International Journal of
Science, Architecture, Technology and Environment

Power SCADA and the Future of Energy: Enabling Resilient, Smart, and Sustainable Grids through Real-Time Intelligence.

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DOI: https://doi.org/10.63680/ijsate0226007.006

Abstract

As the global energy landscape shifts toward decentralisation, digitalisation, and decarbonisation, Power SCADA (Supervisory Control and Data Acquisition) systems have emerged as a cornerstone of resilient and sustainable power infrastructure. This paper examines the evolution, architecture, and integration of Power SCADA with emerging technologies, including IoT, AI, machine learning, and blockchain, to enhance the real-time intelligence of modern power grids. It discusses the critical role of SCADA in enabling smart metering, demand response, renewable energy integration, and grid resilience in both urban and rural settings. Additionally, the study addresses cybersecurity challenges and regulatory frameworks necessary to safeguard critical infrastructure. Through an analysis of technical components, use cases, and future trends, the paper presents Power SCADA as not only a monitoring and control platform but as a transformative enabler of intelligent, flexible, and sustainable energy systems for the 21st century.

Keywords: Power SCADA, Real-Time Grid Intelligence, Smart Grids, Renewable Energy Integration, Cybersecurity in Energy Systems, Demand Response and Smart Metering

1. Introduction to Power SCADA

Power system operators have constantly been challenged to maintain service continuity when a component or network configuration fails or exhibits unpredictable behaviour. The initiatives worldwide to design power grids and networks of the near future aim to enable fast recovery from failures, self-healing of systems, and rapid dynamic reconfiguration of the power network following a system contingency. The goal is to enhance the reliability, availability, and robustness of grids while facilitating power flow from distributed renewable energy sources and storage devices, thereby enabling a resilient, efficient, and distributed generation network. Advanced measurement and monitoring technologies that will allow real-

time system awareness are constructive approaches to achieving these aims. Variability and uncertainty due to the unpredictable behaviour of renewable sources, changing operating points, the rapid growth of power-electronics-based components, and an increasing number of remotely located control elements complicate checkpointing and system control. Real-time monitoring, therefore, constitutes a necessary element for balancing the system under continuously dynamic operating conditions. A supervisory control and data acquisition (SCADA) system can provide a real-time view of the system, enabling the monitoring of the grid over decades. SCADA measurements, combined with emerging monitoring techniques and communication technologies, allow real-time energy resilience and the development of smart, sustainable grids and power systems. Power SCADA, therefore, represents an essential system capable of transforming the generation and distribution of electricity (Agrawal et al., 2019).

2. The Evolution of SCADA Systems

Since the 1970s, power SCADA (Supervisory Control and Data Acquisition) systems have evolved from stand-alone control systems into integrated platforms that dynamically monitor and control transmission, distribution, and generation assets across electrical networks. This progression has empowered operators to implement intelligent automation rules, protecting assets and customers from various risks while minimising operational costs. Current advances in power SCADA are highlighted through the layered integration of resilient, smart, and sustainable energy systems, recognising the technology's complex, interdisciplinary role in future power grids. SCADA systems initially developed for applications such as water treatment, oil refineries, and manufacturing have become widely deployed across large-scale industrial and critical infrastructure projects. By enabling supervisors and operators to remotely monitor and control distributed components using devices such as Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs), SCADA architectures have undergone four distinct phases of development—these range from first-generation mainframe-based central architectures to second-generation distributed systems that employ multiple computers in LANs. Third-generation network architectures extend these functions over WANs using IP protocols, and emerging IoT architectures harness cloud services for easier deployment, maintenance, and integration (Pestana Duarte Rocha, 2019). The preferred architecture depends on the industry, developer, and client requisites.

