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DIGITAL TRANSFORMATION AND INTELLIGENT AUTOMATION IN AZERBAIJAN'S ENERGY SECTOR: SMART TECHNOLOGIES, HUMAN CAPITAL DEVELOPMENT, AND PERSPECTIVES

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ЦИФРОВАЯ ТРАНСФОРМАЦИЯ И ИНТЕЛЛЕКТУАЛЬНАЯ АВТОМАТИЗАЦИЯ В ЭНЕРГЕТИЧЕСКОМ СЕКТОРЕ АЗЕРБАЙДЖАНА: УМНЫЕ ТЕХНОЛОГИИ, РАЗВИТИЕ ЧЕЛОВЕЧЕСКОГО КАПИТАЛА И ПЕРСПЕКТИВЫ

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Abstract. The article discusses the prospects of scientific and technological development in Azerbaijan’s energy sector and the process of digital transformation up to the year 2030. The explored directions include the transition to environmentally friendly energy technologies, the creation of innovative energy systems, the optimization of energy consumption, and the regulation of resilient energy system management. Digital transformation is implemented through mechanisms such as the transition from analog to discrete digital signals, the application of digital technologies, the use of intelligent energy systems, and the utilization of simulated models. The article also highlights the development of human capital in the energy sector, the enhancement of engineers’ digital literacy and competencies, and the formation of essential and additional digital skills. Ongoing digital energy projects in Azerbaijan, including “smart” grid and metering systems, SCADA and automated control systems, as well as the next-generation engineering education model based on STEAM, are reviewed. A modified STEAM education framework is proposed for training engineers in digital energy. The article emphasizes the strategic importance of digital transformation for improving the efficiency of energy production and distribution, reducing operational costs, and strengthening the competitiveness of the country's energy sector.

Аннотация. Рассматриваются перспективы научно-технологического развития энергетического сектора Азербайджана и процессы его цифровой трансформации на период до 2030 года. Исследуемые направления включают переход к экологически чистым энергетическим технологиям, создание инновационных энергетических систем, оптимизацию энергопотребления, а также регулирование и управление устойчивыми энергосистемами. Цифровая трансформация реализуется с помощью таких механизмов, как переход от аналоговых сигналов к дискретным цифровым, применение цифровых технологий, интеллектуальных энергетических систем и использование симуляционных моделей. В статье также особое внимание уделяется развитию человеческого капитала в энергетическом секторе, повышению цифровой грамотности и компетенций инженеров, а также формированию базовых и дополнительных цифровых навыков. В работе рассматриваются текущие проекты цифровой энергетики в Азербайджане, включая «умные» сети и системы учета (Smart Grid), системы SCADA и автоматизированного управления, а также модель инженерного образования нового поколения на базе концепции STEAM. Для подготовки инженеров в области цифровой энергетики предложена модифицированная структура образования STEAM. В заключении подчеркивается стратегическая важность цифровой трансформации для повышения эффективности производства и распределения энергии, снижения операционных расходов и укрепления конкурентоспособности энергетического сектора страны.

Keywords: digitalization; energy; intelligent systems; digital transformation; STEAM model; innovative; Azerbaijan.

Ключевые слова: цифровизация, энергетика, интеллектуальные системы, цифровая трансформация, модель STEAM, инновационный, Азербайджан.

Smart grid technologies represent one of the key pillars of digital transformation in the energy sector. Unlike conventional power systems, smart grids enable bidirectional communication between electricity suppliers and consumers, allowing real-time monitoring, demand forecasting, and efficient energy management. In Azerbaijan, the deployment of smart metering infrastructure and intelligent distribution systems contributes to improving energy efficiency and reducing technical losses. The scientific and technological development plan of Azerbaijan for the period up to 2030 highlights several forward-looking research directions in the energy sector. These include: transitioning to new-generation, environmentally sustainable, and resource-efficient energy technologies, encompassing solar, wind, hydro, and other renewable energy projects characterized by high power density and operational robustness; developing innovative energy systems that significantly enhance sector management, reliability, and operational efficiency; ensuring efficient energy consumption through the implementation of advanced technologies, technical tools, and methodologies, thereby substantially minimizing energy losses for end-users, particularly in energy-intensive economic sectors and public services; modernizing and digitalizing the electric power grid, including the deployment of smart grid systems and the upgrading of transmission and distribution infrastructure; establishing green energy zones and sustainable industrial areas, with a focus on expanding projects in the Karabakh and Eastern Zangezur regions; optimizing the implementation and management of large-scale energy systems by applying novel methods, mathematical models, and computational tools to ensure the required reliability and safety standards; and promoting human capital and innovation by strengthening the training of specialists in the green energy sector, expanding research activities, and fostering innovative initiatives (https://president.az/ru/).

The realization of these strategic directions is inherently linked to the digitalization and transformation of the energy sector. This transition relies on the conversion of analog signals into discrete digital signals. The question of how accurately a digital representation can capture an analog signal, and how precisely an analog signal can be reconstructed from its discrete samples, was formally addressed by Vladimir Kotelnikov in 1932 through the sampling theorem [1].

By sampling an analog signal at specified intervals and storing these measurements, it becomes possible to reconstruct the original signal with high fidelity. The enhanced computational capabilities of modern computers, coupled with the widespread adoption of information technologies, have facilitated the practical implementation of these digital methods within the energy sector. Consequently, digital technologies are being systematically and strategically employed in the energy domain to execute tasks more rapidly, accurately, and efficiently. The overarching objectives are to increase labor productivity, improve operational quality, maintain competitiveness, and generate tangible economic benefits [2].

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Furthermore, the digital transformation of the power industry represents a critical developmental milestone, entailing the transition from traditional analog control systems and technologies to fully digital solutions [3]

One of the strategic pillars of this digitalization process is the specialization of new engineering personnel and the enhancement or retraining of existing engineers within enterprises, aimed at developing their digital literacy, competence, and technical proficiency [4].

The digitalization of the energy sector is based on automation and telemechanics systems, as well as modern computer technologies and advanced control mechanisms. The primary objective of automation is to allow devices and software to perform certain tasks in place of humans, facilitating operations and enabling faster and more accurate results [5].

The main goal of digitalizing the national electric power system is to ensure reliable, high-quality, and uninterrupted electricity supply to consumers, to organize services more conveniently and cost-effectively, and simultaneously to safeguard national energy and environmental security.

In Azerbaijan, digitalization encompasses all stages of electricity generation, transmission, and distribution, including thermal power plants, hydroelectric stations, solar and wind power plants, electrical grids, substations, dispatch centers, and energy sales organizations. Digitalization optimizes energy production and transmission methods, increases the share of renewable energy sources, transforms the structure of electricity demand, and establishes the concept of “digital consumption” [3].

Practically, it involves extensive automation, electronic storage and real-time processing of data, real-time monitoring and remote control, and the development of digital networks. Digital transformation guides the phased modernization of energy infrastructure, which can be implemented without halting electricity production [6].

Modernization activities are conducted in parallel, integrating new technologies and control algorithms. Particular emphasis is placed on the development of intelligent energy systems, including the use of artificial intelligence for large-scale data processing, replacing analog devices with digital sensors and intelligent equipment, implementing smart grid and smart metering systems, and employing automated and robotic technologies in high-risk areas [7].

The use of digital twins and virtual prototypes enables pre-modeling of energy facilities, early fault detection, and risk mitigation. Overall, digitalization reduces operational costs, improves service quality, strengthens competitiveness, and fosters the development of new digital services while enhancing the security and resilience of energy systems [6].

Digital transformation in the energy sector requires the enhancement of personnel competencies and the development of digital literacy. Currently, digital literacy entails engineers’ ability to safely perform tasks using internet resources and digital technologies [7].

It is not innate and does not conclude with university education; engineers must adhere to the principle of continuous learning, as innovative technologies are increasingly integrated into traditional practices. Continuous learning can be conducted in-person or remotely, using training courses, workplace simulations, and interactive technologies.

Continuous learning fosters personal development, career advancement, and confidence in digital competencies. The success of digital transformation depends directly on the development of human capital. Energy engineers must possess traditional technical knowledge alongside digital literacy and competencies, allowing them to effectively utilize digital technologies and internet resources, process and analyze data, and operate safely and efficiently in digital environments. Engineers’ digital skills are categorized into core competencies, such as using computers, laptops, smartphones, file management, and internet resources, and supplementary competencies, which include conscious application of digital technologies in professional activities, ensuring information security, and developing creative solutions. Key aspects involve digital ethics, online communication, remote collaboration, and data protection. Modern energy engineers are expected to plan and manage production processes using digital technologies, actively participate in teamwork, handle technical documentation in digital formats, monitor energy equipment, analyze decision-making risks with artificial intelligence, respond promptly in emergencies, and develop foreign language skills to acquire international experience. Several digital energy projects are underway in Azerbaijan, including the installation of smart meters, deployment of SCADA and automated control systems in substations and dispatch centers, enhancement of digital monitoring and remote control, and integration of solar and wind power plants into the energy system (https://azerenerji.gov.az).

These initiatives increase network reliability and the efficiency of energy generation and distribution. Educational reforms support the preparation of next-generation energy engineers. Classical engineering education is being transformed using a STEAM-based approach that incorporates artificial intelligence, digitalization, and environmental subjects, providing students with systematic thinking, digital skills, environmental responsibility, and practical problem-solving abilities [5].

AI technologies personalize learning through analysis and forecasting tools, optimizing individual educational outcomes. Thus, digital transformation in Azerbaijan's energy sector targets not only technological advancement but also human capital development. Enhancing engineers' digital competencies, modernizing education and vocational training, and implementing innovative projects strengthens energy security, improves service quality, and ensures long-term sector competitiveness. The remote control of electrical substations is one of the most significant achievements of digital transformation in the modern energy sector. Electrical substations constitute critical elements of power generation, transmission, and distribution networks, ensuring the reliable delivery of electricity from power plants to end users. Traditionally, substations required the continuous presence of operational personnel responsible for monitoring equipment, collecting measurements, performing switching operations, and responding to emergency situations. However, the rapid development of digital technologies, communication networks, automation systems, and intelligent control platforms has fundamentally transformed substation management. Remote control technologies enable operators to monitor and manage substations from centralized dispatch centers without the need for permanent on-site personnel. This capability is achieved through the integration of Supervisory Control and Data Acquisition (SCADA) systems, Intelligent Electronic Devices (IEDs), programmable logic controllers (PLCs), remote terminal units (RTUs), digital sensors, and advanced communication networks. In a modern digital substation, various operational parameters such as voltage levels, current values, power flows, transformer temperatures, circuit breaker status, frequency, and equipment health indicators are continuously measured by digital sensors. These data are transmitted in real time through communication channels to a central control center where operators can visualize the status of the entire power network using graphical interfaces and analytical software. One of the primary advantages of remote-controlled substations is the ability to perform switching operations from distant locations. Circuit breakers, disconnectors, transformers, and other equipment can be controlled remotely, significantly reducing response times during faults or maintenance procedures. In emergency situations, operators can isolate damaged sections of the network within seconds, minimizing power outages and improving system reliability.

SCADA systems serve as the technological foundation of remote substation control. These systems collect, process, store, and display operational data while providing operators with tools for real-time monitoring and decision-making. Modern SCADA platforms incorporate advanced visualization technologies, event recording, alarm management, and historical data analysis. The integration of artificial intelligence and machine learning algorithms further enhances their

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capabilities by enabling predictive maintenance and fault forecasting. Another important aspect of remote substation control is the implementation of Intelligent Electronic Devices. IEDs combine protection, measurement, monitoring, and control functions within a single device. They continuously evaluate system conditions and can automatically initiate protective actions in response to abnormal events such as short circuits, overloads, voltage instability, or equipment failures. This automation significantly increases the speed and accuracy of system protection. The application of communication technologies is equally essential. Modern substations utilize fiber-optic networks, wireless communication systems, industrial Ethernet protocols, and international communication standards such as IEC 61850. These technologies ensure reliable and secure data exchange between field devices and control centers while supporting interoperability among equipment from different manufacturers (https://scada-plc.ru/scada).

Remote monitoring and control contribute substantially to operational efficiency. The elimination of routine manual inspections reduces labor costs and minimizes human errors. Furthermore, maintenance activities can be planned based on real-time equipment condition rather than fixed schedules, improving asset utilization and extending equipment lifespan. The ability to detect abnormal operating conditions at an early stage also reduces the risk of catastrophic failures and costly downtime. Cybersecurity has become an increasingly important consideration in remotely controlled substations. Since digital substations are connected through communication networks, they may become targets for cyberattacks. Therefore, modern energy companies implement multiple layers of cybersecurity protection, including encryption, authentication mechanisms, firewalls, intrusion detection systems, and continuous security monitoring to protect critical infrastructure.

In Azerbaijan, digital transformation initiatives have accelerated the deployment of remote monitoring and control technologies within the national power system. Projects implemented by energy organizations have focused on the modernization of substations, the installation of SCADA systems, the development of smart grid infrastructure, and the integration of renewable energy resources into the power network. These efforts contribute to improving system reliability, reducing operational costs, increasing energy efficiency, and strengthening national energy security. The future development of remote-controlled substations is closely linked to emerging technologies such as artificial intelligence, digital twins, big data analytics, cloud computing, and the Industrial Internet of Things (IIoT) [8].

These technologies will enable more autonomous, adaptive, and resilient energy systems capable of responding intelligently to changing operating conditions. As a result, remote control will remain one of the key pillars of digital transformation and intelligent automation in the energy sector. A remote-controlled digital substation integrates intelligent electronic devices (IEDs), digital sensors, remote terminal units (RTUs), and communication networks into a unified control architecture. Operational data collected from transformers, circuit breakers, protection systems, and measurement devices are transmitted to a centralized SCADA platform through secure communication channels. Dispatch operators can monitor equipment status, perform switching operations, detect faults, and manage the power system in real time. Such an architecture improves reliability, reduces operational costs, enhances maintenance efficiency, and supports the implementation of smart grid technologies.

A conceptual model of a remote-controlled digital substation—integrating SCADA, intelligent electronic devices, smart sensors, and smart grid technologies—is proposed as a component of Azerbaijan's digital energy transformation framework. The digital transformation of Azerbaijan's energy sector represents a strategic pathway toward increasing the efficiency, reliability, and sustainability of energy production, transmission, and distribution processes. The implementation of smart grids, SCADA systems, intelligent electronic devices, digital twins, and remote-controlled substations significantly improves operational performance and reduces maintenance costs.

Table

ADVANTAGES OF REMOTE-CONTROLLEDDIGITAL SUBSTATIONS

Feature	*ConventionalSubstation*	*DigitalSubstation*
Monitoring	Local	Remote and Real-Time
Data Collection	Manual	Automatic
FaultDetection	Delayed	Instant
Maintenance	Periodic	Predictive
PersonnelRequirement	High	Reduced
OperationalCost	Higher	Lower
Reliability	Moderate	High
Integration with Smart Grid	Limited	Full

Remote monitoring and control technologies enable real-time supervision of power system components, rapid fault detection, and efficient emergency response, thereby enhancing energy security and service quality. Furthermore, the integration of intelligent automation and digital communication technologies supports the development of resilient and adaptive energy infrastructure. The study also emphasizes the importance of human capital development in achieving successful digital transformation. The proposed STEAM-D educational framework contributes to the preparation of next-generation energy engineers equipped with digital competencies, artificial intelligence skills, and expertise in smart energy technologies. Overall, the adoption of intelligent automation and digital energy solutions will strengthen the competitiveness of Azerbaijan’s energy sector and facilitate its transition toward a sustainable and innovation-driven energy future. Smart grid and SCADA systems enhance the reliability of power networks. Remote-controlled digital substations reduce operational costs and ensure prompt response to emergency situations. The STEAM-D model presents a promising approach for training digital energy engineers.

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