study II - the questionnaire study - addressed through RQ2a, RQ2b, and RQ2c, examined the current and future tasks and tools of operators in the TSO domain, as well as the operators' attitudes toward changes in tasks, tools, and implementation of higher degrees of automation. The findings indicated that several recent initiatives have significantly altered the nature of operators' tasks in the TSO domain. The participants in both Study I and II generally expressed a positive outlook on increased automation, viewing it as a necessary response to the growing dynamism of the power system. Moreover, many participants anticipated that additional tasks will soon be automated. Nonetheless, concerns were raised regarding potential drawbacks, particularly in relation to skill retention. Despite these reservations, questionnaire respondents expected that improved tools will facilitate faster and more accurate calculations, thereby enhancing operational performance.

Categories of Findings

This section builds upon the summarising bullet points presented in the findings in chapter 4, responding to the RQs. Here, the bullet points are organised into the following five categories: Socio-Technical System Approach, Trends Across Domains, Tool Implementations, Attitudes Toward Automation, and Skills, Training, & Human Role (Table 6.1).

Table 6.1: *Categorisation of the summarised bullet points in the findings chapter.*

Category	**Summarised Points from Findings**
Socio-Technical System Approach	Volatile EPS, Operational Complexity, Decision Making, New Tasks
Trends Across Domains	Varying Trends
Tool Implementations	Outdated Tools, Rapid Tool Introduction, Implementation Challenges
Attitudes Toward Automation	Automation as a Solution, Perceived Drawback of Automation, Perceived Benefits of Automation, Reliability Expectations, System Feedback, SA
Skills, Training & Human Role	Deskilling, Training

Socio-Technical System Approach

One of the key assumptions behind the research in thesis is that the EPS can be viewed as a larger system made up of smaller, interconnected CRSs. These CRSs are socio-technical systems, where people and technology work together to ensure the power supply remains safe and reliable. From this Socio-Technical System perspective, changes to one element in the system will cause ripple effects throughout the whole system due to the interactions between these elements and the environment. The findings presented in this thesis contributes to the Socio-Technical System literature by empirically demonstrating how developments, such as technical development, in the EPS reshape operator roles and organisational structures in CRSs.

The findings from Studies I and II, based on the operators' accounts, revealed a domino effect driven by a systems approach, hence, changes in the environment lead to shifts in operator tasks, which then prompt the introduction of new technologies. These technologies, in turn, reshape tasks, required skills, and organisational structures. The transition towards renewable energy sources—particularly wind and solar—has introduced considerable variability and unpredictability into the EPS [1]. Correspondingly, the empirical findings of Study I and II indicated that these changes have has necessitated more active and adaptive roles for the TSO and HPP operators. In response, the CRS has implemented higher levels of automation to manage these challenges.

However, this shift has also redefined operator responsibilities, often turning them to more passive roles and introducing new operational demands. In addition, while the operators in the TSO domain in Studies I and II view increased automation of CRSs as essential for managing growing system complexity, these developments were also described to introduce challenges—particularly in terms of skill retention, system reliability, and trust in automation. These issues underscore the value of adopting a Socio-Technical Systems perspective, which broadens the analytical lens beyond purely technical considerations. The importance of considering a system's 'domino effects' cannot be overstated, as neglecting them can jeopardise the success of any system change. Based on this assumption, it was deemed appropriate to investigate changes in the Socio-Technical System using Leavitt's System Model, which focuses on the interrelationships between people, technology, structure, and tasks. In line with Socio-Technical Systems theory, this thesis has assumed that changes within the system inevitably affect operator work. The increasingly volatile nature of the system has shifted the focus from simple monitoring to active intervention. However, as automation becomes more prevalent, operator tasks are expected to become more passive, posing significant challenges during system failures. Despite potential shifts in skills towards bug fixing, extensive training is needed to manage system failures and maintain manual operation capabilities. Additionally, focused training, skill development, and effective communication are essential to ensure smooth transitions and maintain engagement and morale. Furthermore, organisational structures must evolve to support these changes, including the development of new IT departments and tailored training programs. These organisational adaptations reflect broader shifts in how Socio-Technical Systems evolve in response to technological change.

To conclude, a Socio-Technical Systems perspective was applied to understand how technological and organisational changes in the EPS affect operators, highlighting the interdependence between people, technology, tasks, and structure. As the supra-system evolves in terms of power dynamics and technological developments, the roles and tasks of operators, as well as the organisational structure, will change. Additionally, when automation and digitalisation increase, operators face shifting roles, requiring new skills, training, and organisational support to maintain system reliability and resilience.

Trends Across Domains

The trends identified in Study I aligned with previous findings in the literature, particularly regarding the challenges of integrating renewable energy systems into the dynamics, control, and automation of electrical power systems [14], [38]. Trends discussed in Study I and mirrored in literature also point to a potential increase in flexible operations within NPP domain [39], [40], driven by these heightened dynamics, as well as a possible shift towards the adoption of SMRs in the distant future [41]. However, this licentiate thesis provides a complementary perspective by incorporating empirical perspectives from domain experts, human factors specialists, suppliers, and both current and former operators to explore future trends and their implications. The interviews in Study I were conducted to explore emerging trends and their implications—an approach particularly well-suited for capturing forward-looking insights that may not yet be fully reflected in the literature. By engaging with practitioners and stakeholders, the research gains access to context-specific foresight, enriching the understanding of potential future developments in the field.

Moreover, many interviewees in Study I described the CRS sector as conservative, with a strong emphasis on risk management. Also, it was described that this often results in a preference for proven technologies over untested innovations. In safety-critical domains like NPPs, this conservatism is particularly pronounced, prompting extensive human factors research aimed at reducing human error. While the TSO domain is also critical, the consequences of failure are generally less severe, which may explain the relatively lower emphasis on human factors research in the TSO domain. Another possible explanation is that the Human Factors field—particularly the HTO area—maintains a strong historical affiliation with the NPP domain, as the discipline of Human Factors partly emerged in response to a series of incidents within the NPP domain [42].

Moreover, suppliers and human factors experts offered more research-oriented perspectives, often referencing broader industry discussions, while many operators provided insights into how changes have been experienced in practice. This means that the operators often described their outlook on the future as an ongoing process of change, basing their assumptions on the transformations they have recently experienced. Furthermore, in the NPP domain, most of the interviewed operators have experienced little to no technological change over the years. In contrast, the interviewed operators working in the HPP and TSO domains have witnessed more frequent developments, largely due to changes in the EPS. This imbalance suggests that a lack of exposure to innovation may hinder the ability to envision future developments. To summarise, it was fruitful to include different categories of interviewees in Study I to get a wide and nuanced understanding of the topic.

Finally, to explore how operators, their responsibilities, and organisational structures may be influenced by anticipated technological advancements, Study I adopted an open-ended, exploratory approach. Interviews with domain experts and questionnaires completed by operators in the TSO domain offered insights into both current developments and future expectations. While predicting the future is inherently uncertain, many participants in study I and II were speculating on the topic by grounding their views in historical trends, ongoing changes, or cross-domain comparisons.

In conclusion, Study I revealed emerging trends across control room domains. Main trend discussed was Automation, which may increase in the CRS domain in general, but at varying rates in the different domains. Meaning, the TSO and HPP domains appear more inclined to adopt higher levels of automation, due to system dynamism and operational stress. In contrast, the NPP domain showed a slower pace of change, with some CRS systems remaining largely unchanged since the 1980s. Here, automation was more frequently discussed by human factors specialists than by operators, who tended to focus on gradual digitalisation through new interfaces and data tools. For informants to effectively discuss future developments, it is often easier when they can anchor these projections in changes they have already experienced.