The widespread embrace of ICT across multiple sectors has spurred numerous innovations in supporting infrastructure. In the power sector, for example, integrating data acquisition and control technology with modern communication and networking solutions has transformed SCADA systems into essential real-time information infrastructures. They enable operators to monitor, acquire, and optimise power generation and distribution processes without incurring system downtime, a basic yet fundamental prerequisite with significant economic implications (Agrawal et al., 2019). Real-time intelligence enabled by emerging technologies such as IoT, artificial intelligence (AI), and machine learning has positioned SCADA systems at the centre of contemporary applications such as smart grids, microgrids, and smart buildings (Soetedjo et al., 2014). The result is enhanced grid resiliency, increased system efficiencies, and improved economic benefits.

3. Key Components of Power SCADA

A SCADA system comprises three essential components: data acquisition systems, control systems, and human–machine interfaces (HMIs), which together provide a comprehensive framework for monitoring and controlling power grids in real time (Agrawal et al., 2019). Power system data are acquired continuously and transmitted to SCADA controllers, enabling timely analysis and decision-making within the energy supply framework. Control mechanisms, including programmable logic controllers and automated relays, operate

centrally or locally to allow rapid responses to system changes. The HMI provides operators with a graphical overview of system status, facilitating the interpretation and formulation of remedial actions. Such a configuration supports load shedding, loss reduction, and steady-state maintenance, thereby enhancing grid resilience (Soetedjo et al., 2014).

3.1. Data Acquisition and Control Systems

The process of data acquisition involves collecting field data such as voltage, current, power, and frequency from various sources within a power system. These sources act as analogue devices that must be converted into digital signals for recognition and processing by the central control unit, the Programmable Logic Controller (PLC). This process is a form of Attitude, Heading, and Position (AHP) measurement, which involves regenerating and processing signals across four data types: voltage, current, active power, and frequency. Signal regeneration starts with a signal conditioner that scales the signal to an optimal amplitude of less than 2 volts and provides isolation to prevent interference (Vargas-Salgado et al., 2019; Soetedjo et al., 2014). Next, the analogue signals are converted to digital signals using an analogue-to-digital converter after the signal conditioner, to avoid ambiguity in subsequent measurements. However, the high cost of AD converters limits system affordability and processing cycles. Once digitised, the signals are transformed into engineering units to facilitate data interpretation. Without this step, the PLC can only recognise the magnitude, not the sign, of the data. The acquisition process for voltage, current, and power signals follows this exact sequence. Control systems, which govern and manage equipment behaviour, are not physical devices but algorithms and methods that direct system functions (Agrawal et al., 2019). Modern control theory relies heavily on differential equations, and the state-space representation is particularly beneficial for multivariable systems. In state-space form, an output y(t) depends on external inputs u(t), the system state x(t), and possibly time t, as described by the equation $y(t) = f(x, u, t)$. The state variables themselves evolve according to $\dot{x}(t) = g(x, u, t)$, which reflects their dependence on the current state, inputs, and time. Inputs, whether scalar or vector functions of time, can be artificial or environmental disturbances. Each initial condition, x(t0), determines a unique system trajectory; therefore, the state variables contain all the necessary information to describe the system at any moment and to predict its future behaviour based on inputs and dynamics (Soetedjo et al., 2014). .1. Signal Conditioning and Digital Conversion

Let $V_a(t)$, $I_a(t)$, $P_a(t)$, and $f_a(t)$ be the raw analogue signals for voltage, current, power, and frequency, respectively. After conditioning:

$V_c(t) = S_v(V_a(t))$,

$I_c(t) = S_i(I_a(t))$,

$P_c(t) = S_p(P_a(t))$,

$f_c(t) = S_f(f_a(t))$

These are then passed through an Analogue-to-Digital Converter (ADC):

$V_d[n] = ADC(V_c(t))$,

$I_d[n] = ADC(I_c(t))$,

$P_d[n] = ADC(P_c(t))$,

$f_d[n] = ADC(f_c(t))$

2. Transformation into Engineering Units

To translate digital values into interpretable engineering units:

$V_{eng}[n] = k_v \times V_d[n]$,

$I_{eng}[n] = k_i \times I_d[n]$,

$P_{eng}[n] = k_p \times P_d[n]$,

$f_{eng}[n] = k_f \times f_d[n]$

3. State-Space Representation of Control Systems

For the system's control dynamics, the general nonlinear state-space form is:

$\dot{x}(t) = g(x(t), u(t), t)$

$y(t) = f(x(t), u(t), t)$

Where x(t) is the state vector, u(t) the input vector, y(t) the output vector, and f and g are system-specific functions.

For linear time-invariant systems, the equations simplify to:

$\dot{x}(t) = A \times x(t) + B \times u(t)$

$y(t) = C \times x(t) + D \times u(t)$

3.2. Human-Machine Interfaces

SCADA systems monitor and control operations via a network of remote stations and master units. Each remote station samples data via digital and analogue I/O, then transmits it to a PC or PLC for processing. This data flows to the master SCADA for archiving and display. A digital switch manages alarm conditions from faults. Operators need tools to access stored data and control systems. A human-machine interface (HMI) displays the system's status but has been mainly limited to static displays with simple colour indicators, offering little decision support. Modern graphics, which are dynamic and autonomous, offer high-level visual abstraction and can identify faulty elements and data, thereby enhancing decision-making. These graphics can be generated locally, supporting robust, integrated decision tools within the TUCC framework. Utilities often expand existing commercial platforms with semantic routines for data analysis, alarm aggregation, and event interpretation. However, this can increase costs and security risks. Alternatively, intelligent HMIS with embedded objects transform raw data into meaningful system representations, offering a more straightforward, secure, and effective solution.

4. Real-Time Data Processing and the Significance of Immediate Data

Real-time data processing is central to energy system resilience, especially in smart grids and intelligent operating centres. Next-generation monitoring depends on the continuous acquisition and processing of point-on-wave (CPOW) measurements, which enable high-fidelity, high-resolution situational awareness and effective control of fast, stochastic grid dynamics (Tong et al., 2024). Real-time capabilities also underpin applications based on the "Internet of Things," such as smart metering, demand response, and microgrid dispatch, and complementarities with Artificial Intelligence and machine learning algorithms. Indeed, the growing penetration of variable renewable energy resources and power electronics devices results in highly stochastic grid dynamics. Hence, the grid requires much more advanced online monitoring and control to maintain stability, security, and resilience (Soetedjo et al., 2014). Real-time data stands out as an essential category of information that shapes the energy perspective. Its unceasing availability enables new and expanded possibilities for remote monitoring and control of power systems, modernising the grid while enhancing both reliability and efficiency (Adyinka et al., 2024). Accurate real-time sensing is fundamental

for the operation and further development of innovative and resilient energy systems. Moreover, integrating real-time, data-driven SCADA systems with smart grids enables energy distribution while upholding sustainability principles. Such data enable the inclusion of resilience strategies in sustainable energy systems, with analysis and interpretation underpinned by technologies such as the Internet of Things, artificial intelligence, and machine learning (Soetedjo et al., 2014; Belašić et al., 2011).

4.2. Technologies Enabling Real-Time Processing

The fundamental challenge in power systems is extracting and processing real-time data to produce useful information and operational intelligence. The rapid growth of advanced measurement, monitoring, and control technologies is accelerating the transition from an established SCADA system to an enhanced SCADA system, characterised by greater interoperability and real-time intelligence. User awareness of the power system's operational status and security margin should be shifted from colour-coded gauges and predefined set points to a qualitative and quantitative understanding of the security margin and the consequences of different emergency scenarios in a dynamically changing operational environment. As in other industries, the development of real-time intelligence in power systems enables informed, timely decisions that reduce risks and lower the consequences of operational problems.

Real-time intelligence for the development of innovative and meaningful energy infrastructure enables the transition of infrastructure serving from a “one-size-fits-all” utility to flexible, customised systemic services, reducing economic, social, and environmental costs (Tong et al., 2024). In practice, resilience-oriented Power SCADA solutions should address the complexity of ongoing and newly adopted technologies that undermine existing grid operating mechanisms, posing a significant barrier to a sustainable energy future. Real-time data processing involves a collection of technologies and processes that support the acquisition and interpretation of streaming data. This is a key prerequisite for the real-time intelligence required by future innovative and resource-constrained energy systems. It captures a significant reporting activity that underpins this capability. Digital real-time processing of SCADA information benefits from emerging technologies, such as the Internet-of-Things (IoT), artificial intelligence, and the augmented world, which will be blending the physical and information infrastructure, empowering a new dimension to the energy systems' real-time intelligence, often characterised as “cognitive energy systems” (Soetedjo et al., 2014). The ability to employ emerging technologies on real-time data transforms SCADA systems into resilient systems, enabling free adaptation and extension of classical functionality and coverage. The novel resilience-oriented SCADA bridges the gap toward wider utilisation of smartness at the high-level intelligence level, integrating self-adaptation/control, distributed pseudodispatching control, and system-wide forecasting and optimisation. Real-time data processing brings new opportunities and operational intelligence for innovative smart systems, smart design and operation, and services. At the same time, the balance of priorities and development can be achieved through integration with smart grids.

5. Integrating SCADA with Smart Grids

Smart-grid electricity networks can enhance the management of renewables and demand response, thereby improving sustainability. Power SCADA can augment smart-grid functions with capabilities such as smart metering and demand-response mechanisms, thereby improving load management through enhanced supply availability (Strasser et al., 2015). Smart-grid SCADA extends traditional distribution automation by incorporating real-time measurement and control throughout the network. A range of communication technologies, including potentially publicly operated media, may be used to transmit signals between customer premises and control centres. By offering robust interfaces for the precise and timely management of customers' charge control signals and integrating distributed renewable generation information, real-time

intelligence facilitates increased penetration of distributed renewable energy. Further discussion of power system resilience in sustainable energy contexts is presented below.

5.1. Smart Metering

Smart meters are measurement devices utilised in the Advanced Metering Infrastructure (AMI) of Power SCADA systems. They record and communicate data, including both active and reactive energy, as well as the energy consumed and delivered, to a central or local server. The meters can be configured for up to eight multi-tariffs to accommodate prosumers. Data from smart meters is gathered into centralised databases and is accessible in real time for electricity estimation and billing purposes (Dumitru et al., 2023). At the substation level, smart meters supply input data relating to power exchange with other distribution networks, while meters installed at industrial, commercial, and residential sites provide output data. The entire data flow is supervised by the AMI subsystem, which interfaces with the meters via power line communication (PLC), radio transmission, DSL, or broadband networks. Because smart metering is a core component of Power SCADA, the development of a flexible, multi-utility and multi-service metering architecture with active prosumers promises significant benefits (PATTI et al., 2015). Such an architecture, known as multiFLEX, integrates different meter types into a distributed infrastructure that collects, post-processes and analyses diverse information streams.

Smart meters have evolved from mechanical to electronic and now to brilliant devices. Mechanical watt-hour meters, which rely on physical rotation, face challenges relating to wear and environmental conditions that impair their function. Electronic meters utilise electronic technologies for sampling and data processing, thereby enhancing accuracy and enabling remote reading; however, they still face limitations, such as complex data processing requirements and limited communication capacity (Zhang, 2024). Unlike their predecessors, smart meters leverage the Internet of Things (IoT), big data analytics and cloud computing to facilitate real-time monitoring, analysis and prediction of power consumption. By drawing on user behaviour patterns, they can offer personalised suggestions and energy-saving options. Communication technologies have advanced from wired systems to wireless networks, including power line communications, enabling real-time data sharing between smart meters and the power grid. Outstanding concerns include data security, privacy protection, and enhanced integration with complementary grid devices for optimal energy management.

5.2. Demand Response

Demand response (DR) adjusts electricity use during peak times or price surges. It can be incentive- or price-based, with buildings offering controllable appliances like air conditioning and lighting. A supervisory system helps managers monitor and control consumption. Small reductions in HVAC and lighting enable active market participation and efficiency. DR provides control signals and financial incentives to shift demand, with small flex power typically only a fraction of the peak load, which is expected to grow. Flex power is often activated daily for approximately an hour, with some use cases allowing for more extended periods. Rebound effects, about one-third of displaced energy, occur when demand resurfaces after DR events, modelled to reduce demand spikes. DR programs include implicit (responding to price) and explicit (monetising capacity) types. OpenADR enhances security and interoperability. DR is used in ancillary markets and DSO frameworks, with flexibility services divided into explicit (market participation) and implicit (price signals), each with different visibility and operation.

6. Improving resilience in sustainable energy systems within Power SCADA

Enhancing operational integrity with Power SCADA promotes the adoption of renewable energy and supports sustainable energy systems. Resilient infrastructure enhances efficiency and facilitates the

achievement of sustainability goals. Power SCADA's ability to strengthen energy infrastructure resilience, crucial for coping with disruptions and maintaining service, includes mitigation, adaptation, and recovery strategies. These involve proactive risk reduction, flexible procedures, and rapid restoration after incidents such as weather events or cyberattacks. Resilient energy systems enhance energy availability, improve service reliability, and increase system flexibility. Resilience and sustainability are interconnected, with Power SCADA playing a crucial role in integrating renewables and enhancing energy efficiency. This integration ensures systems can adapt and operate effectively amidst variable renewable generation, thereby advancing sustainability objectives.

6.1. Approaches to Strengthening Resilience

Extreme weather events pose a significant threat to electric power transmission and related socio-economic systems. Malicious attacks also pose high risks to service reliability. Strategies to improve grid resilience include hardening existing components and adding redundancy through lines, switches, generators, and power electronic devices. The effectiveness of proposed upgrades can be evaluated from a resiliency perspective to quantify benefits beyond traditional expansion planning. AC power flow relaxations appear suitable for quantifying resilience compared to the DC approximation. A resiliency model and associated algorithms applied to a standard test system provide insights into transmission-grid design practices to enhance resilience (Nagarajan et al., 2017).

6.3. Renewable Energy Integration

High penetration of renewable energy affects the operation and control of power systems. Integrating renewable resources into existing transmission and distribution systems creates a hybrid renewable energy system that combines multiple energy sources and networks. Renewable energy is considered a green energy resource, offering the advantages of being pollution-free and providing a sustainable energy source. The SCADA system comprises supervisory computers and Remote Terminal Units (RTUs) that are connected to various sensors and actuators via communication channels. An extensive surveillance and control system utilises programmable logic controllers, SCADA software, and communication devices. SCADA systems monitor and control the parameters of various electrical and environmental factors in a hybrid wind and PV power system, including current, voltage, power, wind speed, solar irradiation, and photovoltaic temperature. Data from remote locations is transmitted to a master terminal unit (base station). The Web-SCADA project utilises an embedded system as the RTU to acquire data, send commands, and exchange status information between the master and the RTU. Low-cost sensors are developed to measure electrical and environmental parameters; the Internet serves as the communication channel between RTUs and the SCADA server. Moreover, a Web-based SCADA system builds the human–machine interface. It enables control and monitoring of a hybrid wind–PV power system through the Internet (Soetedjo et al., 201) (Apata et al., 2024).

6.4. Advancing Energy Efficiency Strategies

The increasing penetration of renewable energy in power grids heightens uncertainty and poses challenges to the performance and resilience of conventional control and automation systems (Strasser et al., 2015). Consequently, there is a need for innovative approaches and technological advances to enhance resilience and ensure a reliable, sustainable smart grid. Integrated Power SCADA offers a promising solution with several resilience strategies designed to promote efficient energy use and facilitate the integration of renewable energy sources. Power SCADA is an indispensable real-time instrument for the sustainable management of the power grid and the promotion of practices aligned with energy-efficiency themes. It enables a reinterpretation and modernisation of the systemic conceptualisation of energy efficiency by supporting the transformation of the industrial, urban, and building sectors, thus contributing to the

realisation of a resilient, innovative, and sustainable energy system.

7. Cybersecurity Challenges

Security of SCADA systems has become a significant research topic within the area of Smart Grid systems (Tang, 2019). Wireless sensor networks and remote communication between the control centre and irradiating stations heighten Smart Grid vulnerabilities. Device and protocol heterogeneity also introduces multiple avenues of attack. These systems may be compromised by false data injection, attacks on signal transmission channels, adequacy attacks, phishing, and unauthorised remote control. SCADA components and field devices are susceptible to direct cyber threats. Even transient disruptions can cascade into widespread power outages (Sridharan, 2012). Intrusion detection systems and corresponding rules have gained increased attention as mitigation strategies. Recent research has emphasised the need to assess system reliability under combined cyber and physical contingencies. Proposals have also been made for frameworks to select protection strategies that maximise resilience against deliberate attacks and random failures. The security of communication technologies and standards—such as GPRS, 3G, LTE, WiMAX, Fibre Optic, DNP3, TCP/IP, and IEC 104 is also crucial for safeguarding Smart Grid systems. Regulatory and policy requirements now strongly emphasise the need for organisations to address the risks associated with cyberattacks.

7.1. Strategies for Threat Landscape Mitigation

The complexity of energy systems and sustainability goals raises concerns about the resilience of power grids. Real-time operational intelligence that predicts failures and recovers from disruptions is crucial for smart grids. Utilising energy-as-a-service principles, real-time data in Power SCADA, informed by analytics, enables resilient and sustainable grids. Currently, strategies rarely leverage fundamental-time dynamics. Power SCADA has evolved from electro-mechanical systems, integrating innovative grid concepts and energy-as-a-service. When combined with ICTS such as IoT, cloud, edge computing, and AI, these technologies create an intelligent infrastructure that interacts with physical grids, providing real-time insights for operations and planning to foster resilient networks. Resilience depends on advanced measurement, control, and communication systems. Power SCADA enables real-time monitoring and control to reduce losses, improve stability, secure supply, support load shifting, and promote sustainable trading. Its data provides information on system frequency, voltage, and ramp rates. Sophisticated architectures that incorporate data resampling, compression, and environmental data can enhance the resilience of renewable energy. Upgrading Power SCADA with real-time intelligence—focused on data analysis, prediction, and control—is key to future resilience. Strategies like smart metering, demand response, authentication, encryption, and perimeter Defence improve Power SCADA's resilience, enabling real-time insights. Interoperability enables the swift integration of resilience and load balancing. Automation reduces human error and protects networks. The success of Power SCADA in sustainable energy depends on mature supporting technologies, but widespread deployment requires significant investment and faces challenges in coherence and research.

7.2. Regulating AI in Energy: Global Frameworks, Compliance Standards, and Regulatory Responsibilities

The IEA and global groups emphasise updating regulations to ensure responsible AI in energy, helping guide innovative finance, smart cities, and governance (Robu et al., 2019). Increased power grid overhead is boosting interest in above-ground high-voltage equipment, with WSNs offering flexible, cost-effective solutions. This chapter describes an infrastructure that integrates legacy electrical equipment into a smart grid through WSNs and web services. It was tested with a LoRa-based setup at Universitas Gadjah Mada,

Indonesia, demonstrating its potential in remote areas (Régis C. de Araújo et al., 2018). The UN Agenda 2030's 17 goals highlight the urgency for modern energy infrastructure. Recent research offers two key insights: a shift towards low-carbon energy with diverse options and overcoming the barriers of carbon and technology lock-in while developing accessible, low-carbon systems (Pestana Duarte Rocha, 2019). In industrial control systems (ICS), compliance is crucial. Governments require utilities to adhere to ICS security standards to protect their networks. Power grids must meet standards to prevent, detect, and combat cyberattacks, though enforcement is often weak (Pestana Duarte Rocha, 2019). Frameworks like NIST help organisations assess cybersecurity, while ISA/IEC standards set procedures for secure automation. DHS ICS-CERT discusses cybersecurity challenges and solutions; NERC CIP standards protect North America's electric grid, and the NRC manages nuclear plant cybersecurity. Compliance involves layered security strategies, including firewalls, gateways, vulnerability management, vulnerability assessments, intrusion detection, secure protocols (such as VPN, SSH, and HTTPS), attack detection, incident response, and mitigation. Network audits are vital for identifying vulnerabilities and developing defences. The complexity and multiple connections increase cyber risks, exemplified by the 2015 Ukraine power grid attack, underscoring the importance of securing power SCADA systems in ICS regulations.

8. Case Studies of Successful Implementations

Smart cities are turning to Power SCADA to address long-term infrastructure and supply challenges. Although several scenarios have been proposed, preferred options continue to be evaluated. These dependencies on fossil fuels present considerable vulnerabilities to economic and operational stability. Power SCADA forms the backbone of modern urban environments, leveraging real-time intelligent communication to optimise grid stability (Pasztor, 2018). It enables integration with innovative technologies, distributed generation, and electric vehicles. Networks based on Power SCADA rely heavily on real-time information, enabling energy suppliers to reduce consumption and emissions efficiently. Accountability is ensured by tracking energy use at substation levels. In Japan, Super-ESCO companies use Power SCADA to manage numerous small solar installations and promote electric vehicle charging across firms and communities (Soetedjo et al., 2014). Power SCADA facilitates critical energy monitoring and supply chain management, enabling significant capacity shifts from one smart city to another. The deployment of Power SCADA in innovative cities helps coordinate supply enhancement with reduced demand, improving overall resilience.

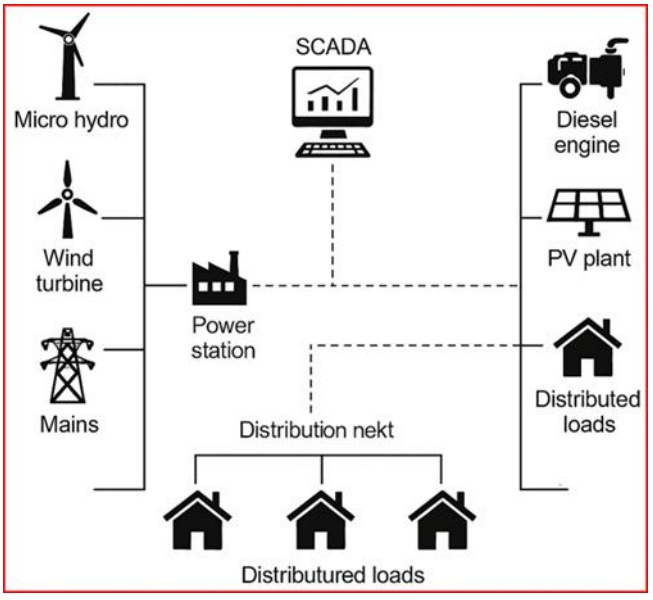
8.1. Urban Energy Systems

In brief, a Power Supervisory Control and Data Acquisition system (Power SCADA) comprises hardware and software used to remotely monitor and control power systems in real time at a supervisory level. It serves as an essential platform for realising ingenious, resilient, and sustainable urban energy systems. The systems incorporate real-time power data, sensing, and system awareness, and integrate distributed power generation, energy conversion, delivery, and consumption. In the 21st century, urban energy systems are undergoing a fundamental shift away from delivering energy to large groups of customers through a centralised, one-way, long-term plan. This shift is moving towards providing ubiquitous, seamless, reliable, and customised power delivery to a wide range of end users. A set of enabling technologies and emerging paradigms has been proposed to fulfil this evolving role, including the smart grid, microgrid, smart city, Internet of Things (IoT), data-driven intelligent energy networks, and peer-to-peer energy trading. Modern Power SCADA systems guide oversight and control by applying real-time intelligence to coordinate better and optimise grid infrastructure (Chicco & Napoli, 2018). The transformation of urban energy infrastructure into localised storage, transfer, conversion, and consumption also leads to changes in energy use, delivery, and management (Konstantinou, 2021). Meeting the resulting demand requires substantial modifications to

potential processes for accurate prediction and anticipation.

8.2. Rural Electrification Projects

Power SCADA has enabled the economic and effective expansion of power systems. The typical approach to rural electrification projects involves establishing a power distribution framework and constructing power generation facilities. A single power station designed to a standard output level can meet the demand of the rural population; however, the sections of the power network from the power station to rural areas constitute an extensive electrical distribution network. Power SCADA addresses this challenge. In systems of this kind (Fig. 1), various small power sources, such as micro hydro, wind turbines, diesel engines, mains, and photovoltaic plants, supply rural areas. These small sources deliver power through a distribution network to dispersed loads. They can be combined in various configurations, including a single source feeding all loads, a single source feeding specific loads, a combined system feeding all loads, and an interconnected system that allows loads to switch between sources (Agrawal et al., 2019). Power SCADA represents the automation of electrical distribution and power generation systems. Such a system removes the requirement for service personnel to travel between sites for inspection, data collection, and analysis. SCADA provides precise and automated supervision of operating variables at the plant's generation points. The SCADA functions as a graphical interface, continually interpreting operational statistics and loading data into its system. Efficient, timely database generation is possible because data are monitored directly at the plant site (Vargas-Salgado et al., 2019).



9. Future Trends in Power SCADA

Emerging technologies, such as edge computing and blockchain, offer promising opportunities to enhance Power SCADA and achieve an unprecedented level of grid real-time intelligence. Edge computing enables distributed data processing close to data sources, facilitating timely responses to grid events. At the same time, blockchain provides secure and transparent transaction records, supporting new energy trading schemes that decentralise grid management, enhance reliability, and boost economic efficiency (Tong et al., 2024). Power SCADA can be extended beyond its traditional monitoring and control functions with faster, more reliable communications and improved network capacities. The introduction of advanced analytics,

such as multidimensional sequential anomaly detection algorithms, enables faster and more accurate identification of abnormal system conditions, allowing grid operators to respond more quickly and reduce the risk of outages (Agrawal et al., 2019). Continual innovation and proactive adoption of these emerging digital technologies are vital to developing integrated, efficient, and sustainable energy systems. Drivers of innovation include government-funded development initiatives, shifts in consumption patterns with increasing reliance on distributed energy resources, the ongoing expansion of data and communication infrastructure, and the adoption of new ICT solutions.

9.1. Edge Computing for Blockchain Applications

Electric grids have evolved from traditional networks to advanced real-time systems that integrate smart devices, networks, and communication protocols. The future infrastructure will orchestrate sensors and components to facilitate complex energy management among suppliers, operators, and consumers. Continuous monitoring and data exchange enable innovative functions, but also risk overload and latency. Edge computing challenges cloud-centric models by providing computation, storage, and services closer to the network edge, enabling more efficient addressing of smart-grid scenarios. It is a key technology for next-generation smart grids, with open-source simulators and frameworks supporting the development of edge architecture (Boccadoro, 2018; Himeur et al., 2023). The digital transformation introduces concepts like real-time forecasting, automated sensing, and user-controlled load management. Integrating cloud, edge, fog, and IoT expands the smart-grid architecture. Real-time data allows condition-based maintenance, demand and generation optimisation, network verification, and automated control of various energy resources, including CHP, storage, renewables, and EVs. Security and privacy concerns drive the use of blockchain for decentralised access and audit in microgrids. Blockchain also supports decentralised energy trading, exemplified by TAMEB, a scalable, privacy-focused transaction scheme that ensures identity privacy and resists double-spending (Alladi et al., 2019; Singh et al., 2023).

10. Challenges and Obstacles in Adoption, Collaboration, and Engaging Stakeholders

Despite its apparent benefits, Power SCADA faces numerous financial, technical, and operational challenges that hinder widespread adoption and overall system resilience. The high cost of deployment is a significant barrier, particularly in remote or rural areas (Zheng & Dedrick, 2015). Technical challenges include integrating SCADA with renewable energy sources, smart meters, and demand response systems, as well as addressing privacy and cybersecurity concerns (Gupta, 2012). Limited digital literacy among some consumers also complicates adoption (Chicco & