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Towards the integration of IT/OT technologies in Electricity Based Digitalized Energy Systems

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ABSTRACT:
This integration of information technology (IT) and operational technology (OT) in electricity based digitalized energy systems (EBDES) holds significant influence in data driven decision making, improved real time monitoring, and increased operational efficiency. However, this integration also introduces numerous complicated challenges notably with regards to interoperability, cybersecurity issues, and effective deployment of advanced technologies like machine learning (ML) and artificial intelligence (AI).

Additionally, the study emphasises on the increasing cybersecurity threats to the energy systems due to the digitalization. It further explores the role of energy components in energy systems and challenges associated with it, highlights the critical role of energy components in the integration of IT and OT and cybersecurity challenges associated with it- variable frequency drive (VFD).

The study also investigates the role of programmable logic controllers (PLC) and supervisory control and data acquisition (SCADA) systems with the integration of IT and OT. PLC and SCADA are critical parts of industrial control systems and are crucial for enabling automation, real time monitoring and control of infrastructures. The research underscores the importance of implementing the best cyber security practices to enable this industrial automation that facilitates secure digitalized monitoring and control of operation technology.

Further, the study emphasizes the necessity of an integrated strategy that incorporates investments in the adoption of technologies that enable modernization of current energy systems. The findings of this thesis call for the adoption of advanced technologies such as AI and machine learning, IoT devices and blockchain technology to add security features towards system resilient against cyber-attacks.

This thesis examines these reported issues by using a mixed method approach, that utilizes triangulation analysis method for the study and integrates quantitative data from surveys of energy professionals with qualitative data from workshops and interviews. The results reflect that integration enables predictive maintenance and allows flexible responses to operational changes, but interoperability is still a significant challenge between IT and OT integration in digitalized energy systems specifically dependent on OT role in these critical infrastructures, with emphasizing the criticality of cybersecurity in vulnerable energy systems.

KEYWORDS: electricity based digitalized energy systems, energy system, integration, IT/OT.

Contents

List of Figures

List of Tables

1 Introduction

The modern energy system in the utilities is a combination of control of physical assets and digital assets. These systems are also seen as the innovation of the future whose maximized potential is yet to be explored. However, historically utilities have performed secured operations but digitalization within energy systems brings in host of opportunities and challenges. Figure 1 shows the evolution of energy system, the energy sector globally is undergoing serious transfiguration propelled by digitalization, decarbonization and decentralization. This transfiguration denominated as digitalization of energy systems is remodelling the methodologies of energy generation, transmission, distribution, and consumption.

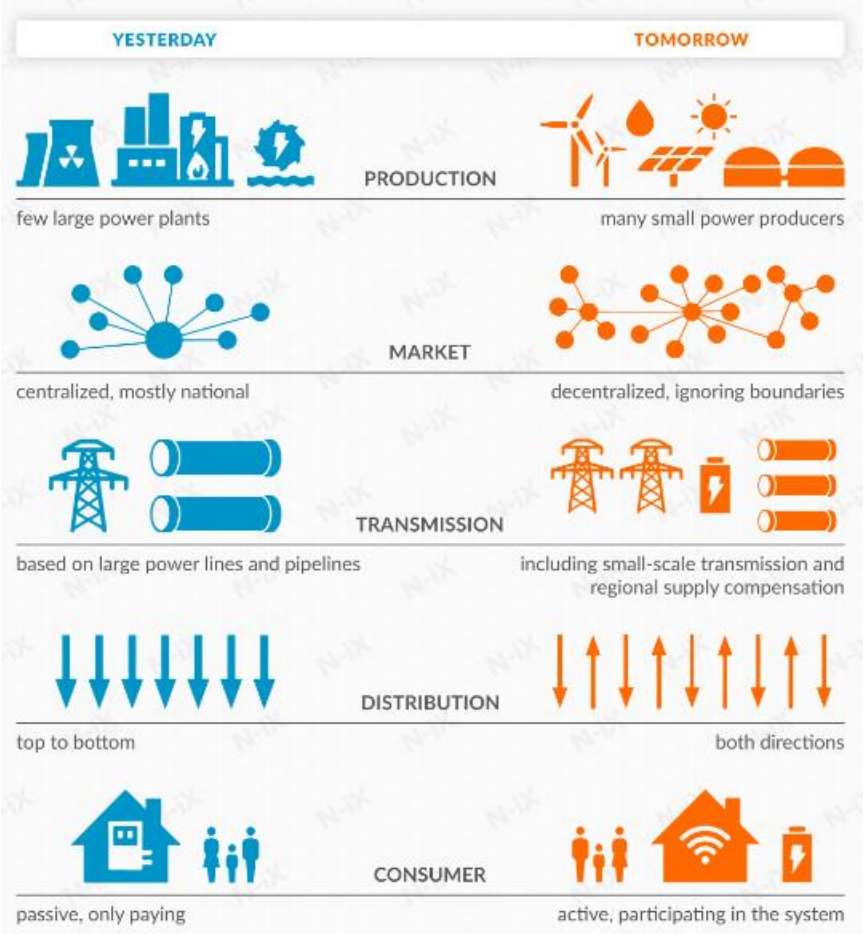

Figure 1. Digitalization of Energy system, (N-iX)

The evolution is a result of not only demand & requirement but technological innovation and environmental concerns also. Traditionally, energy systems were centralized and one directional which relied heavily on fossil fuels and distributed through hierarchical grid to end users. In the late 20th century, industrial automation was introduced to energy systems that enhanced operational efficiency. As the awareness for climate change and need for sustainable solutions grew, the 21st century witnessed an important shift to inculcate renewable energy sources (RES) such as wind, solar and hydropower. However, the integration was overall cost effective but introduced new challenges in the traditional energy system as they were not designed to handle variability and decentralization linked with renewable energy. Distributed generation, which supports energy consumers to also act as prosumers began to emerge, demanding a more dynamic, proactive and responsive system.

This paradigm shift introduced the concept of smart grids which creates critical phase in the evolution towards digitalized energy systems. These smart systems provide two-way communication between the grid and end users. The transition also resulted in increased decentralization of energy production and consumption with the enabling of energy storage systems such as battery and electric vehicles. The comprehensive digitalization of energy infrastructure includes deep integration of information technology (IT) and Operational technology (OT), transforming conventional power grids into cyber physical systems.

1.1 Background on Digital Energy System

Today digitalization is equivalent to smart and interconnected, which is why technological advancements are being made to develop smart cities, smart towns, smart buildings, smart grids. These smart plannings to meet the growing demand of clean energy and sustainable solutions have also necessitated the digitalization of Electricity Based Digital Energy System (EBDES) which have made them interconnected and automated. EBDES includes smart grids, that uses sensors and automation to process energy demands dy-

namically, it also includes distributed energy resources- solar panels, wind turbines, battery energy storage systems, and advanced metering infrastructure that allows consumer to monitor their energy usage in real time, it also include IoT devices like smart meters, sensors and actuators, smart thermostat, EV chargers, distributed energy resource controllers, energy management systems (EMS), additionally it also includes future technologies that enhances interconnectedness, data analytics, software platform, AI technologies. Together these components function together to build an intelligent, flexible and interconnected energy ecosystem that lowers down emissions, supports integration of renewable energy sources, and strengthens resilience and reliability of power gird. The digital advancements in EBDES have changed the dynamics in energy market by facilitating energy savings, flexibility and convenience. Companies in the industrial sector are now advancing into the technological part which now no longer limits the industries to only manufacturing but makes them data driven too. The recent industrial efforts towards the data centric operational process of manufacturing highlights the importance of standardized and easily accessible data.

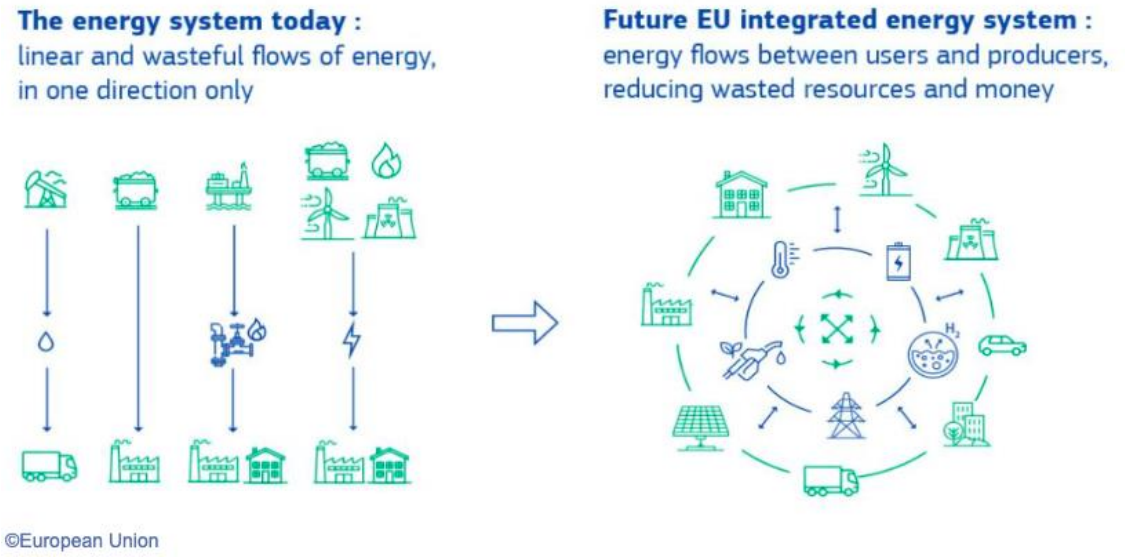

Figure 2. EU strategy on energy system integration, *Source: [EU strategy on energy system integration (europa.eu)]*

Additionally, the official website of European union (European Commission) states that there is a strong focus on digitalization from the European union (EU) under the European green deal targeting climate neutrality by 2050 and deep decarbonization by 2030 which is a strategy of energy system integration. Under this strategy the EU has taken initiatives such as renewable energy directive, electricity market design, energy efficiency directive, and energy performance of energy directive which aims to optimize energy systems by planning demand, supply, storage and consumption. The European commission also highlights the wastage of energy through current linear energy models of traditional energy systems where energy flows in one direction only therefore, EU promotes bidirectional direct electrification to end users which empowers consumers, prioritizes self-production, local production and reduces wastage of energy and resources as can be seen in figure 2.

Moreover, digitalization in EBDES facilitates flexibility in the energy system, generation of energy from renewable resources, supports energy storage technologies such as grid-based battery storage, pumped hydropower and distribution of energy through interconnected distribution management system (DMS) and demand response system (DRS) in buildings to support consumption with optimized planning. The successful implementation of flexible, reliable, integrated renewable energy production in electrical grid resulted in smart grids with the help of digital technologies, sensors, and advanced software's.

Overall, digitalization has led to the convergence of information technology (IT) and operation technology (OT). Infact, OT is hardware and software that has been traditionally part of energy systems to capture and monitor real time data. It is therefore involved with physical devices and processes. Technologies such as supervisory control and data acquisition (SCADA) which is a centralized control system that supports real time monitoring, programmable logic controllers (PLC) support automation of machinery, distributed control systems (DCS) support control processes in power plant, remote terminal

unit (RTU) supports communication and ensures operational continuity are part of EBDES. While IT encompasses tools that support large data management, real time data analysis and communication. It makes system autonomous by making machine to machine communication possible because of employing wireless communication over standardized network protocol to communicate data bidirectionally from physical system to central server and vice versa. Additionally, data driven innovation has made technologies such as data analytics, cloud computing, machine learning integral of EBDES.

However, the integration of IT and OT in EBDES is promising huge potential, it also presents consequential challenges of cyber intrusion. One of the most imperative challenges is cybersecurity. Though the interconnected systems provide proactive, advanced infrastructure and functionality it also makes it more susceptible to cyberattacks. Robust security measures are required to protect IT/OT integrated systems so that operational data and control systems are not compromised to hackers. Furthermore, establishing interoperability between IT and OT could be an additional challenge. The integration procedure is complicated and expensive because OT systems were not designed to integrate with advanced IT platforms or to connect with internet.

1.2 Research Gap

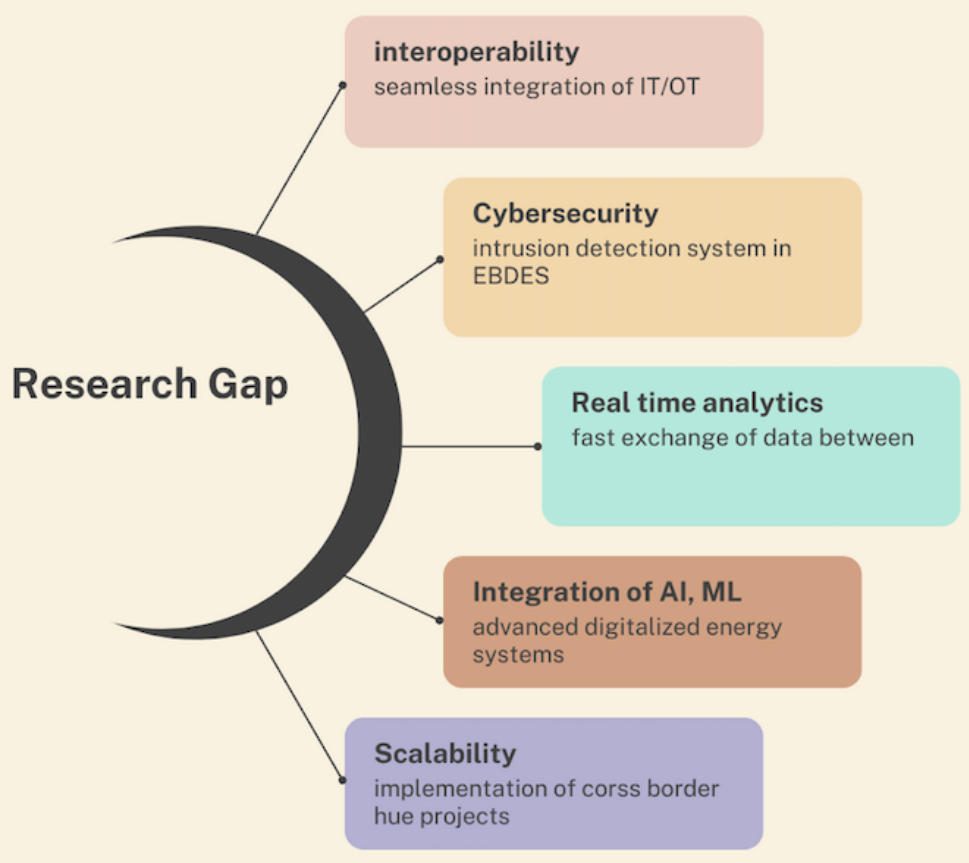

Figure 3. Research Gap highlights

The energy system traditionally has always comprised of generation, transmission, distribution and consumption irrespective of introduction of digital technologies today. When the revolution of power grid took place, it was growing with huge demand mostly in industrialized countries. The traditional electric power generation from grids were centralized systems with huge transmission and distribution system. Effectively, with technological innovation and implementation transmission lines underwent scientific upgradation with human monitoring which introduced digital OT systems into the grid such as SCADA. The electrification has resulted in numerous technological advancements, it has been recognized as the engineering achievement of last century by US National Academy of Engineering (Simões et al., 2012). Historically after the year 1970 the

information and communication technologies (ICT) flourished, which marked the beginning of industrial revolution. This information era changed to digital era and formulated new business and economic models by adopting technologies of electronics, telecommunications, and computers. A study on data by Timmer & Ark (2005) reflected on slow economic growth in EU in the early 2000 due to the low investment in ICT and rapid productivity growth in the U.S due to capital deepening in the energy sector. Eventually with higher demand for energy and intelligent energy systems to fulfil the requirement the introduction of ICT into the grid was formulated which was mainly focused on ICT software. With the integration of IT in the energy system, advancements were adopted on the distribution side also facilitating integration of renewable energies. Gradually IT/OT integration paced, and concept of smart grid emerged. This convergence of IT and OT improved energy efficiency facilitated generation and integration of clean energy, and reliability of the EBDES. However, despite potential benefits the convergence possesses strategic and technical challenges.

Due to different working environments and distinct processes of IT and OT systems they have disparate work matrix which does to completely support seamless exchange of data and command between business applications and OT control systems which is a limitation and requires modern solutions and research. IT systems are typically predesigned for cybersecurity that emphasize on principles of confidentiality, integrity, and availability (CIA triad) to ensure security of information from unauthorized access while OT are traditional systems which deals with physical assets monitoring, designed for physical security, and prioritize availability to perpetuate uninterrupted operations. Consequence of these attributes OT tends to be less flexible in accommodating updates and security patches due to the strong requirement of operational continuity, in contrast to the IT systems that can accommodate persistent security updates and modifications. Thus, highlighting that OT can become vulnerable when connected with IT networks. Current research lacks the tailored cybersecurity model for IT/OT integration in EBDES. Moreover, large scale projects for transnational grid integration and adaptation of decentralized energy architecture require dynamic and scalable solutions. Collectively, research is void

in the areas of interoperability, cybersecurity, real time data analytics, integration of AI and machine learning, scalability presents strong areas for exploration to make EBDES more efficient, reliable, secure and resilient.

1.3 Motivation for research

The motivation for this research arises from the pressing need to address the opportunities and challenges that come with convergence of IT and OT, specifically considering energy sector's transition to a more decentralized and digitalized paradigm.

The ascent of RES, distributed energy resources (DER), smart grids, and prosumer engagement has added complexity to energy management. Real time- coordination, improved system control, data driven decision making and cyber intrusion detection are the key areas which necessitate research in collaboration with digitalization enabling technologies.

1.4 Objective and scope of thesis

The primary objective of thesis is to investigate the shift in energy system in transforming to critical systems which will explore the opportunities and challenges associated with the integration of IT and OT in electricity based digitalized energy systems. The study particularly focuses on determining effective solutions to improve operation efficiency, improve cybersecurity, and implement real time data analytics to facilitate energy consumer and energy company both and at the same time. Also, this research aims to contribute to industry knowledge and future research directions.

Additionally, study will address following research questions:

- What is the state of efficiency of electricity based digitalized energy systems when IT and OT integration is implemented?

- What are the challenges associated with the integration of IT and OT in electricity based digitalized energy systems and how can these challenges be effectively addressed?
- How are the electricity based digitalized energy systems vulnerable to cybersecurity?

Traditionally IT and OT networks individually delivered the expected efficient, reliable outputs within their scope of work. Now with the digital advancements in the utilities the convergence of IT/OT has proved a future picture of modern, reliable outputs with enhanced productivity which merges the digital information domain with physical operational domain to implement one uniform body for business processes, comprehensions and controls. The scope of this thesis focuses on the integration of IT and OT in the energy based digitalized energy system. It will explore the crucial areas of integration that will strengthen the operations of smart grids, enable implementation of renewables, enable efficient decision making and energy management, improve resilience of EBDES. It will also examine the challenges subjected to technical and operational field of IT/OT integration in EBDES such as lack of universal standards to implement effective integration that challenges data exchange and interoperability due to traditional legacy systems. A significant underscoring will be done in the area of cybersecurity because the convergence results in increased exposure to cybersecurity threats due to interconnected energy systems. Additionally, the research will delve into the cultural and organizational impediment that constrains the collaboration of IT and OT within the energy companies. This thesis aims to explore the future trends of working on large amounts of data to drive actionable insights which will investigate how the next generation technologies such as AI, machine learning (ML), internet of things (IoT), and 5G operates in EBDES and drive next phase of paradigm shift in the digital transformation in energy sector. The evaluation of this thesis will reflect on the notable skill gap within the field of IT/OT and its importance. Subsequently, research is also required in the area of cost benefit analysis for the integration of IT/OT in EBDES to make sure the implementation reaches the small,

medium and large capacity companies to develop innovative energy systems. Geographically the research will primarily focus on developed markets of Europe, North America and parts of Asia.

1.5 Structure of thesis

This thesis is structured to provide a comprehensive exploration of the topic towards the integration of IT/OT in energy based digitalized energy system. The approach to thesis follows a list of chapters which cover specific areas.

Introduction: This section presents background to the topic and introduces electricity based digitalized energy systems. The idea of discussion is to familiarize with the subject digitalization in energy system, its evolution and explains the objective, motivation and goal of the study.

Literature Review: This section presents the previous relevant research around the topic and its importance within the field of energy sector. It discusses various study around IT/OT integration, its development, application, opportunities and challenges. Additionally, it will explore study in the area cybersecurity challenges, key enabling technologies. Another key area within our study is the component of energy systems that will explore the technicalities of variable frequency drive and related cyber risks. OT systems such as PLC, SCADA will also be discussed and explored. It also highlights different perspectives on studies with a common goal to improve and modernize the functionality of energy systems.

Methodology: This part covers the method of study on the topic. It will present details of the mixed method approach and related qualitative and quantitative data which will be collected through interviews, workshops, and surveys.

Results and discussions: This section interprets the findings of the study and provides insights into the research objective. Additionally, this part will also discuss the findings and outcomes.

Conclusion and Future recommendation: This section summarizes the key findings and insight into the study, highlights the importance of study of research gap and its results. Further, this chapter will provide actionable suggestions based on the study.

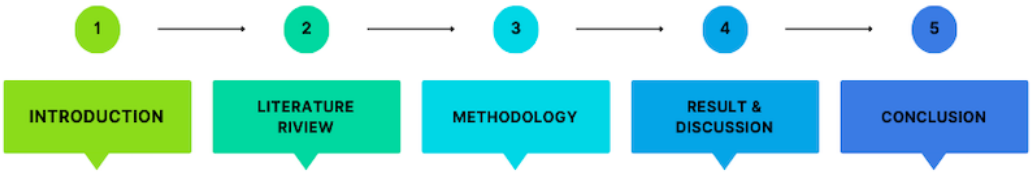

Figure 4. Structure of thesis

2 Literature Review

Expansion of digitalization in the field of energy systems has resulted in the research of IT/OT convergence in utilities. However, the studies are mostly centered around IT/OT technologies in the smart grid such as deployment of advanced metering infrastructure (AMI) and SCADA together will facilitate integration of IT/OT and introduce complete visibility of distribution company's residential, commercial and industrial energy consumer as well as distribution transformers, substations and feeders (Ahmed, 2016) to the end user. Convergence of IT/OT in EBDES is integral and building future to deliver smart analytics will consider whole data of product and system life including product structure data, manufacturing process data, logistics data, operations data generated from machines (Yi and Mueller, Yu and Chan, 2017). Lately, cyber security in modern energy system is another area of research which is focused and includes case studies such as risk management approach in smart grids from IT and OT domain in Shriaz power distribution company (sajjadi and Niknia, 2013). A study from Hofstedes (1998) theory of organizational culture as a lens explains the differences between IT and OT and concludes OT is prone to cyber-attack because convergence of IT and OT is inevitable (Murray, 2017). The digital advancement of OT in EBDES has made IT a crucial area of research and interest. Following this a study has been conducted on the distributed denial of service (DDoS) attack on IT to develop a model to predict vulnerabilities in the interconnected digital network (Rao et al.,2022). Considering previous research, a cyber security analysis capability automatic modelling was also proposed for smart grid load balancing (Välja and Margus, 2018). However, despite having numerous studies in the past and ongoing body of research the energy system is dynamically evolving every day, there remains a need for further investigation into the opportunities, challenges and risk posed by the convergence of IT/OT in the EBDES.

An understanding of topics related to integration of IT and OT in secular areas will be covered hereafter along with discussion on literature related to emerging technologies in this field which could lead to new innovations.

2.1 IT/OT integration in electricity based digitalized energy system (EB-DES)

The transformation of the energy sector into digitalized data driven ecosystem has re-shaped the process of production, distribution and consumption of energy, it also added efficient storage as integral part of EBDES. According to a study by Mohammed et al. (2020) the key to the digitalization in energy system lies in the proficiency of bridging the gap between IT systems that has the ability to handle enormous amount of data and analytics, and OT systems that control physical infrastructure like substation, transformer, transmission lines.

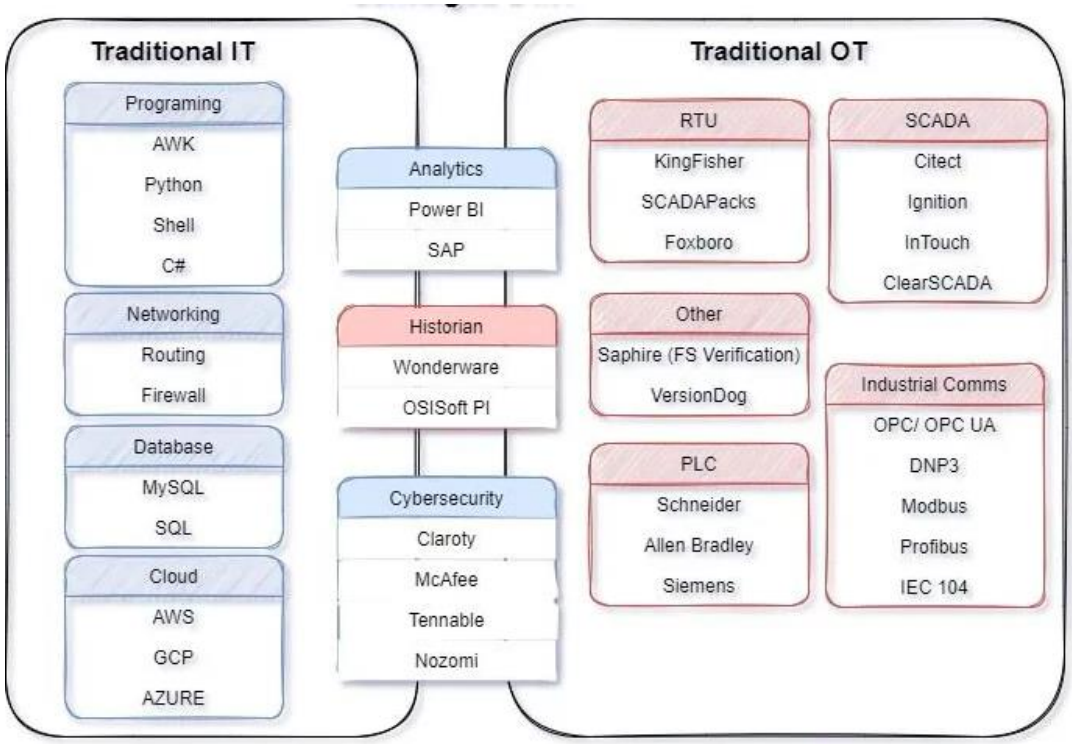

Figure 5. system integrator competencies in the age of IT/OT convergence, Yifan J.,2021

Underscored by Alahakoon and Yu (2016), smart grids are formed as product of convergence of IT/OT, enabled by real time data exchange to balance supply and demand. Technologies such as SCADA, PLC, DCS are legacy systems of OT that enables real time control and monitoring of physical infrastructure (Brundage et al., 2019) as can be seen in figure

5 and are part of energy sector. This OT system operates in isolation from IT infrastructure with minimal exposure to external networks due to its predefined operations and features like independent operability, longstanding stability, reliability of its functions unlike IT operations of managing data at organization level, inter data communications, cloud storages and business management processes (Mayo & Turnipseed, 2018). Sustainability and decarbonization can be achieved through the convergence of IT and OT and is vital for achieving operational efficiency as explained in table 1. Research by Fischer and Jones (2020) about integration of IT and OT puts light on the opportunities of seamless flow of information for energy companies in this constantly changing environment for the possibility of flexible and remote monitoring, asset management and involuntary controls. The convergence also presents support in the area of grid optimization because of challenging intermittent nature of renewable energy integration by developing energy management system (EMS), automated distributed management system (ADMS). Another study on the integration of renewables and distributed energy resources explains that it has made energy systems complex, leading to challenging real time data exchange between IT and OT for fault detection, load balancing and predictive maintenance (Mayo & Turnipseed, 2018).

Table 1. Aspects of IT and OT in Energy sector (comprehended with AI)

Aspect	IT (Information Technology)	OT (Operational Technology)	Convergence in Digital Energy
Focus	Data processing, business insights	Real-time control of physical systems	comprehensive regulation and control for decision making
Primary Users	IT staff, analysts	Engineers, operators	Cross-functional teams to increase efficiency
Data Processing	Batch, historical analysis	Real-time data	Predictive and real time data analysis
Security	Cybersecurity	Physical and cybersecurity	Integrated multi-layered security
Reliability Needs	High availability	Critical uptime	Enhanced fault tolerance and reliability
Protocols	TCP/IP, HTTP	Industrial protocols (Modbus, IEC 61850)	Protocol translation and secure gateways
Devices	Servers, cloud systems	SCADA, PLCs, sensors	IoT, edge devices
Role in Energy	Business optimization	System control and monitoring	Optimized, sustainable energy management

2.2 Cybersecurity challenges in IT/OT integration

The current scenario depicts the recognition and acceptance of IT/OT convergence in the utilities over IT and OT as siloed department because of its advantages of improving operational efficiency and improved decision making but practically it also possesses vulnerabilities and threats. The merger of IT and OT has resulted in a bigger surface attack which is one of the primary cybersecurity challenges as shown in figure 6. Due to this reason the traditionally confined OT networks exhibit digital vulnerabilities including malware, ransomware, and distributed denial of service that afflict IT networks too (Humayed et al., 2017).

In 2015 Ukraine's power grid was attacked, the attackers gained access and shutdown parts of grid and disabled telephony systems (Murray, Johnstone and Valli, 2017). This attack reflected the threat on critical infrastructure due to the limitation of OT working in relative isolation from IT systems and infrastructure which is also termed as air gapped

(Murray, Johnstone and Valli, 2017). The air gap theory presents the drawback of OT companies of not taking measures for cyber-attacks due to not considering it as a threat to OT components. This complacent approach may arise another vulnerability during the maintenance period by using maintenance aids such as USB flash drive, laptops, portable hard drives which are not secure. The malware attack of Stuxnet worm attack which was transmitted into the system through an infected USB flash drive took control of the PLC and destroyed the system (Falliere, Murchu, and Chien, 2011). Both the Stuxnet and Ukraine power grid attack explains the role of advertent or inadvertent human intervention led to the opportunity of exploitation of OT operations which highlights the inefficient integration of IT and OT, lack of standardization and increased security risk as in figure 6.

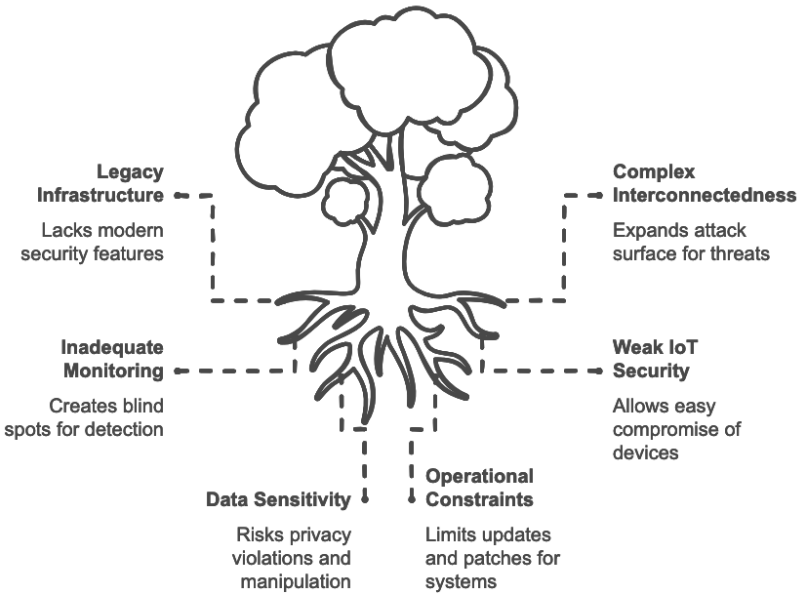

Figure 6. cybersecurity challenges in EBDES (generated with AI tool Napkin)

The OT are legacy systems and are built on outdated technologies with minimal consideration for cybersecurity. These systems often cannot be patched without discontinuing operations, have nominal encryption and are controlled by secured private protocols (Krotofil et al., 2018). On the other hand, IT is a self-evolving modern system that can undergo downtime for updates and patching. Consequently, often OT systems remain

unpatched thus, presenting system to vulnerabilities as in figure 6. Therefore, lack of compatibility makes the system complex and inefficient.

One of the studies by Shahid and Farooq (2020) highlights the importance of presence of encryption and authentication mechanisms and argues that lack of these features in OT communication protocol increases the risk of attacks such unauthorized access, denial of service and data mutation, and operational disruptions.

OT systems such as PLC, SCADA are operated via standardized network-based communication protocol such as DNP3 and Modbus which puts them at risk due to interconnections. According to Ten, Liu and Manimaran (2010) SCADA systems often use communication protocols that do not support security measures and have constraints to facilitate encryption or authentication procedures, making them vulnerable to illicit access. Because these OT systems are designed as a physical isolated traditional system with a definite process therefore on merging with IT systems, these systems often lack built-in security features which makes them vulnerable to man in the middle attacks, denial of service attacks (Zhou et al., 2020). IT and OT integration together has created an expanded attack surface and more potential vulnerabilities in the system. With the increase of deployment of devices such as IoT devices, sensors the networks are more exposed to threats besides offering data communication. As a result, critical infrastructures become more vulnerable to cyberattacks from malware to advanced persistent threat (APT). A study is conducted by Lu et al. (2020) to emphasize the importance of development of intrusion detection system (IDS) and firewalls in critical energy system.
The digital transformation in digitalized energy systems is enabled by internet of things (IoT) and industrial IoT (IIoT) that facilitates real time monitoring, predictive maintenance and operational efficiency (Gunduz and Das, 2020). The integration of IoT devices, smart meters and DER's creates a big, interconnected network surface with multifarious probable entry points for cyber threats. Amin, Giacomoni, and Sastry (2011) argue that there is high probability of cyber-attacks to penetrate through the system leading to potentially causing widespread disruptions due to interconnected systems. Additionally,

the expansion of DER's (solar panels, wind turbines and electric vehicles) results in increased cybersecurity challenges. Digital platforms enable connection of these resources to the grid to maintain system stability via real time communication. However, Liang et al. (2017) emphasize that decentralized nature of these resources complicates the implementation of centralized security measures, leading to increased susceptibility to attacks that may compromise the stability of grid.

The literature highlights many IoT and IIoT devices fall short of security features for example encryption and secure authentication and are usually present at the end of network chain, therefore, are likely to be the main target of any cyber-attack (Alcaraz and Lopez, 2021). Zhang et al. (2019) evidently presented how fragile IoT devices with feeble security can be compromised in industrial environment to launch large scale attacks or to act as a channel of exploit for malware introduction.

Saxena, Singh, and Misra (2017) asserts that data generated by smart meters and other devices holds sensitive information concerning energy consumption patterns to a household which can be accessed by unauthorized parties to exploit data. For instance, if an attacker gains access to smart meter data will also acquire information of resident's activity which may lead to privacy violations or criminal activities. Subsequently, any manipulation to data may culminate to false billing, energy theft, or market manipulation, resulting in serious risk consequences to both consumer and energy provider.

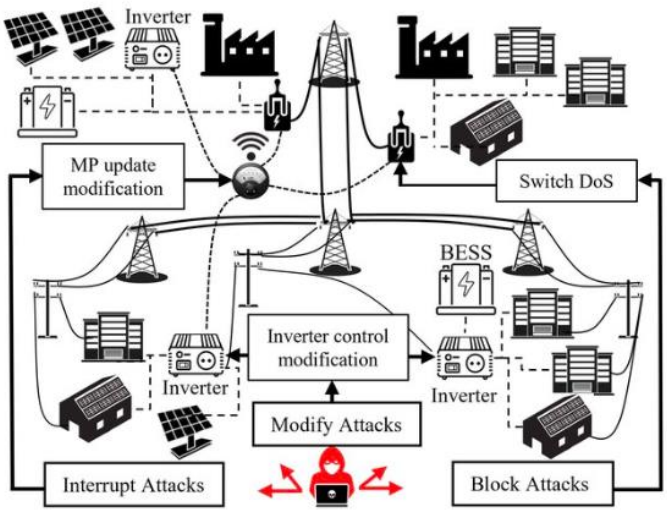

Figure 7. security assessment and impact analysis of cyberattacks in power system, Ioannis et.al, 2021

Figure 7 depicts that power grid possess the risk of cyber-attack where malevolent actor can take control of the grid and destabilize it, the type of attacks on power grid ecosystem can be categorized in three classes namely data modification attack, loss/blocking attack during critical system operations, interrupting critical systems operation attack. These attacks could be where the inverter is forced to operate at a fixed power factor which is causing voltage issues and system ineffectiveness, making power cuts by limiting the active power injected into the grid, the reactive power in the grid is controlled to make voltage issues at connection point (Ioannis et.al, 2021).

The cybersecurity challenges corresponding to IT/OT integration are miscellaneous and heterogeneous that can comprise technological, operational and human aspects together. The literature presents critical areas of concern in EBDES.

2.3 Cybersecurity in Energy component- Variable Frequency Drive (VFD)

Electricity based digitalized energy systems pivot on third-party components and software which makes them vulnerable to supply chain risks. Kushner and Bou-Harb (2021) highlights in their research that adversaries often exploit weak links in the supply chain

to introduce malware, compromised devices. Variable frequency drive (VFD) is an important component in energy systems and in EBDES.

2.3.1 Role of Variable frequency Drive (VFD) in Energy Systems

VFDs are power electronic devices that modulate frequency and voltage of the electrical power supplied to electric motors to regulate speed and torque. Because of VFDs capability of optimizing motor driven systems it is used across a vast range of industries. This energy component is widely used in ICS, specifically in automated processes and industrial machinery.

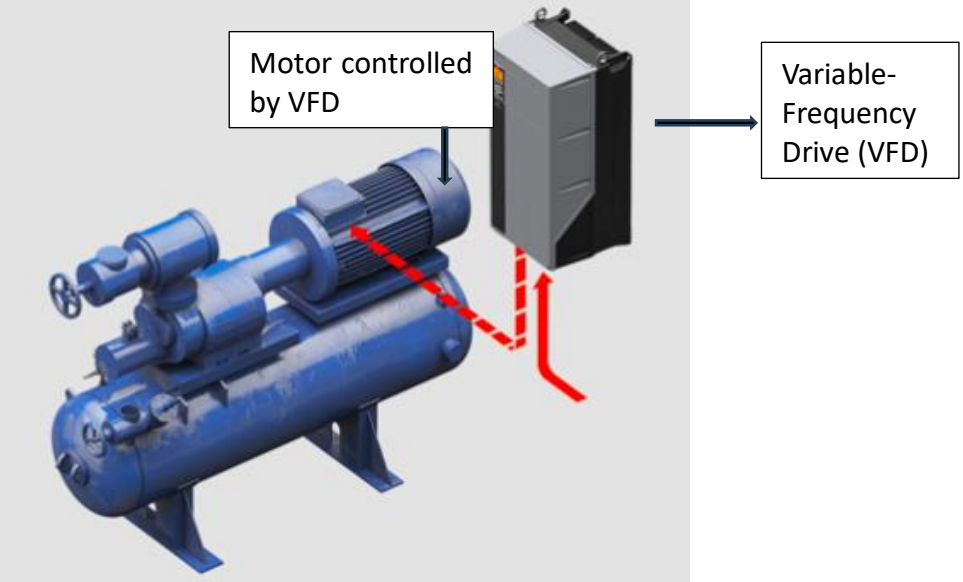

Figure 8. Variable Frequency Drive (VFD), (Danfoss)

The integration of VFDs into smart grid with the convergence of IT and OT improves grid's ability to respond proactively to fluctuations in energy demand and generation. These promote effective load balancing, optimizing energy usage and support grid stability by controlling motor speed in applications including industrial operations, Heating, ventilation and air conditioner (HVAC), and water pumping. Additionally, the ability to moderate output power in accordance with the demand corresponds effectively with smart grids requirement for flexibility, particularly as the grid accommodates an increasing proportion of intermittent renewable energy resources (Doe and McArthur, 2019).

VFDs have applications in both residential and industrial context in smart grids. These are used in HVAC systems and motor driven equipment in commercial and industrial buildings and facilitate energy management by lowering energy consumption during off-peak times and enabling remote control operations through smart grid (Green and White, 2018).

Frequency drives are an important part of wind and solar power generation. For instance, VFDs maintain grid stability and maximize energy production by regulating rotational speed of the wind turbines and enabling effective operation across spectrum of wind velocities (Chen and Lee, 2019). Similarly, VFDs may enable the flow of energy from photovoltaic panels to the grid in solar power systems by adjusting control of inverters and other motor-driven components. VFDs significantly augment the resilience and efficiency of renewable energy in smart grid infrastructure by enabling these critical functions (Patel et al.,2020).

One of the primary benefits of VFDs is their ability to enhance energy efficiency. Research demonstrates that VFDs have the potential to save motor driven systems up to 30-40% by energy usage, specifically in applications where precise speed control is of benefit, such as water pumping and HVAC (Johnson,2022).

Moreover, VFDs in smart grid promote demand response strategies by allowing grid operators to make changes to motor speed in response to demand inputs. During peak times VFD can balance load by refraining from placing any strain on the grid by reducing consumption and turning off non-essential motors (Robert and Singh, 2021). According to empirical research, VFD's ability to regulate in response to demand fluctuations can contribute to preserve grid stability, which is particularly important considering the increasing integration of RES, which can add unpredictability to the power supply (LEE and Williams, 2020).

While VFD's provide a multitude of advantages for smart grid operations, their integration entails distinct challenges specifically in cybersecurity and harmonics management. As VFDs are frequently interfaced with communication networks in smart grids, they are vulnerable to cyberattacks that could compromise operations and disrupt system. According to studies, VFD that employ prevalent industrial communication protocols, such as Profibus and Modbus are vulnerable to attacks intrusions that could compromise the stability of smart grids (Garcia and Kim, 2020). To protect drives in smart grid infrastructure, experts recommend the adoption of security measures including network segmentation and data encryption (Thompson and Evans, 2021).

Harmonic distortion is another challenge with the integration of VFD that can adversely influence power quality in smart grids. Drives operation to regulate motor speed can result in generation of harmonics which causes electrical disruptions and can impact on the functionality of other grid connected equipment's. In renewable energy systems, implications of harmonic distortion are concerning because maintaining power quality is crucial for grid interoperability (Lagner, 2022). Scholars advocate that power control filters, and sophisticated control algorithms can be used to mitigate harmonics and to enhance overall performance and dependability of smart grids that incorporate VFDs (Smith et al., 2021).

2.3.2 Cyber Security in Variable Frequency Drives

VFDs are the energy component devices that traditionally used to operate in confined isolation, but now with the integration of IT and OT are progressively interconnected to cloud computing, IoT networks, and central control systems, which makes them susceptible to cyber threats (Karnouskos, 2011). While integration of drives into the networked systems facilitate remote monitoring and control subsequently, it also introduces security vulnerabilities. Consequently, safeguarding the cybersecurity of VFD is paramount to keeping industrial processes stable and safe.

The interface of VFDs are critical parts for data exchange, monitoring, and control that make them easily susceptible to cyber-attack. Interface is the point of access therefore, it requires a strong access control system. Hence, access management is the fundamental layer of defence in cybersecurity in drives as unauthorized access to VFD interface precipitate operational disturbances and potential physical injuries (Mahendra et al., 2018). Research conducted by Pan et al. (2019) further highlights significance of user authentication and access control hierarchies, that restricts the rights of user and limits unauthorized changes to VFD configuration. According to Baig et al. (2021) recent developments in role-based access control and multi-factor authentication contribute an additional layer of security which ensures that only authorized individuals are allowed to access critical VFD functions. Communication interfaces such as Modbus, CANopen, and Ethernet/IP are used by segmented VFDs are often susceptible to eavesdropping and man-in-the-middle attacks, as presented in table 2.

Transport layer security (TLS) and other encryption methodologies have been illustrated by researchers Patel et al. (2020) to safeguard connection between VFDs and other industrial equipment, preserving data integrity from tampering and eavesdropping.
According to research by Zhang and Li (2022), implementing encryption in resource constrained VFDs is challenging, therefore, the author suggests using lightweight encryption techniques to balance security and processing performance.

Additionally, interface settings in VFD enable network segmentation, that limits the vulnerability of VFDs to more extensive network attacks. According to Zhou et al. (2021) segmenting VFDs into demilitarized zones (DMZs) or isolated networks diminishes the attack surface and stops and obstructs unwanted access from less secure network segments. As per study, protocol control minimizes the possibility of adverse traffic by limiting access to specific communication protocols (e.g., Profibus, Modbus). These research contributions highlight the importance of secure network designs.

The interface's function in intrusion detection has been examined as a proactive strategy towards enhancing cybersecurity in VFDs. LeMay et al. (2020) claims that surveillance of VFDs via their interfaces present insights into unusual activity, such as non-anticipated changes in parameters or persistently unsuccessful login attempts. According to Setiawan et al. (2021) the integration of VFDs with IDS facilitates real time notifications and incident response.

Table 2. Variable frequency interface (Danfoss)(comprehended with AI)

Parameter	**Description**
Digital Inputs	Programmable digital inputs for start/stop, forward/reverse, jog, preset speeds, and more.
Digital Output	Digital output for status signals like running, warning, or fault.
Analog Inputs	Inputs for speed or torque reference signals. Commonly used for external potentiometers or PLC signals.
Analog Output	Provides drive feedback, like actual speed or load percentage, for monitoring or control systems.
Relay Outputs	Relay contacts programmable for status indications such as drive running, fault, or alarm conditions.
Fieldbus Communication	Built-in communication protocols like Modbus RTU and optional add-ons for Profibus, Profinet, Ethernet/IP, CANopen, etc.
Safe Torque Off (STO)	A safety input used to disconnect power from the motor without shutting down the drive completely.
Serial Port	Standard serial port for Modbus RTU communication and programming.
Control Card Interface	Interface for external control cards, allowing advanced I/O expansions and programming flexibility.
HMI (Keypad)	Local display and keypad interface for programming, status monitoring, and diagnostics.
USB Interface	Port for firmware updates, parameter upload/download, and PC-based programming.
Pulse Input (PI)	High-speed digital input for pulse signals, often used for encoder feedback or flow meters.
Power Supply for I/O	Provides power to external I/O devices such as sensors or switches.

Subsequently, firmware administration via interface is still a major challenge for cybersecurity in VFD. Vulnerability in firmware can be manipulated through unprotected interfaces resulting in unauthorized updates or injection of malevolent firmware Zhang and Chen, 2019).

A study by Chen et al. (2020) highlights the importance of safe firmware update procedure, including digital signature verification. Further, Pei et al. (2021) recommends the adoption of secure boot mechanisms to secure firmware authenticity and advice to use them to maintain VFD integrity.

2.3.2.1 Cyber security threats to Variable Frequency Drive

Since VFDs are part of critical infrastructure in EBDES, cyber-attacks to these drives can have serious operational, financial, and safety repercussions. Drives may fall victim to variety of attack vectors, from basic misconfigurations to advanced cyber physical attacks that are aimed to disfunction system operations, can be understood by figure 9.

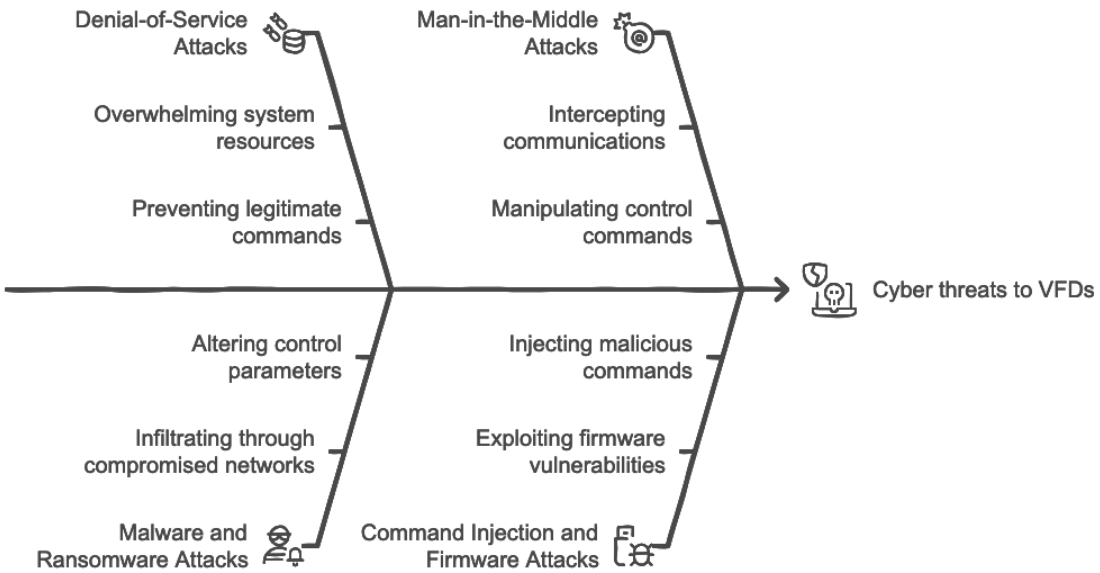

Figure 9. cybersecurity threats in Variable frequency drive (generated with AI Napkin)

Attacks such as DoS overload a system's capacity with unnecessary traffic to the point where it becomes non serviceable. Within the framework of VFD, a DoS attack may obstruct motor controls by interfering with drive operations and preventing it from executing legitimate commands. As per He and Yan (2016) DoS attack can significantly disrupt the operational continuity of systems that highly depend on VFDs, distinctly in industries like manufacturing where any downtime can be expensive.

Attacks such as malware and ransomware are also threats to VFDs. These types of attacks can enter the system through compromised hacked networks. Malicious attackers are capable of manipulating control parameters, causing motor malfunctioning, or even halting operations until a ransom is paid once a VFD has been compromised (Shoukry et al., 2013). Any cybersecurity breach can lead to potential damage in the system, particularly in critical infrastructure systems (Stouffer et al., 2011).

In case of Man-in-the-middle-attack (MitM) a malevolent entity intercept and manipulates communication pathways between VFD and control system. This type of attack empowers attacker to change motor control commands, which might lead to VFD operating beyond safety thresholds (Alcaraz et al.,2013). For example, modification in frequency parameters may damage the motor or the equipment energized by the motor.

Another type of attack can be command injection and firmware attacks where attackers can take advantage of the exposed vulnerability in VFDs communication protocols or firmware and introduce malicious command straight into the control system. Zhu et al. (2011) emphasizes that many VFDs are susceptible to command injection attacks because they exercise outdated and proprietary communication protocols that don't encompass strong security features. As a result of these attacks erratic motor operations may lead to equipment damage, operating inefficiency, or even significant safety risks.
Furthermore, attacks on VFDs can fulfil the purpose of physical damage via cyber-attacks on motors and other associated machinery by compromising systems. For instance, a

motor may operate at hazardous velocities, due to intentional attacks, which might result in overheating and mechanical failure. Angle and Madnick (2017) states that real world cyber-physical occurrences have demonstrated restructuring of VFDs to operate beyond acceptable limits can result in physical damage.

2.3.2.2 Vulnerabilities in variable frequency drives

VFDs vulnerabilities stem from their expanding interconnectivity with larger networks and dependence on antiquated technologies that were not engineered with cybersecurity in consideration. Literature identifies numerous critical vulnerabilities.

Significant number of VFDs still continue to operate via unencrypted protocols rendering them susceptible to interception and eavesdropping by hackers. Highlighted by Abdelwahed et al. (2018) when VFDs and control systems operate without encryption and effective authentication procedures it exacerbates the vulnerability of unauthorized access and command manipulation.

Outdated firmware is an addition to the vulnerability of VFD, several drives are powered by outdated software. Attackers can misuse this as an opportunity to exploit, take control of system, deteriorate operations, or steal confidential data (Roth et al., 2017). In certain situations, operators are not acquainted with vulnerabilities of the system and firmware upgrades are not part of frequency process.

There is a possibility that unauthorized people may be able to access VFD control settings due to poor and non-existent access control constraints. Stouffer et al. (2011) presses the need for more robust user authentication procedures, for example multifactor authentication (MFA).

Safety oriented interfaces, such as safe torque Off (STO) have been acknowledged as a critical supplemental cybersecurity defence for VFD. A study by Yao et al. (2019) examines the function of STO and other safe operating modalities in emergency response scenarios, where a compromised VFD can be promptly deactivated to prevent damage or Safety threats.

2.3.2.3 Cybersecurity standards and protocols for variable frequency drive security

As the cybersecurity vulnerabilities are being exposed with the integration of IT and OT, increased awareness of cybersecurity risks to ICS and VFDs have resulted in the development of number of international standards and frameworks to increase security resiliency. Two principal standards in this domain are the international electrotechnical commission (IEC) 62443 series and the national institute of standards and technology (NIST) cybersecurity framework that provide helpful guidance for VFD security.

The NIST cybersecurity framework outlines a through methodology for addressing cybersecurity risks in critical infrastructure that emphasizes on five functions- identify, protect, detect, respond, recover. The framework suggests implementation of network segmentation, access control measures for VFD, incident response procedures to reduce potential risks (NIST, 2018). For instance, NIST recommends strongly implementing data transmission channel security where VFDs accommodate insecure protocols like Modbus. Organizations can secure access control by implementing segmentation of networks and limiting access to critical systems (Thompson and Evans, 2020).

Next, the IEC 62443 series represents an internationally recognized collection of standards pertaining to industrial automation and control systems, that addresses component and network security requirements. This framework underscores the necessity of role-based access control, secure device setup, and regular updates (IEC, 2019) to safeguard devices like VFDs. Additionally, IEC 62443 presents security standards for suppliers, ensuring that manufacturers comply with optimal practices throughout the process of development and maintenance phases. The adoption of IEC 62443 for VFDs necessitates

the application of secure programming techniques, strong authentication procedures, regular security updates (Patel and Singh, 2021).

Another security protocol for VFD security is Modbus security protocol that incorporates conventional Modbus standards with encryption and authentication. The implementation of Modbus security reduces the danger of data interception and unauthorized command manipulation by protecting data transfer between VFDs and other ICS components (Williams and Lee, 2022).

2.4 Securing PLC and SCADA in digitalized energy system

Smart energy management is achieved by integrating isolated energy systems that are used to rely on reliability rather than security to IT networks. The transformation to the digitalized energy system EBDES with the integration of IT and OT, which are accentuated by automated and networked infrastructure, has resulted in greater dependency on SCADA and PLC systems. While these technological systems play a crucial role in the regulation, monitoring, and assurance of reliability of energy infrastructure operations subsequently, they have also established novel cybersecurity challenges. An increasing body of research has identified the significance of PLCs and SCADA, their operations and vulnerabilities within the cybersecurity framework of digitalized energy system as vitally important in EBDES.

In modern energy management PLC and SCADA constitute the most essential roles, especially in regulation and automation of power generation, transmission and distribution. Figure 10 shows the industrial automation network with PLC and SCADA system.

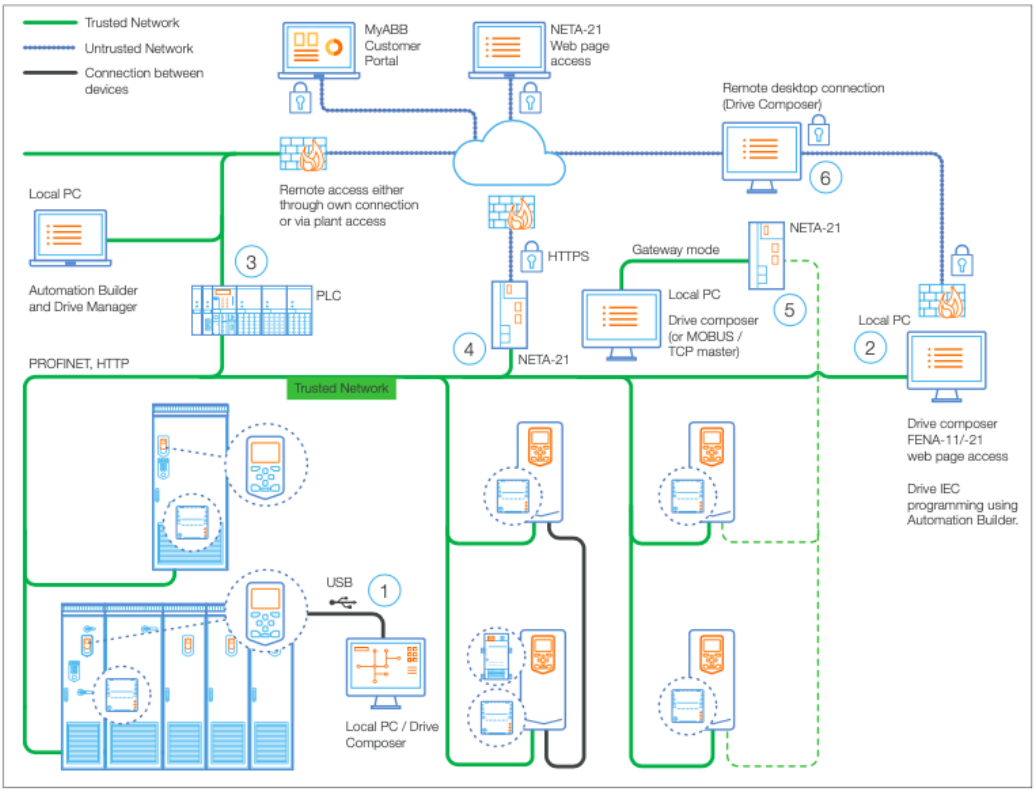

Figure 10. Industrial network (ABB, 2016)

The SCADA systems are the central nervous system of digitalized energy infrastructures that allow real time data acquisition and decentralized assets, for example substation and power plants (Miller and Rowe, 2012). Conversely, PLCs are responsible for management of direct machine level control, conducting programmed instructions essential to the operation of equipment and preserving system stability (Mackay et al., 2015).

According to the literature, the integration of IT and OT in these systems has augmented operational efficiency and flexibility. SCADA system promotes monitoring and dynamic balancing of power supply and demand for grid operators, which is a critical task in grids that are increasingly intricate and reliant on renewable energy sources (Yan et al., 2018). By introducing automation in machine level procedures, PLCs improve responsiveness by minimizing human error and encouraging prompt local decision making in the event of disturbances (Chikumba and Cilliers 2020).

PLCs and SCADA system were initially designed with minimal cybersecurity consideration, despite practical advantages. Modbus, DNP3 and other SCADA protocols are deficient in authentication and encryption mechanisms, which makes them vulnerable to eaves-dropping and modification (Stouffer et al.,2011). This vulnerability has been intensified because of the transition towards open and standardized communication protocols in digitalized energy systems, while these standards are advantageous for interoperability, simultaneously providing bigger attack surface (Pan et al., 2020). The vulnerabilities in-herent in PLC are concerning since these devices regularly operate in settings that are not conducive of frequent cybersecurity upgrades, making them vulnerable to attack by malicious actors capable of exploiting essential operational functions. Vulnerability in PLCs can cause disruption in energy networks because of their legacy attributes (Khalid et al., 2019).

Network segmentation in SCADA systems is emphasized by recommending separate cor-porate IT networks from OT networks to avoid unauthorized access (Cardenas et al., 2008). A body of research highlights the importance of firewalls and IDS is safeguarding PLC and SCADA networks (Krutz, 2016). These systems are capable of filtering communi-cations, identifying irregularities and notify operators of any potential security threat. However, implementing IDS in energy systems presents challenges in achieving a balance between security measures and operational performance since SCADA communication is latency sensitive (Huitsing et al.,2008).

Assessment of vulnerability in PLC and SCADA security are key research areas in the dig-italized energy systems, particularly intrinsic limitation characteristics such as limited processing power and memory. These restrictions inhibit challenges of implementing traditional IT security measures with OT systems such as real time encryption pr resource demanding anomaly detection algorithms in energy networks (Alkussayer and Mesbahi, 2020). Literature highlights that PLC in the energy sector are legacy devices, which makes them vulnerable to threats that can lead to disruption in operations and cannot be easily patched or replaced. Further, within this area, the studies underscore the importance of

firmware analysis. Vulnerability scanning techniques should be developed tailored to PLC and SCADA components in energy systems (Cui et al., 2021). Because of their operational centric design, these systems possess limited inherent threat detection and incident response capability. To provide automated responses to cyber threats, centralized monitoring and enhanced speed of incident detection, SCADA and security information and event management (SIEM) system may be integrated (Zhou et al., 2015). An investigation is done in application of behaviour modelling in the identification of authorized alterations in PLC controlled systems (Ahmad et al., 2021). To analyse PLC process data for any type of manipulation researchers are looking into machine learning (ML) and anomaly detection methods. Due to limited resources, there are challenges in adapting these technologies in PLC devices (Ahmad et al., 2021).

Krause et al. (2020) propose integration of hybrid anomaly detection solutions with sophisticated ML models used at the SCADA or cloud level with rule-based frameworks for real time anomaly detection at the PLC level. Such stratified techniques are essential for EBDES that elevate accuracy and operational efficiency. Scenarios where ML model may prove impractical due to hardware constraints, statistical anomaly detection has also been highlighted as substitute or supplementary technique (Hamed et al., 2021).

Additionally, access control is of paramount importance in EBDES to safeguard PLC and SCADA systems against unauthorized intrusions. Two types of access control are highlighted Role-Based-Access-Control (RBAC) and Attribute-Based-Access-Control (ABAC) which are beneficial for SCADA systems, particularly emphasizing ABAC provides more layered approach granting access rights based on specific aspects like user roles, device types, and situation factors (Farooq et al., 2020). The presence of this flexibility is vital in energy systems, where employees may necessitate varying access credentials based on their positions and operational responsibility.

Additionally, the integration of MFA is widely supported with scholarly discourse. Research supports conjunction of MFA together with biometric verification to achieve robust identity verification, however, this strategy may have implications in practical approach and usability issues in high stakes, time critical operation environments (Alcaraz et al., 2021). Furthermore, behavioural analytics and adaptive access control are becoming interesting areas of study, that has huge potential for application to preserve remote access in digital energy networks.

Defence in depth is a stratified security approach that is strongly advocated for digitalized energy systems. This strategy incorporates multiple layers of defence mechanisms such as network segmentation, endpoint protection, perimeter security, and ongoing surveillance, all of these play an important role in securing IT/OT integrated networks. Network segmentation is a pivotal defence strategy for digitalized energy systems that lowers the possibility of lateral movement by segregating critical resources from less secure IT components (He et al., 2022). Researchers presses the need to implement network segmentation and zoning as paramount to reduce the attack surface in IT/OT converged systems. Alcaraz and Lopez (2020) promotes the adoption of these strategies in addition with monitoring techniques such as IDS, firewalls, and ongoing network traffic analysis. In the energy industry, where nonoperation can have impact on economic and societal repercussions, continuous monitoring is fundamental as it allows early detection and rapid response to aberrant behaviours.

2.5 Advanced technologies driving IT/OT integration

The accelerated digital transformation in the energy sector is making OT increasingly integrated and smarter, which is enabled by the integration of IT and OT that is redefining energy management, distribution and security. This convergence of IT and OT is underpinned by the advanced technologies that provide real-time data exchange, seamless communication, automation, and data driven decision making. Advanced technologies such as internet of things (IoT), edge computing, artificial intelligence, digital twins, blockchain technology and 5G networks are pivotal to future energy systems as these

systems develop to incorporate smart grids, DERs, and predictive analytics. The key technology enablers supporting integration of IT and OT in EBDES are discussed in this literature review, elucidating their applications, advantages and challenges.

2.5.1 IoT in electricity based digitalized energy system (EBDES)

IoT puts a significant influence on digitalized energy systems by enhancing operational adaptability, enhancing efficiency, and data driven decision making, in various energy management domains. It is fundamental to the emergence of smart grids, where real time energy flow, load distribution, and grid health monitoring are made achievable by interconnected devices like smart meters, sensors, and controllers. As per recent studies IoT initiated real time data allow utilities to improve grid stability, corporate the variations in demand, and proficiently manage DERs, such and wind and solar electricity, both of them have variable outputs (Johnson and Yang, 2023; Zhang and Li, 2024). In addition to optimization of energy distribution, this real time flexibility supports the integration of renewables, which is important for promoting sustainability. The adaptation of RES, enabled by IoT derived data, allows grid operator to manage supply and demand, this capability is crucial in grids with substantial integration of renewables (Garcia and Olsen, 2023).

Another, impact of IoT on energy systems is improving energy efficiency and enabling demand response programs, where IoT facilitates data communication to energy systems, thereby enabling load modification during peak hours. This ability eliminated auxiliary power plants, reduced costs and ultimately reduced grid overloads. IoT supported demand response encourages sustainability by reducing waste of energy and generates cost savings for consumers and utilities (Nugyen and Ahmed, 2023). It also allows the possibility of predictive maintenance. By installing sensors to assets energy suppliers can monitor equipment health by monitoring temp and vibration data, that allows condition-based maintenance, ultimately reducing downtime and extends asset life (Turner and Yao, 2024; Wang and Zhao, 2023).

Big data analytics is possible advancement with the IoT generated data, providing utilities the ability to forecast demand variations, enhance long distribution and enhance long term planning. Historical data provides insight that supports utilities to optimize and operations over period of time, real time analytics derived from IoT data support prompts decision making in grid management (Ortega and Brown, 2024). Data collection by IoT introduces challenges of cybersecurity and data privacy. The IoT devices often have absence of security standards and are high interconnected, which make these devices vulnerable and susceptible to threat (Ali and Kumar, 2023; Alcaraz and Lopez, 2023). Researchers suggest implementing IDS, device authentication, and encryption, to mitigate these risks.

Interoperability is a significant challenge in implementing IoT in energy system, as these devices when procured from various manufacturers usually have distinct communication protocols, which obstruct seamless integration across the grid. To achieve device compatibility standard organizations such as IEEE and IEC are working to introduce universal protocols for IoT energy applications, but the wide range of devices still make efforts complex (Jackson et al., 2024; Kumar and Le, 2023). IoT has an unprecedented effect on digitalized energy systems by providing tools that support sustainability, promote resilience and optimize allocation of resources.

2.5.2 Machine Learning in Electricity based digitalized energy system (EBDES)

ML is transforming digitalized energy systems and presents a robust and effective energy infrastructure by advanced capabilities in demand forecasting, predictive maintenance, energy optimization, and cybersecurity. Research by Liu et al. (2023), elucidates that ML based forecasting models, for instance support vector machines and neural networks, impart superior accuracy in anticipating periods of peak of demand, and supporting grid operators to optimize energy distribution efficiently. Furthermore, by allowing real time changes easily to fluctuating supply, ML plays important role in the integration of RES, and in case of variation of sources such as wind and power, it supports in stabilizing the grid (Rahman and Kholsa, 2023).

ML is widely accepted in the field of predictive maintenance, data gathered from sensors embedded in equipment, for example transformers, turbines, and substations, must beforehand indicate any sign of potential failure. Another research conducted by Wang and Zhao (2024), demonstrates that by changing approach from scheduled to condition-based maintenance, ML algorithms that employ anomaly detection techniques and pattern recognition methodologies help in minimizing downtime and saving maintenance cost. This approach manifolds system reliability along with asset longevity, which has become significant in energy industries with the increased operating requirements. Additionally, by evaluating customer behaviour and pattern, accordingly, regulating load in real time, ML tool enhances demand response techniques to control energy consumption specifically during peak hours (Ahmed et al., 2023).

ML based anomaly detection systems can examine traffic present in network to find any unusual pattern that may indicate cyber threats, presenting cybersecurity another area where ML plays crucial role. Considering the increased number of cyber-attacks on key infrastructure, it has been argued that ML models, those are based on clustering and deep learning, offer a proactive approach to cybersecurity in energy systems (Khan and Lee, 2023). Since ML are data-based technologies and require a large set of operational data, privacy issues are also concerning area, requiring strict governance systems (Singh and Roberts, 2023).

2.5.3 Blockchain in electricity based digitalized energy system (EBDES)

To ensure security in digitalized energy system blockchain is a potent tool that may improve efficiency, security, and transparency, specifically in decentralized energy networks. A recent study states that blockchain facilitates peer-to-peer energy trading, lowering transactional costs and promotes greater involvement in renewable energy market by processing its fundamental technology of securely recording transactions between prosumers without any need for centralized authority (Li and Zhang, 2023). Since it has the ability of tamper resist, the ledger in it reduces the possibility of data breaches, blockchain plays a critical role in improving data security when a serious concern in IoT

enabled energy systems is that sensitive data is constantly exchanged across networks (Nguyen and Ahmed, 2023).

Another noteworthy application of blockchain within digitalized energy system framework is managing and confirming carbon credits and renewable energy certificates (RECs). Research highlights blockchains transparent and auditable record keeping procedures assures the precise tracking and verification of RECs, which is an essential mechanism for supporting green energy programs and empowering businesses to reach sustainability goals (karam and Patel, 2024). Furthermore, by securely orchestrating information among DERs, this technology supports real time grid management, this procedure improves system stability by allowing grid operators to effectively monitor and regulate energy flows in response to the changes in demand (Fernandez and Silva, 2023).
Concerns regarding endangering sustainability are highlighted by the energy usage of several consensus techniques, such as Proof of Work (PoW). The transition to more energy conserving consensus mechanisms, such as Proof of stake (PoS), or Proof of authority (PoA), might reduce these problems while preserving the security advantages of blockchain (Garcia and Olsen, 2023).

3 Methodology

This chapter presents the research strategy. The study adopts a mixed methodological approach to investigate how IT and OT converge within the framework of electricity based digitalized energy systems, with an underline on the implementation of IT and OT integration on practical level and response of the existing industry employed people to it at small and big industries, secondly comprehension of cybersecurity awareness and its challenges in the industries is also discussed during the method approach. The employed mixed method approach in this study integrates both qualitative and quantitative data collection methodologies, proficiently builds the understanding around the topic by offering in depth individual detailed viewpoints and quantifiable insights from industry wide datasets (Creswell and Plano Clark, 2018). Precisely this approach consists of a structured survey, a specialized workshop, and qualitative interviews, that provide triangulation of findings and assures with comprehensive responses to the research questions as shown in figure 11. Basically, triangulation analysis is a research technique which combines data and findings from three sources, processes it and analyses result for validity and accuracy, it reduces the possibility of bias and strengthen the validity. From the methodological approach adopted during the study each has its own strengths and summing them up results in exploratory and confirmatory insights.

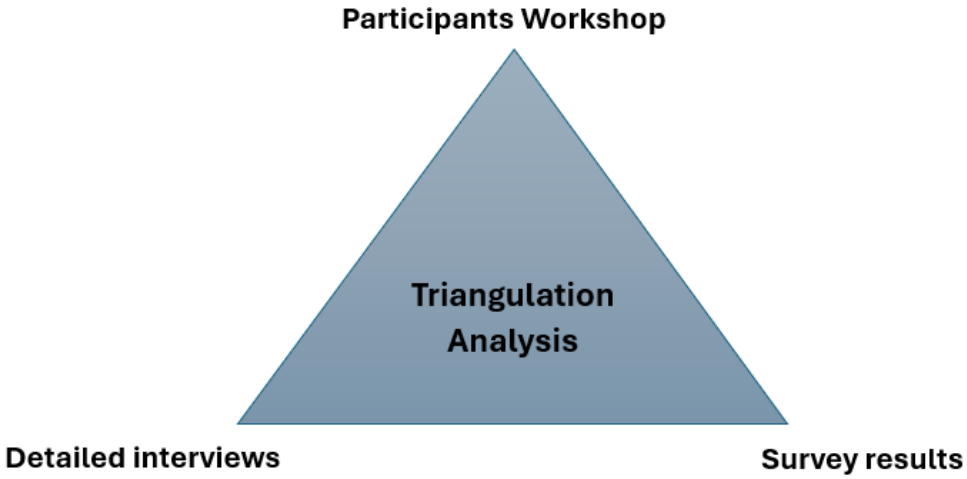

Figure 11. Triangulation Analysis

Since the mixed method approach collaborates qualitative (interviews and workshop) and quantitative (surveys) techniques to collect data thoroughly:

- Interviews provide in depth understanding of technical and operational issues with contextual insights concerning distinct experiences and challenges of every stakeholder (Patton, 2015).
- Surveys present a systematically quantified perspective by assessing more inclusive patterns, opinions and evaluation of IT and OT integration effectiveness over broader sample data by respondents (Teddlie and Tashakkori, 2009).
- Similarly, workshops present a collaborative event where participants irrespective of their backgrounds can cooperatively formulate solutions and proactively determine preliminary findings, consequently providing the research with pragmatic insights and validating results from the approaches (Gill, Stewart, Treasure, and Chadwick, 2008).

The benefits of mixed method approach for the study of IT and OT integration in electricity based digitalized energy systems are:

- Complex Technical Insights: The integration of IT and OT in digitalized energy systems while providing new avenues for applications, it also necessitates the solutions to the challenges pertaining to technical compatibility and cybersecurity. The comprehensive examination of these intricate facets has made possible the application of mixed method approach to gain distinct insights (Knapp and Langill, 2014).
- Stakeholder-centred approach: The implementation of integration of IT and OT in electricity based digitalized energy systems influences a broad spectrum of stakeholders, engineers, IT staff, and decision makers. A comprehensive understanding of these people's perspective is made possible by using the mixed method approach (Mahmood and Ergu, 2020).
- Triangulation of Validation: The convergence of the results derived from surveys, workshops, and interviews confirms one another, thereby increasing the accuracy and thoroughness of the resultant conclusions (Creswell and Plano, 2018).

The study on integration of IT and OT allows a comprehensive evaluation of research that considers both technical and human inputs by integrating surveys, workshops, and interviews (Farhangi, 2010).

3.1 Data Collection

The data collected for this study plays a pivotal role in answering research challenges, validating hypothesis, and drawing insightful conclusions. This study underscores the cybersecurity challenges at energy related companies, the discussion also marks the need for integration of IT and OT in digitalized energy systems and the technologies that enable integration.

To expand the scope of study, a two-way data mining framework is created, that incorporates primary data from expert interviews of people from the energy sector and a questionnaire survey from people from different industries but are directly or indirectly involved in the digitalized energy systems, while the secondary data is derived from cy-

bersecurity framework and current industry practices, as well as from review of publications that are related to specific research plan. An optimal framework that addresses the main research issues, related challenges and recommendations for future system upgradation is developed. Figure 12 reflects the methodology that is adopted for the study.

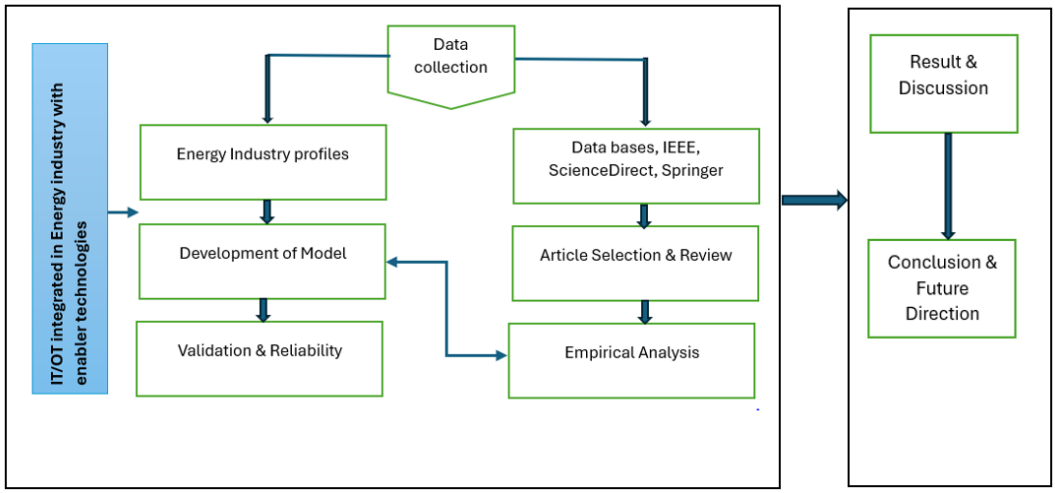

Figure 12. Methodology process design

The empirical part of the investigation consisted of a comprehensive examination and in-depth study of the topics concerned to collect a substantial amount of primary information concerning the examined phenomenon. This process included organizational culture, participant experience and role in the industry, perspectives on the digital advancements in the energy sector, and potential advantages and challenges pertaining to integration of IT and OT, future technologies within the IT/OT integration.

Subsequently, the search was narrowed down by inclusion of specific criteria of including component producing energy industries that automate and optimize the energy systems in Finland, people who are involved in designing of these energy system solutions through academics.

For the workshop seventeen people from diverse backgrounds in the energy industry were invited, including four volunteers from an academic background of energy studies

to conduct the multidisciplinary mixed method approach for the study in this area. The invitees were shortlisted on the basis of their background, which included people working in energy supporting industry, researchers from energy and sustainability field, and IT system professionals. The event further divided the participants into four groups where they were involved in tree problem solving tasks which encouraged to discuss integration challenges like protocol, compatibility, cybersecurity, data sharing. These discussions enabled people to discuss a wide range of issues and share an understanding of modern digitalized energy systems.

The data from the workshop consists of recorded and transcribed sessions, notes from the facilitator, and feedback forms completed by the participants.

The survey consisted of a total of 41 questions including both closed-ended and open-ended questions as shown in appendix 1. The key areas for the survey included cybersecurity and integration effectiveness. The survey form was shared with the respondents via webropol, the responses were collected and analysed later for the study. This method supports qualitative data.

For the interview, the data pertaining to energy industries in Finland was collected that are part of digitalized energy system. The interview participants were shortlisted on their profiles and background in the energy industry and a purposive sampling approach was accepted to select people from diverse perspectives from IT professionals, OT engineers, cybersecurity experts, and management within electricity based digitalized energy systems. These chosen respondents were contacted via email. Three interviewees were involved in this process to conduct semi structured interviews. An interview guide was developed to address questions based on literature and current trends as shown in appendix 2. The interviewees were sent a brief about the discussion topic to ensure that they are aware of the objective. The interview took 50 minutes and was conducted through Microsoft teams and physical meetings at the company premises. To ensure that the interviewer acquires the correct comprehension of the responses, the remarks were

expeditiously interpreted. Consequent to this, the researcher gained a profound understanding of the subject matter from the industry experts.

For research purposes literature was collected from sources such as Scopus, Web of science IEEE, science direct, springer, Tritonia and digital library. These data libraries cover a diverse array of subjects from engineering, business, energy management, corporate strategies and other additional related fields. Furthermore, the energy companies involved in the practical implementation of IT and OT integration develop videos, and reports, their contextual applications and content blog also acted as secondary source for the analysis, encouraging comprehensive understanding for the study.

3.2 Data Analysis

Data collected from interviews, workshop dialogues and survey feedback were amalgamated through a thematic analysis to discover prevalent subjects associated with IT and OT integration, cybersecurity awareness and implementation, and industry specific challenges. This methodological approach encouraged enabling triangulation which supports validation of findings across different data sources and provided a holistic understanding of cybersecurity challenges and practices within digitalized energy systems (Braun and Clarke, 2006). Secondly the coding process was accepted, an initial open coding phase was followed by axial coding, where related causes of cybersecurity were grouped under broader category reflecting core cause of issues. This process enabled structuring and understanding of variance of data, that resulted in highlighting the chain of issues, challenges and consequences of events. The coding process that was adopted follows preparation of flowchart consisting of insights and various causes including consequences. This process was adopted to implement problem tree. The insights from interviews, and the workshop were compared to conclude variations in the cybersecurity related operations awareness and IT/OT integration experiences across various roles.

The quantitative data collected presents descriptive statistics such means, frequencies, and percentages to provide an overview of cybersecurity knowledge levels, IT and OT integration familiarity.

3.3 Validity and reliability of the study

In the evaluation of IT and OT integration in the digitalized energy systems, the assurance of validity and reliability for creating credible outcomes is of prime importance. The validity of this study is augmented through a myriad of strategies, starting from the triangulation analysis of data sources. Further, by integrating interviews, workshop discussion and survey responses, the research confines a multi-dimensional viewpoint and validates the outputs. This triangulation methodology serves as a tool to ensure that the insights accurately communicate the presentation of empirical practices across different roles within the energy sector, thereby reinforcing construct validity (Patton, 2002). Furthermore, to strengthen the validity, member checking was enforced; after the completion of interview process, participants were able to review summary of their responses to confirm accuracy of representation of data from collected responses (Creswell and Creswell, 2017). Additionally, the survey was meticulously designed by taking reference from relevant literature and based on industry standards, with expert consultations included to confirm that it effectively measures cybersecurity awareness and practices relevant to the domain. A pilot test conducted with the selective group of energy professionals ensures an additional layer of validation, ensuring the clarity and relevance of questions prior to comprehensive deployment (DeVellis, 2016).

The reliability of this study is supported by the adoption and implementation of consistent methodologies for data collection and data analysis. The semi structured interview framework allowed participants to share context specific insights with the consistency of the questions. Additionally, workshops discussions were also followed by open ended questions, that established consistency throughout the session discussion. During the qualitative analysis, inter reliability and transparency was ensured through the participation of multidisciplinary researchers in the coding of subset of the data. By

the integration of these extensive strategies, the study achieves a significant level of validity and reliability, thus delivering results that are both robust and applicable in the digitalized energy systems.

4 Result and Analysis

The results of empirical research included open-ended answers from the participants in the workshop and from the interview participants answers to the question related to IT/OT integration and its challenges. The survey provided results of quantitative data. The answers are not limited to “Yes” and “No” responses, since the answer were multiple choice options, therefore the responses are based on their opinion and understanding. The interview covered discussions basis of following themes:

- General questions regarding the background of the participant within the area of digitalized energy systems.
- Questions regarding their opinion on the integration of IT and OT integration and what opportunities it brings to the operations.
- Questions regarding challenges that have come up with the integration of IT and OT integration and what measures are we taking.
- Questions regarding cybersecurity concerns in the energy industry.

Table 3 summarizes the responses from the interview participants based on their reply to the above questions.

Table 3. Interview responses

Interviewee	Status	Expertise	Feedback
Interviewee 1	Product Manager	functional safety and cybersecurity	1. The interviewee explains that integration has made the process simpler, however the complexity has increased at product design level. 2. Cyber security implementation is ongoing but one of the challenges is to implement this in existing products. 3. Since some industries are component based so they ensure cybersecurity is standardized so client can ensure operability and security with other energy management integrations.
Interviewee 2	People leader, software platform engineering	software architecture, functional safety	
Interviewee 3	Consultant in energy industry	Operational technology operations	

During the interview all the participants frequently stated that IT/OT integration has improved energy systems operational efficiency, specifically the ability to remote control operations, data driven decision making and real time monitoring. It was also mentioned that there is an improvement in the accuracy and speed of data flow between the IT and OT levels which allows faster responses to any kind of anomalies in the system. One of the participants mentioned specifically the minor faults get reported before they escalate, which reduces downtime and maintenance costs.

Various significant issues were mentioned during the interview, interoperability problems, complicated data management and cybersecurity considerations were the most common complexities. interoperability was further explained as challenges in incorporating cybersecurity in legacy products, components because these are established products in the market and have reputation, so it is important to secure these energy components.

The participant highlighted issues with data volume and quality and sometimes it takes time to assure that data can be used for operational purposes because of its quality, however it was mentioned by only one interviewee.

Cybersecurity is the most serious concern among mentioned by all participants. Participants from the interview and in the workshop, both demonstrated a high degree of understanding of the cybersecurity related concerns with the IT/OT integration.
The responses from the workshop were collected through a problem tree approach underscoring the cybersecurity challenges. Figure 13 and figure 14 shows the outcomes of the workshop.

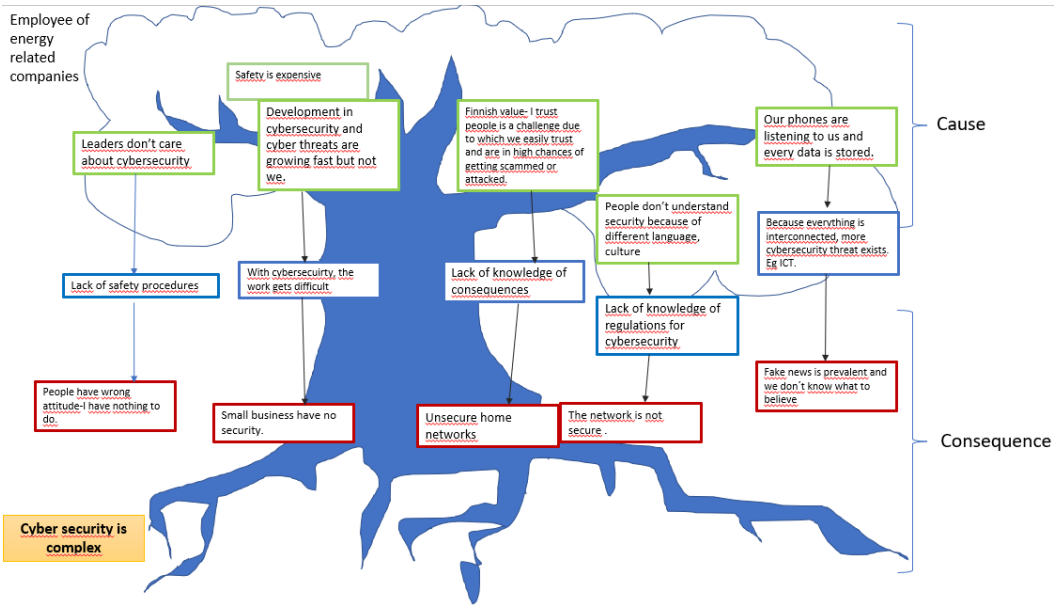

Figure 13. Problem tree- workshop result for group Energy company employee

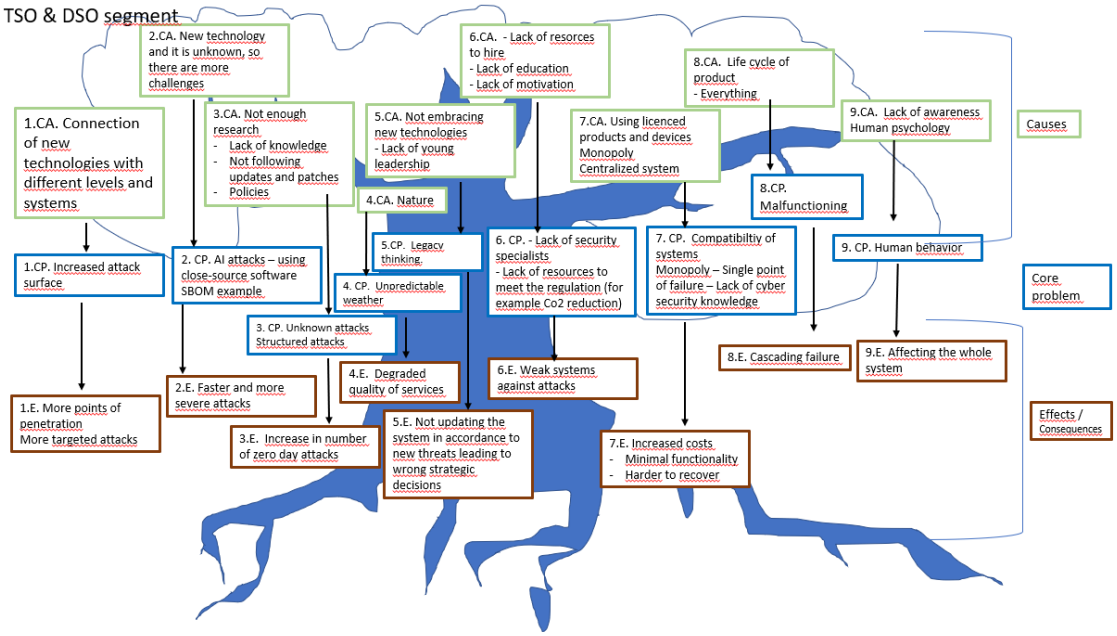

Figure 14. Problem tree- workshop result for group-TSO/DSO

Table 4 compiles the responses collected from the problem tree activity from the workshop for the two groups, one is the employees working in energy companies, other group is the employees of Transmission system operator (TSO) and Distribution system operator (DSO). Although the total number of participants were divided into five groups, the other two groups were defence people group, prosumers group, policy and regulations group. Only two groups were considered for the study because of the relevance with the study and the interviews conducted.

Table 4. compiled problems from the workshop

problems - TSO/DSO	problems - Energy company employee
Increased attack surface	Lack of safety procedures
AI attacks- SBOM, using close source software	Complexity in work, e.g.-product cybersecurity design
Unknown attacks	Lack of knowledge of consequences, unsecure networks
Unpredictable weather	Lack of knowledge of regulations
Legacy thinking, not embracing new technologies	Digitalization is bringing in new cybersecurity threats
Lack of security specialist, lack of resources	
Single point of failure	
Lack of awareness	
Malfunctioning	

The Survey was participated by the participants from the workshop, a total of 14 people participated in the survey that highlights their knowledge regarding the cybersecurity. Among the participants three were women with 21.4% and 11 were men with 78.6% as can be seen in figure 15 and figure 16.

Category	participant	Percent
Male	11	78,60 %
Female	3	21,40 %

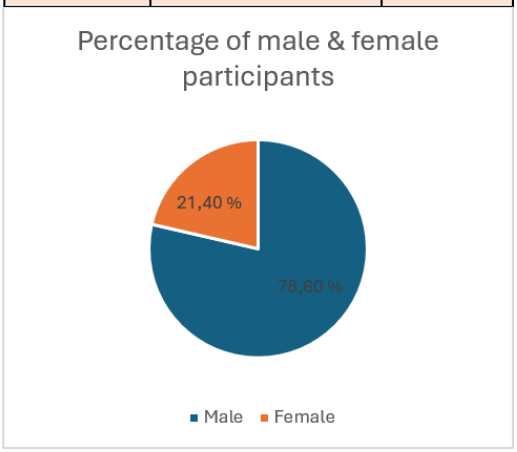

Figure 15. Male & Female Participants

The data was further analysed which confirmed work status of the people participating in the survey, 31% were the people who have a background of energy industry and may have different roles based on their experiences. 46% categorized themselves in the else category which reflects anonymous response.

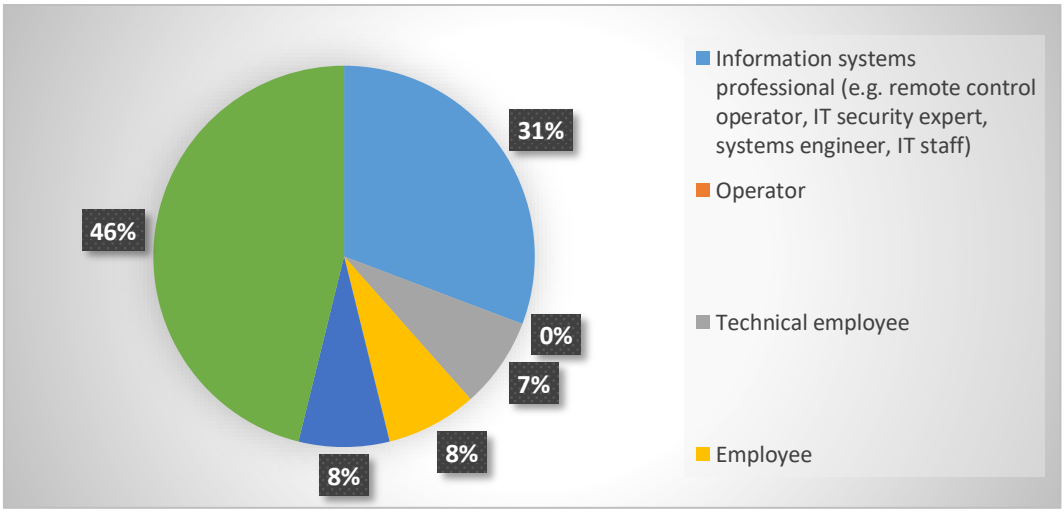

Figure 16. survey result-work status

Further the participants marked their cybersecurity knowledge on a matrix of level 1 to level 5. Figure 17 shows the survey report for the individual cybersecurity level. Among all the participants 29% consider themselves at level 3 and other 29% consider themselves at level 4, subsequently remaining percentage of people are at 21%, 14%, and 7% respectively for level 2, level 5, and level 1 which brings us to conclusion that people are aware of cybersecurity challenges and consequences which also reflected in the workshop outcomes in table 4.

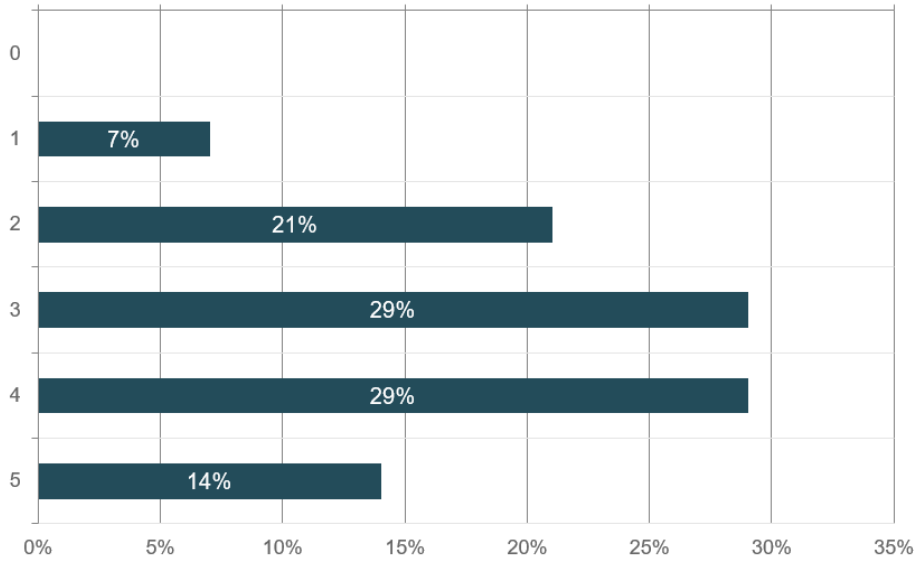

Figure 17. cyber skills of participants according to themselves

Additionally, table 5 reflects response of the participants towards the technologies in the digitalized energy systems where 64.3% responses think investment in new technologies is way to the future. These new technologies could be for example- AI/ML, digital twin.

Table 5. response to advancements in cybersecurity

In defence, what below could be a good initiative to advance cybersecurity	**Participants**	**Percent %**
Investment in new technologies	9	64,3%
Abandon the legacy technologies	4	28,6%
Developing the existing technologies	5	35,7%
Addressing the immediate cybersecurity requirements	10	71,4%

Furthermore, figure 18 shows from the participants response that for cybersecurity compliance programme in companies risk assessment and employee training are the most important steps.

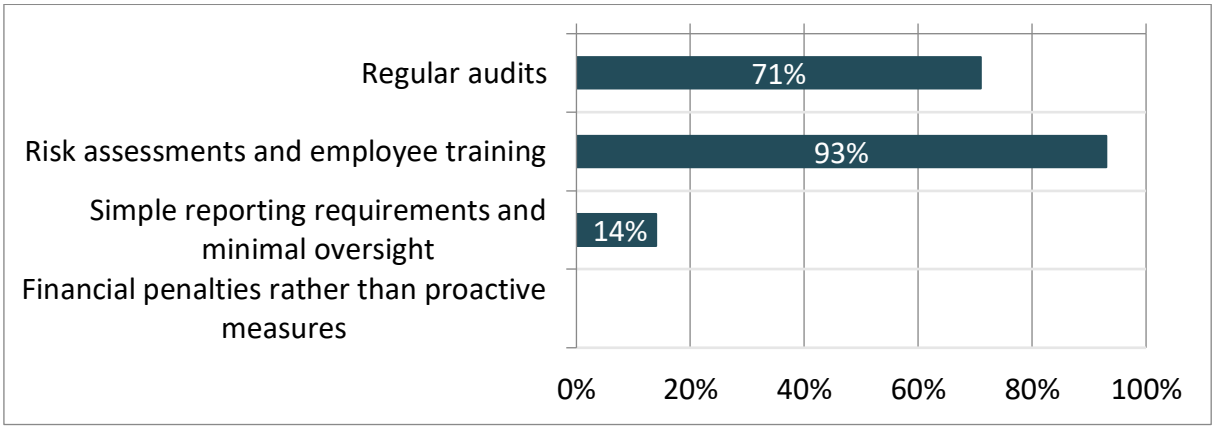

Figure 18. survey result- cybersecurity compliance

The findings of the study after analysing the outputs from the triangulation analysis on the integration of IT/OT in digitalized energy systems offers information about cybersecurity awareness, system efficiency, and challenges.

4.1 Discussions

The survey results emphasized significant preference for proactive cybersecurity measures, with 93% of respondents agreeing that risk assessment and staff training are important to cybersecurity measures. This aligns with ongoing research on cybersecurity that highlights the importance of creating a value system of security awareness within the organization and conducting risk assessment under fundamental procedure periodically to mitigate cybersecurity risks (Gonzalez and Patel, 2021). Considering that attack surfaces are widening with the integration, these findings imply that energy industry understands the relevance of proactive, continuous monitoring and education as critical to preserve digital infrastructure.

The result from the survey shows how participants see the investment in new technology. Most respondents agree that addressing urgent cybersecurity needs is priority, underscoring the imperative of improving cybersecurity infrastructure to rule out cotemporary threats. Furthermore, the second highest majority of people favour in investing in new technologies, which explains that energy industry is open to implement advanced technological solutions that could improve cybersecurity capabilities. Recent studies also emphasize on incorporating new technologies that support comprehensive cybersecurity solutions like AI based anomaly detection, intrusion prevention systems, and blockchain for secure and tamper proof data exchange in integrated IT and OT systems (Rahman and Chen, 2023). The other responses also suggest that although new technologies are advantageous, but it may come with high costs which can make its implementation slow.

One of the prominent challenges in the integration of IT and OT in digitalized energy systems is interoperability, which is a critical attribute to cybersecurity and operational effectiveness. During the interview and workshop many participants mentioned the difficulty of communication of seamless data with the integration of IT and OT systems, when the legacy OT systems are involved. This is consistent with previous research that identified interoperability problems are the major obstacle to IT and OT integration, which results in segmented control, data silos, and delayed responses to operational changes (Fernandez and Wong, 2021).

The result of survey and interview demonstrate how AI/ML technologies have the potential of improving real time data analytics and cybersecurity in IT/OT integrated settings. This is in agreement with the previous literature and studies that AI/ML can support in improving cybersecurity by notifying any unusual network traffic patterns because of their ability to handle large data, thus making system automated and allowing rapid attack detection and reaction (Singh and Ahmed, 2022). Participants also highlighted that despite advantages of AI/ML in digitalized energy system, it involves lot of cost resources in adoption of this technology and lack of knowledge. Business seeking to implement AI/ML poses knowledge gap.

The findings from this study have profound implications for industry processes in electricity based digitalized energy systems.

4.2 Limitations

Although this study has provided insightful information about the challenges and opportunities with the IT/OT integration, it should be noted that it can have many limitations also. Despite the diversity in the mixed method approach, the surveys, interviews, and workshop sample size might not reflect upon the adequate representation of all viewpoints within the digitalized energy sector. Also, the participants in the survey are from different industries so the responses could vary depending on their understanding. Furthermore, the results are contingent to the information provided by the respondents, the information may be biased.

5 Conclusion and Future recommendations

The energy industry is currently undergoing its most profound transformation in over fifty years, this shift is accelerated by the need of decarbonization and the promising capabilities of emerging digital technologies to decentralize and modernize the energy sector.

The integration of information technology (IT) and Operational technology (OT) within the electricity based digitalized energy system presents revolutionary approach to energy management that improves efficiency, dependability, and sustainability. The results of study from this thesis underscores that convergence of IT and OT is not limited to technical integration but serves the purpose of strategical alignment that harnesses digital technologies to improve the optimization of energy generation, distribution, and consumption. Moreover, this integration also enhances the grid stability and resilience by making energy systems dynamic and flexible to fluctuating requirements that supports enabling of predictive maintenance, provides insights into the operational data. Since data collection, analysis, and utilization are the important aspects of digitalization, these should be at the forefront of electricity based digitalized energy system. The study highlights that generated data from energy systems should be standardized, centralized and made easily accessible.

The study of the cybersecurity within the landscape of digitalized energy system has highlighted the vulnerabilities present in the energy sector, specifically within the fundamental components that enable IT and OT integration such as variable frequency drive (VFD), programmable logic controllers (PLCs), and supervisory control and data acquisition (SCADA) systems. The VFDs function to regulate motor speed, however the digitalization has made them vulnerable to cyberattacks that can cause cascading repercussions throughout the entire energy system. Similarly, safeguarding PLCs, SCADA systems is crucial in digitalized energy system as these devices operate within legacy energy infrastructure that lack robust cybersecurity protocols and expose them to internal and external

cyber threats. This insight into the energy component and devices necessitate a cyber-security framework to secure key elements and ensure system integrity and security of operations.

This thesis further investigates into the advanced technologies that propel IT and OT integration in energy systems. IoT devices provide connectivity, enables operational efficiency and real time monitoring in energy distribution. ML offers predictive analysis, anomaly detection that lowers the downtime and provide foresight into possible operational fault. Although blockchain technology is at an early stage in electricity based digitalized energy system, it holds exciting opportunities for safe data exchange and transaction verification, particularly in decentralized energy systems. Collectively, these technologies provide strength to the value of IT/OT integration for system optimization and strong security measures.

In the process of methodology this research utilized meticulous data collection and analysis to verify the hypotheses and asses the reliability of the proposed solutions. The results of the study emphasize on the importance of aligning cybersecurity measures with data driven techniques due to presence of vulnerabilities in digitalized energy system. Moreover, the reliability and validity ensure that insights collected are important and requires attention.

In conclusion, the integration of IT and OT within digitalized energy systems provides a mechanism to manage energy more efficiently, effectively and robustly. Nevertheless, the realization of this integration also has challenges on interoperability and cybersecurity in particular. To mitigate these risks a balanced strategy is required that incorporates advanced technologies like ML, AI and blockchain with advanced cybersecurity framework and continuous cooperation from energy industry.

The study highlights the strong need for further research in area of seamless interoperability of IT/OT without compromising on grid performance, flexibility and security. Additional required area of exploration is scalability of integration of large-scale projects consisting of national and transnational grid with grid stability and advanced data analytic techniques tailored to IT/OT environment. Furthermore, to create resilient systems that can endure and accommodate the changing threats and technological developments, future research should continue exploring the ways to improve these interconnected systems. This body of study establishes the groundwork for safer, more effective, and sustainable energy systems, thus promoting transition to more reliable, intelligent, digitalized energy systems.

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7 Appendix 1. Survey Questions

The total survey questions are more than 40, therefore these are presented in two separate tables below.

Survey questions
Which of the following best describes your work position?
Which of the following best describes your work position?
What is your level of seniority?
How would you rate your cyber skills according to these metrics?
How would you evaluate where your knowledge should be based on your job role, level of seniority, and other relevant factors?
I am allowed to click on any links in emails from people I know?
It's acceptable to use my social media passwords on my work accounts?
I am allowed to open email attachments from unknown senders?
I am allowed to download any files onto my work computer if they help me to do my job?
I am allowed to enter my information on any website if it helps me to do my job?
I am allowed to send sensitive work files via a public Wi-Fi network?
Sensitive print-outs can be disposed of in the same way as non-sensitive ones?
If I find a USB stick in a public place, I shouldn't plug it into my work computer?
I must not ignore poor security behavior by my colleagues?
Phishing refers to the practice of criminals sending unsuspecting user's malicious emails. What does that make smishing?
And why has smishing become so dangerous in recent years?
What does VPN stand for?
When might you use a VPN?
What's a man-in-the-middle attack?
Why is your phone always asking you to install updates?
And which of the following is the best way to avoid email interception through public wifi?
Which of the following best describes "Friday afternoon fraud"?
. Cookies are small information items (text files) stored in users' PCs and used widely by online service providers for several purposes, such as to capture user preferences (language, background colors, etc.), to identify the user when he/she uses a shopping list etc. By these means, cookies have indeed positive functions (e.g. they help avoiding the need to repeatedly identify yourself). However, cookies also raise some security and privacy concerns, for example:
One of your friends has recently been a victim of a social engineering attack since someone has stolen her username and password for accessing her work email. This name, "social engineering" looks quite strange to you as it puts together engineering with social issues. What does social engineering mean in a security context?
When you travel for work you often need to use open Wi-Fi networks, e.g. at train stations or coffee shops. However, you are aware that there might be dangers with such open networks. In order to protect your communication over these public networks you always:
Passwords are strings of characters used to access online services (e.g. your email or social networks profile). However, they also help to prevent other people from accessing your personal accounts. Unfortunately, because we use so many services, it is difficult to remember each password that we have. In this situation, what could be a good strategy?
While opening the email, you got an interesting but suspicious message from a company. The message said that "you've won the lottery" and the company was asking you specific personal and banking details so that they could lodge a large sum of money in your bank account. These emails are a common type of cyber-attack that goes by the name of:

Survey questions
Malware is software that has a malicious intent to harm users and their devices. A relevant protection in these cases is to have an antivirus software installed. However, even this is not sufficient as the antivirus needs to be constantly updated. What is your perspective about the need for updating the antivirus?
You have noticed that your computer is acting erratically and normal tasks (e.g., open a document/application), are taking a little bit longer to perform. So you called a friend of yours who is a computer technician and always helps you when your computer has problems. After a careful inspection he told you that your computer has been infected by a “Trojan Horse”. You wonder what a “Trojan Horse” could be?
One day when looking at your e-mail inbox, you find you have received an email from a friend you have not heard from for at least one year. When you open the email, the text says “Hi, please click here: http://shorturl.jhdsuyc.com, there is a surprise for you”. What would you do in such scenario?
End user perspective: if someone hacks your smart meter what might get jeopardized?
Smart-home context: what is critical to think about cyber-security perspective?
Does an aggregator pose a cyber vulnerability to the electricity system?
Does an aggregator pose a cyber vulnerability to the electricity system?
Where are the main vulnerabilities when a prosumer enters the market with device and system security?
NIS2 takes newly into account the
What are the key components for a successful cybersecurity compliance programme in companies?
What is the aim of implementing new cybersecurity policies?
What SBOM stands for?
NIST: What is the following sequence of action?
If a cyber incident happens to a grid operator, what should be prioritized within the CIA triad?
In defense, What below could be a good initiative to advance cybersecurity?
How could physical security measures be integrated to cybersecurity measures?

8 Appendix 2. Interview interaction questions

1. How long are you working in the energy industry?
2. How would you define digitalized energy system?
3. How do you see Operation technology (OT) as part of digitalized energy system?
4. How would you define integration of IT and OT in energy industry?
5. Has integration or automation facilitated the company? and how?
6. what do you think could be future opportunities in the integration of IT/OT?
7. What do you think are the challenges in automated energy systems?
8. How do you see cybersecurity in the energy products?
9. Do you think advanced technologies could be part of digitalized energy system?
10. What do you think about the future of digitalized energy systems, energy components and devices?