THE IMPACT OF CYBERSECURITY ON THE ENERGY SECTOR AND POWER GRIDS

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Annotation. *The energy sector is a critical component of modern economic infrastructure, making it a primary target for cyber threats. As digitalization and the integration of smart technologies increase, the vulnerability of energy systems to cyberattacks grows significantly. This article examines the role of cybersecurity in ensuring the stability, reliability, and resilience of energy infrastructure. It analyzes common threats, including ransomware, phishing, and attacks on industrial control systems, and highlights the potential economic and operational consequences of such incidents. Furthermore, the study explores strategies for strengthening cybersecurity frameworks, including risk assessment, employee training, and the implementation of advanced monitoring systems. The findings emphasize that effective cybersecurity measures are essential for sustainable development and uninterrupted energy supply.*

Key words*: cybersecurity, energy sector, critical infrastructure, cyberthreats, risk management, industrial control systems, digitalization.*

KIBERXAVFSIZLIKNING ENERGETIKA SEKTORI VA ELEKTR TARMOQLARIGA TA'SIRI

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Annotatsiya. *Energetika sektori zamonaviy iqtisodiy infratuzilmaning muhim qismi bo'lib, u kiberxavflar uchun asosiy nishonlardan biri hisoblanadi. Raqamlashtirish va aqlli texnologiyalarni joriy etish jarayonida energetika tizimlarining kiberhujumlarga nisbatan zaifligi sezilarli darajada ortmoqda. Ushbu maqolada kiberxavfsizlikning energetika infratuzilmasining barqarorligi, ishonchliligi va chidamliligini ta'minlashdagi roli ko'rib chiqiladi. Shuningdek, ransomware, fishing va sanoat boshqaruv tizimlariga qaratilgan hujumlar kabi asosiy tahdidlar tahlil qilinadi hamda ularning iqtisodiy va operatsion oqibatlari yoritiladi. Bundan tashqari, xavflarni baholash, xodimlarni o'qitish va zamonaviy monitoring tizimlarini joriy etish orqali kiberxavfsizlikni kuchaytirish strategiyalari o'rganiladi. Tadqiqot natijalari samarali kiberxavfsizlik choralarining barqaror rivojlanish va uzluksiz energiya ta'minoti uchun muhim ekanligini ko'rsatadi.*

Kalit so'zlar: *kiberxavfsizlik, energetika sektori, muhim infratuzilma, kibertahdidlar, xavflarni boshqarish, sanoat boshqaruv tizimlari, raqamlashtirish.*

ВЛИЯНИЕ КИБЕРБЕЗОПАСНОСТИ НА ЭНЕРГЕТИЧЕСКИЙ СЕКТОР И НА ЭЛЕКТРОСЕТИ

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Аннотация. *Энергетический сектор является ключевым элементом современной экономической инфраструктуры, что делает его одной из основных целей для киберугроз. По мере цифровизации и внедрения интеллектуальных технологий уязвимость энергетических систем к кибератакам значительно возрастает. В данной статье рассматривается роль кибербезопасности в обеспечении стабильности, надежности и устойчивости энергетической инфраструктуры. Анализируются основные угрозы, включая программы-вымогатели, фишинг и атаки на системы промышленного управления, а также их потенциальные экономические и операционные последствия. Кроме того, исследуются стратегии усиления кибербезопасности, включая оценку рисков, обучение персонала и внедрение современных систем мониторинга. Результаты показывают, что эффективные меры кибербезопасности являются необходимым условием устойчивого развития и бесперебойного энергоснабжения.*

Ключевые слова: *кибербезопасность, энергетический сектор, критическая инфраструктура, киберугрозы, управление рисками, промышленные системы управления, цифровизация.*

Introduction. The rapid digital transformation of the energy sector has significantly increased its efficiency, automation, and operational flexibility. However, the integration of information technologies with operational technologies (OT) has simultaneously expanded the attack surface of critical infrastructure. Modern energy systems - including power generation, transmission, and distribution - rely heavily on interconnected digital platforms, industrial control systems (ICS), and smart grid technologies, making them vulnerable to cyber threats.

Hypothesis. The increasing level of digitalization in the energy sector significantly raises cybersecurity risks; however, the implementation of comprehensive cybersecurity frameworks, advanced monitoring systems, and personnel training can effectively mitigate these risks and enhance the resilience of critical energy infrastructure.

Literature overview. The issue of cybersecurity in the energy sector has been widely discussed in both academic and professional literature. Existing studies can be grouped into several key directions: protection of critical infrastructure, security of industrial control systems, and resilience of smart grids.

One of the fundamental works in this field is the book “Cybersecurity in the Electricity Sector: Managing Critical Infrastructure” by Rafal Leszczyna [1]. The author provides a

systematic approach to cybersecurity management in energy systems, emphasizing risk assessment, cost evaluation, and compliance with security standards. Leszczyna argues that effective cybersecurity requires not only technical solutions but also organizational and economic considerations, forming a holistic protection framework .

Another important contribution is the edited volume “Cyber-security of SCADA and Other Industrial Control Systems” by Edward J.M. Colbert and Alexander Kott [2]. This work focuses on vulnerabilities and protection mechanisms in SCADA and ICS systems, which are widely used in energy infrastructure. The authors highlight that failures in these systems can lead to serious operational disruptions and emphasize the importance of intrusion detection, risk assessment, and secure system design .

Modern perspectives on securing industrial systems are presented in “Securing Industrial Control Systems: Advanced Strategies and Technologies” by Mohammad Ashiqur Rahman [3] and co-authors. The book examines the architecture of ICS, emerging threats, and advanced protection techniques, including intrusion detection systems and cyber resilience strategies. It also underlines the importance of integrating IoT security measures into industrial environments .

In addition, the book “Power Systems Cybersecurity: Methods, Concepts, and Best Practices” edited by Hassan Haes Alhelou, Nikos Hatziargyriou [1], and Zhao Yang Dong provides both theoretical and practical approaches to ensuring cybersecurity in power systems. The authors stress the need for resilient control methods capable of maintaining system stability under cyberattack conditions .

From a practical perspective, Charles J.Brooks and Philip A. Craig in “Practical Industrial Cybersecurity” [1] emphasize real-world tools and techniques used by professionals to protect industrial environments, including those in the energy sector. Their work bridges the gap between theory and implementation by aligning cybersecurity practices with international standards such as NIST .

Additionally, the book “Hacking Exposed Industrial Control Systems” by Clint Bodungen and colleagues provides insight into real attack vectors and vulnerabilities in ICS/SCADA systems, demonstrating how cyberattacks can disrupt critical processes and emphasizing the need for proactive defense strategies .

A broader conceptual perspective is offered in “Brittle Power” by Amory Lovins and L. Hunter Lovins, which, although written earlier, highlights the inherent vulnerability of centralized energy systems and the importance of resilience - ideas that remain highly relevant in the context of modern cyber threats.

According to researchers such as Matthew Boeding and Hamid Sharif, the convergence of IT and OT systems creates new security challenges related to confidentiality, integrity, and availability, particularly in power grid environments . Cyberattacks targeting energy infrastructure can lead not only to financial losses but also to large-scale disruptions of essential services, posing risks to national security and economic stability.

Furthermore, the growing adoption of smart grids and Internet of Energy concepts increases system complexity and exposure to cyber risks. As noted by Rafal Leszczyna, the modernization of electricity systems is intrinsically linked with vulnerabilities introduced by digital technologies, requiring comprehensive cybersecurity strategies.

Research methods. The modern energy sector is undergoing a profound transformation driven by rapid digitalization, automation, and the integration of advanced information technologies into traditional industrial processes. Power systems, once largely isolated and mechanically operated, are now increasingly interconnected through digital networks, smart grid technologies, and industrial control systems. While these innovations have significantly improved efficiency, reliability, and scalability, they have also introduced new layers of complexity and vulnerability.

In this evolving environment, cybersecurity has emerged as a critical factor influencing not only the technical performance of energy systems but also their economic stability and national significance. The growing dependence on digital infrastructure exposes energy companies to a wide range of cyber threats, including unauthorized access, data manipulation, and disruptions of operational processes. Such incidents can lead to cascading failures across interconnected systems, affecting entire regions and sectors of the economy.

Moreover, the energy sector represents a key component of critical infrastructure, meaning that any compromise in its functioning can have far-reaching consequences beyond financial losses. The increasing frequency and sophistication of cyberattacks highlight the urgent need for a comprehensive approach to security that combines technological, organizational, and regulatory measures. As digital transformation continues to accelerate, ensuring the protection and resilience of energy systems becomes not only a technical challenge but also a strategic priority for governments and enterprises worldwide.