Tool Implementation

Most participants from the TSO domain, in both Study I and II reported significant changes in their tasks over the past few years, driven by the increasing share of weather-dependent power and the recent introduction of new tools, including higher levels of automation. Their attitudes toward these new tools were predominantly positive, recognising the potential benefits of automation in response to system changes. Interestingly, many of the operators in both studies raised concerns regarding classic examples of the ironies of automation [30], such as potential loss of skills and 'out-of-the-loop' issues because of higher levels of automation. The responding operators' concerns are well-aligned with those highlighted in the academic literature on grid operations. A key issue is the decline in SA, often attributed to a reduction in real-time information from field crews [13]. This challenge is especially important as the power grid becomes more advanced and more difficult to manage. The future grid is in prior research expected to include smart technologies that can monitor the system in real time, communicate securely and reliably, and make quick decisions automatically. These systems will need to react within seconds—or even faster—to keep everything running smoothly, all while dealing with more uncertainty and complexity than ever before [14]. Nevertheless, the findings in this licentiate thesis contributes to the existing body of literature by offering insights grounded in a Nordic context. It is noteworthy that the participants from Study I and II working in the TSO domain - despite positive wordings about applying automation - aware of the potential drawbacks of automation. A tentative explanation to this awareness could be attributed to events that have occurred either in their own control room systems or in others, such as the 2003 Northeast blackout in North America [15], [43]. This blackout was caused by a software bug in the alarm system, leading to a loss of situational awareness among the operators and culminating in a massive power outage affecting millions. Speculating on this, such incidents may underscore the critical need for operators to maintain a high level of engagement and situational awareness, even as automation becomes more prevalent.

In summary, while participants in Study I and II working in the TSO domain, generally regarded automation as a valuable response to the evolving demands of power system operations, they remained aware of its potential drawbacks. Their concerns—ranging from skill degradation to diminished situational awareness—reflected longstanding challenges documented in academic literature and observed in real-world incidents. This awareness highlighted the importance of designing automation systems that complemented, rather than replaced, human expertise. It was considered essential to ensure that operators remained actively engaged and capable of responding effectively in critical situations.

Attitudes Toward Automation

Automation has in Study I been identified as a main EPS trend, though its implementation varies across different domains. In the TSO and HPP domains, automation is seen as a solution to the increasingly dynamic system. In contrast, in the NPP domain, automation seem to be considered a feature of future SMRs or in other modern plants, which are more part of a distant future [41]. Meanwhile, automation initiatives in the TSO domain have already been implemented and are expected to continue to expand. Despite these differing levels of maturity, the interviewees across all domains reported similar potential organisational and operational impacts of automation. These impacts include passive operator roles, which may lead to vigilance issues, potential deskilling, and a shift in skills towards bug fixing and algorithm understanding as well as an increased 'relative importance' of maintenance as reliance on automation grows. In turn, these operational impacts raise critical questions about how operators can maintain SA and construct accurate mental models of the systems they oversee—particularly in environments where automation reduces transparency and direct interaction with the process. These concerns were also evident in Study II, where operators in the TSO domain expressed worries about deskilling as a result of increased automation, and noted that the new skills required may not align with their interests or motivation to learn. Previous research regarding diminished SA are well documented in the literature. The foundational work ofEndsley [28] on SA highlights the importance of maintaining awareness in dynamic systems, while other more recent studies have shown that reduced information flow and automation opacity can impair operators' ability to detect and respond to anomalies [13], [14]. As automation assumes greater control, the operator's role shifts from active engagement to supervisory oversight, increasing the risk of out-of-the-loop performance problems.

A systems approach reveals that as broader changes occur in the power system—such as shifts in energy dynamics and technological advancements—the operator role is also evolving. For example, the increasing reliance on weather-dependent energy sources is making balancing tasks more dynamic, requiring NPP operators to regulate power more frequently. This shift, coupled with rising automation levels, means operators will depend more on prognostic tools while making decisions closer to real-time also increases. As automation increases, the need for active system monitoring to prepare for potential failures also increases. This highlights the critical role of system transparency in enabling operators to understand system behaviour and intervene effectively. Prior research has shown that without clear and transparent feedback, operators may remain unaware of the automation's state [26]. Even when feedback is present, it may lack the transparency needed to capture attention—particularly when operators are engaged in other demanding tasks.

As the role of operators evolves alongside advances in automation, challenges will arise concerning the skills future operators will need, as well as how those competencies will be developed and maintained. Training and experience are crucial to maintaining situational awareness, and as automation increases, operators will need recurrent training to stay prepared. If *human* operators are to remain integral to CRS operations in the future, they must possess the competence and mandate to manually take over when necessary. This requires a comprehensive understanding of the entire Socio-Technical System, along with self-awareness of their roles and how they perform under stress and uncertainty. Consequently, it is vital that training programs are carefully designed to develop the required skills and competencies. As CRSs become more complex, the competence requirements for operators and their training programs must evolve. Furhtermore, the system itself must be designed to handle both external and internal complexities, in line with Ashby's Law of Requisite Variety [31].

To conclude, automation was a key trend examined in Studies I and II, though its adoption varied across domains. While TSOs had already integrated automation to manage system dynamics and were expected to further increase its use, the NPP domain viewed automation more as a future feature, particularly in relation to SMRs or modernised plants. Furthermore, the operators in the TSO domain who participated in the study regarded automation as a necessary response to the evolving nature of the electrical power system. Interestingly, however, they also expressed concerns—particularly regarding the risk of operator deskilling. Despite these domain-specific differences, similar impacts on operator roles were observed, and well-established human factors theories and models, such as Situation Awareness (SA) [28] and the Ironies of Automation [30], were applicable in describing effects such as reduced active engagement, potential deskilling, and a shift toward maintenance and algorithmic understanding. As automation and system complexity increased, maintaining SA required predictive tools and recurrent training.

Skills, Training & Human Role

Historically, operators have played a direct and hands-on role in managing processes across various domains, including NPPs, HPPs, and TSOs. However, with the increasing integration of automation, critical questions arise regarding the evolving role of operators. Specifically, what aspects of the system should future operators be responsible for controlling? What does it truly mean to be **in control**? Under what circumstances should operators intervene? How do operators develop and maintain control? And fundamentally, why is human involvement still considered essential in highly automated systems?

Perceived control [44] is commonly defined as the belief in one's ability to influence internal states and behaviours, affect the surrounding environment, and achieve desired outcomes. Understanding how this perception is formed and sustained in technologically advanced control environments is crucial for designing systems that effectively support human oversight and decision-making. To achieve a sense of control, operators will need to feel confident in their role and skills, as well as their ability to intervene when necessary. This can be supported through continuous training, simulation exercises, and robust support systems that allow operators to practice and refine their skills. Furthermore, another key factor influencing operator performance is how well the system supports trust [45]. When systems are designed to augment or replace human judgment, users may struggle to evaluate their competence directly. Instead, they must interpret the system's intentions, which can be challenging if the system lacks clear or understandable explanations. This ambiguity can hinder users from accurately assessing the system's reliability. Muir [45] emphasises the importance of trust calibration—operators should align their trust with the actual capabilities of the system. Effective operators know when to rely on the system and when to intervene, ensuring optimal performance. Training for future CRS should reflect this need for well-calibrated trust.

The future will likely see a greater emphasis on collaboration between humans and machines and therefore, operators will need to understand how to work effectively with automated systems leveraging their strengths while being prepared to step in when human judgment is required. Ensuring that operators maintain a sense of control is crucial for their psychological and emotional well-being. Organisations should provide support systems to help operators cope with the demands of their evolving roles. As roles and responsibilities change, organisations must adapt by creating new IT departments, developing tailored training programs, and fostering a culture of continuous learning and adaptability.

To conclude, as automation continues to reshape control room operations, the role of operators must be redefined with care and foresight. While technology can enhance efficiency and responsiveness, it cannot replace the nuanced judgment, adaptability, and situational awareness that operators bring. Ensuring that operators retain a genuine sense of control through training, system design, and organisational support is essential not only for operational safety but also for their psychological resilience. In general, as the world of process control move toward increasingly collaborative human-machine systems, the challenge will be to design environments where automation supports, rather than supplants, human expertise.

6.2 Methodological Considerations

The research methodology employed in this thesis involved a combination of semi-structured interviews and questionnaires, providing a comprehensive view of the current and future state of control room operations. The use of qualitative methods allowed for an in-depth exploration of operator experiences and perspectives across domains, while the data from questionnaires offered a more specific understanding of trends and attitudes within the TSO domain.

In accordance with a classical design process [46], investigations typically begin with a broad exploration to understand the context, challenges, user needs, and trends. This broad exploration is then narrowed down to focus on specific challenges, user needs, or other relevant aspects. Following this approach, Study I provided a broader perspective, highlighting trends anticipated by operators and domain experts. Study II narrowed the focus to specific domains (TSO) and themes (current and future operator tasks, tools, and attitudes).

Study I

It is important to note that the systems approach taken in this study provides a broad overview of potential EPS developments. This approach is necessary to lay the foundation for a more detailed and comprehensive future research. By establishing a broad understanding of the current trends and challenges, subsequent studies can delve deeper into specific aspects of the system and explore more nuanced interactions and effects.

A qualitative approach was used to find important aspects according to domain experts. In addition, a and theoretical analysis was then applied to find potential effects of the interview findings from a Socio-Technical System point of view. It is believed that the best insights into the future of control room operations come from those who are directly involved in the system. The perspectives and experiences of operators, human factors specialists, and other domain experts are invaluable in understanding the practical implications of technological and organisational changes. Their first hand knowledge and expertise provided a critical foundation for both current analysis and future research directions. Most of the interviewees concentrated on recent developments or upcoming changes, likely reflecting realistic trends. However, broader future trends may have been overlooked, as the responses often were closely tied to the interviewees' current work contexts and their own immediate future expectations.

Direct observations in control room settings could have provided additional insight into current operational needs, but it would likely not capture the future-oriented visions and reflections of experts with different roles, which was the focus of this study. Therefore, an interview study was chosen, where both current and future operation could be discussed.

Furthermore, the selection of participants was based on convenience sampling and was not intended to provide a proportional reflection of the empirical situation but rather to identify relevant aspects or dimensions of expected change. Consequently, the interview questions were open-ended and exploratory to allow for follow-up questions tailored to each participant's responses and explore themes unknown to, and uninfluenced by, the authors. To ensure consistency, the same interviewer conducted all the interviews.

Given the exploratory nature of the study, assessing its reliability poses challenges. Most of the interviewees based their responses on recent developments and foreseeable changes. While these insights likely reflect realistic trends, other potential future developments were not explored, as the participants focused on their current work situations.

One methodological consideration is the potential bias introduced by the convenience sampling method used for the interviews. While this approach facilitated access to knowledgeable participants, it may not fully represent the diversity of experiences and perspectives within the EPS. Future research could benefit from a more randomised sampling approach to ensure a wider range of viewpoints. In addition, automation has been a major focus of this research, it is not the only trend affecting control room operations. The emphasis on automation in this thesis is due to its prominence in the interviews and the substantial impact it is expected to have on operator tasks and organisational structures in primarily TSO domain.

Study II

When it became apparent in Study I that the implementation of automation was altering operator tasks in the TSO sector, a deeper investigation of this topic was justified. Adopting a user-centred approach, a questionnaire study with operators in the TSO domain was selected as the data-collection method. Given the challenges in reaching operators working in the TSO, this method was deemed most feasible. The questionnaire incorporated a mix of open and closed questions to collect both quantitative and qualitative data. Open-ended questions were particularly valuable in this context, providing deeper insights that are crucial when dealing with a small sample size, as was the case in Study II. Despite the small sample size, the questionnaire respondents' answers were remarkably consistent, which strengthens the validity of the results. However, it is important to note that a larger sample could further have increased the validity of the findings. The difficulty in accessing operators in the TSO domain and the lack of transparency regarding the total number of operators within these organisations posed significant challenges in determining the size of the entire population

Leavitt's System Model

Given the initially explorative research approach, it became apparent that a system model was needed to structure the findings of Study I and II. Leavitt's system model [18] provided a useful framework for understanding the relationship between technology, people, tasks, and structure within changes within the EPS. Given that the aim of this licentiate thesis involves understanding changes in operator work and organisational structure, Leavitt's model is particularly relevant since it emphasises the importance of balancing changes across tasks, people, structure, and technology, which is crucial for effective change management. While the model provides a simplified view of organisational dynamics, it may overlook the complexity and nuances of real-world scenarios. The original model from the 1960's [18] lacks an important component namely the environment. Therefore, this component was added, similarly as other research studies have done, e.g., [20] [21]. This addition not only addresses a key limitation of the original 1960s model but also reflects the evolving understanding of organisations as open systems influenced by external factors.

Leavitt's system model was chosen as an analytical tool after Study I and II had been designed. By choosing the model after constructing the interview - and questionnaire questions, helped avoid bias in the data collection process. If the model had been chosen beforehand, there might have been a tendency to frame questions in a way that fits the model, rather than allowing the data to speak for itself. This approach ensured that the interview material is unbiased and open-ended, leading to more authentic and diverse responses. This approach allowed for assessing of specific needs and dynamics of the study findings before committing to a particular model, ensuring that the chosen framework to be an appropriate fit for the research objectives.

Chapter 7

Conclusion

This licentiate thesis adopted a Socio-Technical Systems perspective to holistically explore and describe how the work of control room operators is affected by EPS changes anticipated by domain experts, with a particular focus on the TSO domain. The research presented in this licentiate thesis highlighted the complex interdependence between people, tasks, structures, technologies, and environments.

The findings revealed several key trends shaping the CRS operations; increasing complexity in grid balancing, higher levels of automation, the introduction of new support systems, and greater digitalisation. Primarily, the TSO domain is expected to gradually adopt higher levels of automation to manage the growing system complexity. In contrast, the NPP domain is expected to undergo a more moderate transformation, with automation likely to emerge primarily in the context of SMRs, potentially part of a distant future. Furthermore, the operators in the TSO domain generally described automation as a necessary response to the shorter time-spans and automation is already reshaping operator roles—shifting them towards increased supervision. However, this transition also raised concerns regarding deskilling and reduced vigilance, which underscores the need for IT skills and recurrent training.

Moreover, this licentiate thesis provided complementary perspectives to that of prior research by incorporating empirical perspectives from varying domain experts to explore the future CRS. Different domain experts contributed with diverse perspectives. For example, human factors experts offered research-oriented views grounded in industry trends, while operators shared practical insights, based on their experienced change. Notably, the interviewed operators working in the NPP domain reported generally minimal technological change, unlike their TSO counterparts who have faced more frequent developments, highlighting how limited exposure to change may hinder foresight and emphasising the value of diverse interviewees for a nuanced understanding.

To conclude, addressing the challenges of the EPS as a Socio-Technical System demands a holistic approach that considers the complex system interplay. Without this perspective, isolated improvements risk undermining overall system performance.

Chapter 8

Future Work

Building on the findings presented in Study I and II together with the Socio-Technical approach, an idea for future research could be to explore the implications of increasing automation on operator roles and system performance across the EPS. Meaning, it could be of interest to explore the impacts of automation initiatives implemented by TSOs on the roles and tasks of operators or other actors within the HPP or DSO domains.

Furthermore, given the generally positive attitudes towards automation amongst operators from the TSO domain, yet scepticism regarding the implementation of new tools, research on technology acceptance could also consider the factors influencing the uptake of new technologies in automated TSO environments.

Moreover, future studies could also investigate how automation is reshaping the nature of operator work, including the emergence of new roles, the competencies required, and how organisations can support staff in adapting to these changes. One important factor to foster skills is thus training, and further research could therefore also investigate how training should be designed for operators to develop the needed future skills.

In addition, it is also important to understand how automation has been received by operators in the TSO domain, what effect it has had on their work, and how it might be further developed to enhance system safety and stability. In this context, factors such as automation transparency and user trust need deeper exploration. Future research could therefore focus on examining how transparent automation systems influence operator trust and performance, and how training strategies can be designed to support operators in adapting to new technologies. Such strategies should aim to keep operators engaged, build their confidence in handling system failures, and support skill retention in increasingly automated environments. They should also explore how future operators can remain **in control** when working in automated CRSs in volatile EPSs.

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