Results of the research. In recent years, the number of cyberattacks targeting oil and gas companies has significantly increased across both offshore and onshore facilities. Due to the rapid digital transformation of the energy sector, industrial operations are becoming increasingly dependent on advanced technologies, including remote monitoring systems, smart sensors, and automated control infrastructures. Although these innovations improve operational efficiency and productivity, they simultaneously increase the exposure of industrial networks to cyber threats and malicious attacks [6].

Offshore oil and gas production environments are particularly vulnerable because they often operate in geographically isolated locations that require remote administration and continuous data exchange. To support these processes, Industrial Cyber-Physical Systems (ICPS), Supervisory Control and Data Acquisition (SCADA) systems, and Industrial Internet of Things (IIoT) technologies are extensively integrated into operational infrastructures [7]. A successful cyberattack against such facilities may cause severe disruptions not only to production activities, but also to environmental sustainability, marine ecosystems, and personnel safety [8].

Researchers have emphasized the growing necessity of implementing continuous cybersecurity monitoring and proactive protection mechanisms within industrial IoT ecosystems. Studies focusing on cybersecurity management in IIoT-based industrial systems identified several strategic approaches for enhancing monitoring and control capabilities, particularly in critical infrastructure sectors such as oil and gas [9]. Previous investigations of cyber incidents in industrial environments demonstrated that integrating advanced monitoring technologies, threat intelligence systems, and adaptive security controls can significantly improve resilience against cyber threats [10].

The global cybersecurity situation further deteriorated following the COVID-19 pandemic and geopolitical conflicts, which substantially increased the number of cyber incidents worldwide. In particular, the energy sector experienced a sharp rise in targeted attacks, forcing organizations to adopt more proactive cybersecurity frameworks that combine technological safeguards with behavioral and organizational security measures [11]. Some researchers proposed cybersecurity models based on the NIST Cybersecurity Framework (NIST CSF) and CIS Critical Security Controls (CIS CSC), demonstrating their effectiveness in strengthening the security posture of gas industry enterprises [12].

The increasing integration of operational technology (OT) and information technology (IT) systems has also expanded the attack surface of industrial control infrastructures. Modern intelligent industrial processes require interconnected architectures, which simultaneously create new cybersecurity challenges for Industrial Control Systems (ICS). As a result, researchers highlighted the importance of context-aware threat detection methods and risk-based cybersecurity mechanisms capable of identifying attacks targeting cyber-physical infrastructures [13].

Intrusion Detection Systems (IDS) supported by machine learning algorithms are increasingly recognized as effective solutions for protecting critical industrial networks. Recent studies evaluated various artificial intelligence techniques, including Long Short-Term Memory (LSTM), Random Forest, Multilayer Perceptron (MLP), and One-Dimensional Convolutional Neural Networks (1DCNN), for detecting malicious activities within oil and gas infrastructures. Experimental results demonstrated that deep learning-based approaches can achieve high accuracy in identifying cyber intrusions and abnormal network behavior [14].

In addition, researchers investigating cyber resilience in the oil and gas industry emphasized that traditional security mechanisms alone are insufficient in highly connected industrial ecosystems. Modern cybersecurity strategies should incorporate both robustness and adaptive capacity to ensure resilience against evolving cyber threats. This approach requires organizations to move beyond conventional risk management practices and develop flexible cybersecurity frameworks capable of responding to dynamic attack scenarios [15].

Several studies also analyzed cyberattacks targeting process control networks (PCN) within oil and gas installations. Common threats include Denial-of-Service (DoS), Distributed Denial-of-Service (DDoS), and Man-in-the-Middle (MitM) attacks. The adoption of public network technologies within operational environments and the necessity of internet

connectivity for maintenance and firmware updates significantly increase cybersecurity risks [16]. Machine learning techniques have shown promising results in detecting anomalies and identifying sophisticated attacks within process control systems [17].

Furthermore, researchers examined the effectiveness of international cybersecurity standards, particularly ISO/IEC 27001, in mitigating cyber risks within the energy sector. The findings demonstrated that implementing structured cybersecurity governance frameworks, improving cybersecurity awareness, and strengthening workforce education contribute substantially to enhancing organizational cyber resilience [18].

Recent studies on offshore oil and gas cybersecurity also highlighted the importance of organizational culture, employee awareness, incident response planning, and external cybersecurity expertise. Human-related factors, including insider threats and insufficient cybersecurity awareness among personnel, were identified as major contributors to security incidents within critical infrastructure environments [19].

The development of Integrated Energy Cyber-Physical Systems (IECPS) has considerably improved the operational efficiency and reliability of Integrated Energy Systems (IES) [17]. Nevertheless, the integration of advanced information technologies with energy infrastructures has also increased the complexity of these systems, creating additional vulnerabilities and exposing critical infrastructures to new cybersecurity risks [18]. Among the major concerns are communication interruptions, system malfunctions, and the increasing frequency of sophisticated cyberattacks targeting operational technologies and interconnected networks [19].

The cybersecurity landscape within energy systems has evolved substantially over time. Early studies primarily concentrated on protecting isolated IT and OT infrastructures in conventional power systems. With the emergence of smart grid technologies and distributed energy resources (DER), attention gradually shifted toward cyber-physical security approaches designed for interconnected and digitally controlled environments. Currently, research is moving toward fully integrated multi-carrier IECPS architectures, where electricity, gas, and thermal networks operate through tightly interconnected infrastructures. This transition reflects a broader shift from securing individual assets toward ensuring the resilience and sustainability of interconnected critical infrastructures.

Several major cyber incidents have demonstrated the vulnerability of modern energy systems to cyber threats. Among the most notable examples are the 2015 cyberattack on the Ukrainian power grid [20] and the Colonial Pipeline attack in 2021 [12]. In addition to targeted cyberattacks, energy infrastructures have also experienced numerous operational disruptions caused by software failures, communication breakdowns, and network instability [21]. Although extensive studies have been conducted on IES planning, scheduling, simulation, and market operation mechanisms [22,23], cybersecurity continues to represent one of the most significant unresolved challenges within the sector [21].

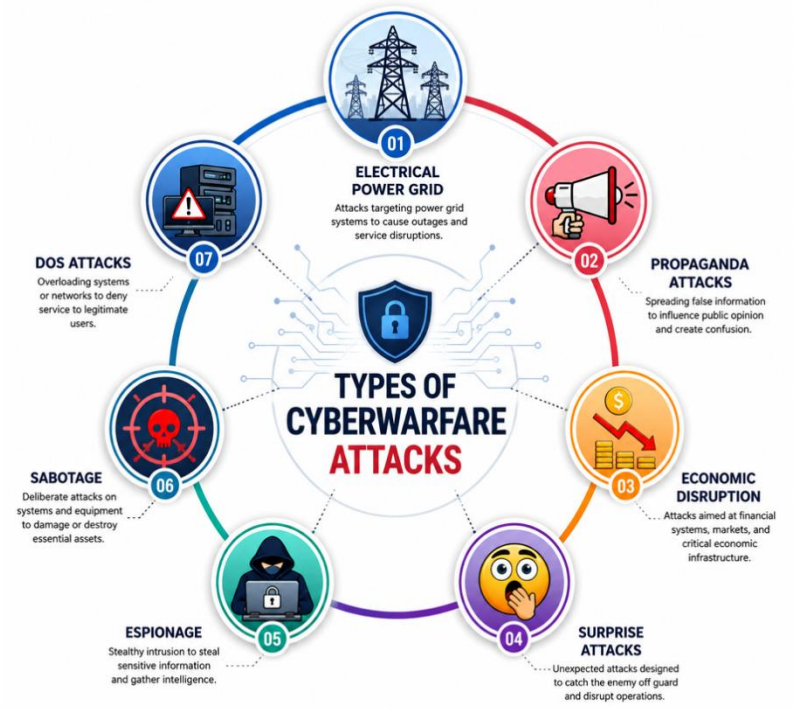

Fig.1. Different attack methodologies used for cyber-warfare [16]

Conventional physical security mechanisms alone are insufficient to mitigate the complex risks associated with cyber-physical integration in modern energy infrastructures [24]. Researchers emphasized that the deployment of large-scale Cyber-Physical Systems (CPS) in integrated energy environments introduces substantial cybersecurity challenges requiring advanced protection strategies [25].

ear	Country/ Region	Targeted Infrastructure	Attack Type/Method	Impact	Availability of Data	Notes/Significance
015	Ukraine	Power Grid	Malware (BlackEnergy), ICS manipulation	Major blackout affecting ~225,000 customers	High	One of the first successful cyberattacks on a national power grid; well-documented, widely analyzed in literature
021	United States	Major fuel pipeline (oil & refined products)	Ransomware attack (DarkSide) targeting IT systems, leading to shutdown	Temporary shutdown of pipeline operations, fuel shortages/panic buying; declared national emergency	High/Moderate	Ransomware disrupted critical energy supply chain; forced shutdown and ransom payment ~$5M

ear	Country/ Region	Targeted Infrastructure	Attack Type/Method	Impact	Availability of Data	Notes/Significance
022	Europe	Renewable energy generation systems	Cyber intrusion/attack on operational technology	Production disruptions in renewable energy output	Low/Moderate	Demonstrates vulnerability of renewable energy systems to cyberattacks; limited technical data publicly available
024	Ukraine	District Heating System	Malware targeting heating controls	Disruption of heating/water for ~600 buildings for 48+ hours	Moderate	Demonstrates attack on thermal energy infrastructure, not just electricity; recent example of ICS targeting
025	Poland	Power Grid & Renewable Integration	Cyber intrusion targeting communication and control systems	No widespread blackout, but revealed vulnerabilities in grid operations	Low	Highlights evolving attack tactics on integrated energy systems; latest publicized incident
025	Canada	Water & Energy ICS	Multiple ICS breaches including pump and sensor manipulation	Operational disruptions in critical facilities	Low	Shows trend of ICS attacks in multiple sectors; emphasizes global threat to critical infrastructure

Table 1. Real-world examples of cyber warfare [16]

Consequently, recent studies on IECPS increasingly focus on cyber-physical integration security, including coupling models, security assessment methodologies, attack detection and defence mechanisms, as well as resilience and recovery strategies after cyber incidents. Despite the existence of multiple cybersecurity reviews for traditional power systems [26], a comprehensive and systematic analysis dedicated specifically to IECPS cybersecurity challenges remains limited within the current scientific literature.

Cybercriminals employ a wide range of attack methodologies depending on the targeted infrastructure and intended objectives. For example, the BlackEnergy malware used during the cyberattack on the Ukrainian power grid infiltrated industrial control systems and manipulated operational processes, ultimately causing large-scale power outages. Likewise, the DarkSide ransomware attack against the Colonial Pipeline disrupted fuel distribution operations by encrypting critical operational data and demanding ransom payments for system recovery. More recent incidents, including distributed Denial-of-Service (DoS) attacks

targeting renewable energy infrastructures, demonstrate an increasing focus on decentralized and digitally connected energy systems, where emerging technologies often introduce additional cybersecurity vulnerabilities [16].

Despite the severe operational and economic consequences of these incidents, the implemented response and recovery measures revealed the critical importance of proactive cybersecurity preparedness within the energy sector. Governments and energy organizations worldwide have adopted various mitigation strategies aimed at strengthening cyber resilience and ensuring operational continuity. These measures include:

– conducting manual recovery procedures to restore critical operations when automated systems become compromised;

– implementing enhanced cybersecurity protocols to reinforce infrastructure protection mechanisms;

– deploying advanced threat detection technologies based on Artificial Intelligence (AI) and Machine Learning (ML) for real-time identification of malicious activities;

– increasing financial investments dedicated to cybersecurity resilience and infrastructure hardening against evolving cyber threats.

Nevertheless, the growing sophistication of cyberattacks requires continuous adaptation of cybersecurity strategies, ongoing investments in advanced security technologies, and stronger international cooperation in developing unified regulatory frameworks and common cybersecurity standards for Integrated Energy Cyber-Physical Systems (IECPS). In this regard, Table 1 presents a detailed overview of some of the most significant cyberwarfare incidents that have affected the global energy sector in recent years.

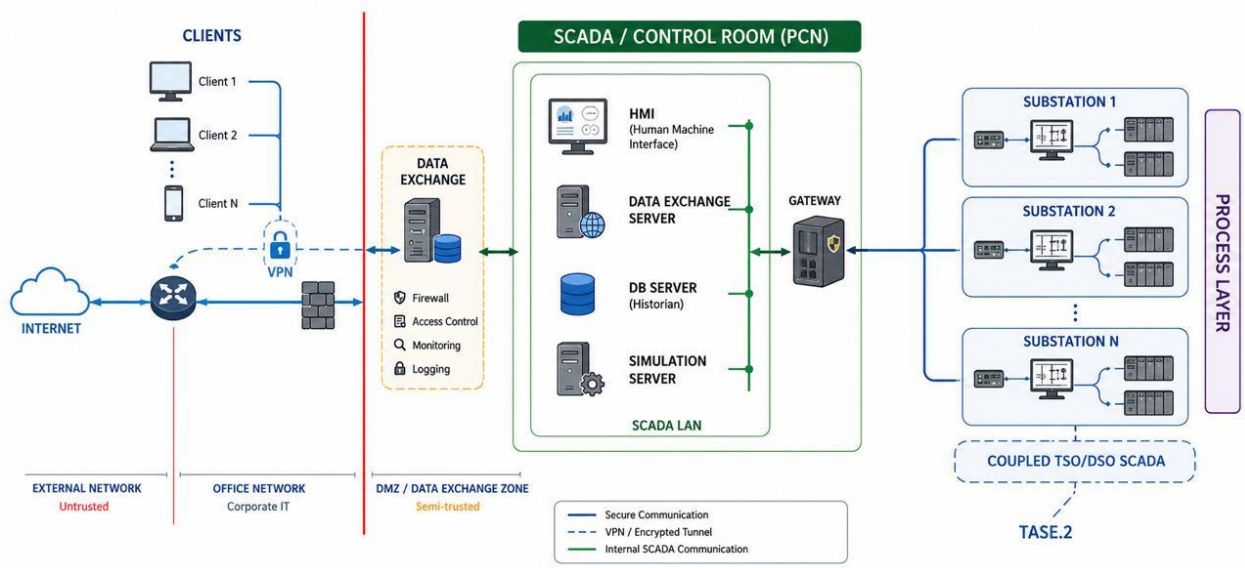

Fig.2. Communication infrastructure of Power grids [17]

Figure 2 presents a simplified representation of the communication architecture commonly used within electrical power grid operator networks, including Transmission System Operators (TSOs) and Distribution System Operators (DSOs). A characteristic feature of such infrastructures is the clear separation between the corporate office network and the Process Control Network (PCN). The office network generally supports standard enterprise activities, including email communication, administrative operations, and data processing tasks. In contrast, the PCN is responsible for connecting the control room with substations and field devices involved in operational grid management. Communication within these environments is typically performed using industrial protocols such as DNP3 [27], widely adopted in North America and parts of Asia, or IEC 60870-5-104 [28], which is commonly utilized in many other regions worldwide.

Control commands generated within the system are usually processed through Programmable Logic Controllers (PLCs) before being transmitted to the process layer. The control room itself generally includes several critical components, such as a Human-Machine Interface (HMI), a database server responsible for storing and managing grid-related information, and simulation servers used for forecasting and evaluating the potential impact of operational changes within the grid infrastructure. Additionally, the control environment is interconnected with multiple substations, each containing gateways, HMIs, and PLC devices, while also supporting communication with other TSO/DSO SCADA systems for coordinated operational control.

To maintain cybersecurity and reduce the risk of unauthorized access, information exchange between the office network and the PCN should be conducted exclusively through a dedicated and secured data exchange server. Such servers are typically configured to inspect all transferred files for malware or suspicious activity before allowing communication between network segments. Nevertheless, practical incidents, including the Ukraine power grid cyberattack [21], demonstrated that alternative communication pathways may still exist within critical infrastructures. These include VPN connections enabling direct communication between corporate networks and the PCN, as well as remote maintenance channels used by external vendors or contractors, which can potentially introduce additional cybersecurity vulnerabilities if not properly secured.

Scope	Difficulty	Impact	Examples
Lateral Movement	Single Operator	High	High
Physical Access	Local	Medium	Medium
Remote Maintenance Access	Multiple Operators	High	High
Third-Party Exploit	Multiple Operators	High	Medium

Scope	Difficulty	Impact	Examples
Overcoming Air Gap	Local	High	Medium
Insider Attack	Single Operator	Low	High
Cascading Effects	Multiple Operators	High	High

Table 2. Real-world examples of cyber warfare. [16]

Cyber attackers may exploit multiple attack vectors to compromise the networks of Transmission System Operators (TSOs) or Distribution System Operators (DSOs) with the objective of causing large-scale power outages or significant disruptions within the electrical grid infrastructure. To accomplish such objectives, attackers typically attempt to gain unauthorized access to the Process Control Network (PCN), which represents one of the most critical components [16] of operational power system management.

Once access to the PCN is obtained, malicious actors may further compromise substations, industrial controllers, or field devices, potentially resulting in operational failures, instability of grid services, or widespread blackouts. Due to the interconnected nature of modern energy infrastructures, unauthorized manipulation of these systems can produce severe technical, economic, and societal consequences.

Various attack vectors may be utilized to penetrate the PCN environment, depending on the architecture and security posture of the targeted infrastructure. These vectors may include vulnerabilities in remote access services, insecure communication channels, compromised vendor connections, phishing attacks targeting employees, malware infections, or exploitation of misconfigured network devices. The following section discusses the most significant attack vectors that can be used to infiltrate industrial energy infrastructures, while Table 2 summarizes the proposed classification of these attack methods.

Conclusion. The ongoing digitalization and decentralization of modern power systems have significantly transformed the communication requirements of grid operators. As energy infrastructures become more interconnected, the volume and complexity of data exchange continue to increase, leading to the expansion of networked environments and, consequently, a broader attack surface for cybercriminals. These developments introduce fundamental cybersecurity challenges and new attack vectors that must be effectively addressed to maintain the reliability, resilience, and operational continuity of power grids as critical infrastructure systems [2,3,4,5].

To strengthen the security of interconnected power networks, researchers and industry specialists have proposed various cybersecurity mechanisms and protective approaches. Depending on the technological maturity and cybersecurity readiness of individual countries and energy companies, implemented security measures may vary considerably, ranging from

minimal protection mechanisms to advanced state-of-the-art cybersecurity solutions. Nevertheless, even limited unauthorized control over a relatively small portion of the grid infrastructure can be sufficient for attackers to exploit vulnerabilities within large-scale power systems and trigger substantial operational disruptions. Therefore, ensuring comprehensive and nationwide improvements in grid cybersecurity remains essential for defending against sophisticated and coordinated cyberattacks. In this regard, a combination of technical and organizational measures - including intrusion detection systems (IDS), software-defined networking (SDN), continuous monitoring, and cybersecurity awareness training - has been identified as particularly effective for improving the overall resilience of energy infrastructures.

The transition toward smart grid technologies, including the widespread deployment of smart meters [16] and electric vehicle charging infrastructures, has further increased both cybersecurity challenges and opportunities for technological innovation [26]. One of the most actively explored research directions in smart grid cybersecurity involves the application of blockchain and distributed ledger technologies. Current studies suggest that these technologies may contribute to enhancing decentralized security mechanisms for national and international smart grid infrastructures, improving supply chain security for grid assets, automating infrastructure verification processes, and securely preserving cybersecurity audit records.

In addition, ongoing research efforts investigate decentralized management and operational control mechanisms within modern power systems. These approaches include the development of flexible local energy markets aimed at supporting the secure integration of renewable energy resources into traditional energy systems, as well as intelligent demand forecasting and automated energy consumption adjustment mechanisms based on fluctuations in electricity pricing. Despite the growing interest in blockchain-based security solutions, their practical effectiveness and suitability for critical infrastructures such as power grids remain uncertain, particularly considering strict regulatory and operational requirements.

Overall, the cybersecurity landscape of modern power grids is undergoing rapid transformation. As societies increasingly rely on uninterrupted and universally available electricity services, energy infrastructures must continuously adapt to emerging cyber threats and evolving attack methodologies. Achieving sustainable cybersecurity within interconnected power systems requires close collaboration between cybersecurity professionals, energy operators, and regulatory authorities to develop specialized protection mechanisms tailored to the unique operational characteristics of power grids. Consequently, the theoretical and conceptual contributions presented in this study establish a foundation for future practical investigations and experimental research aimed at strengthening cybersecurity resilience within interconnected energy infrastructures.

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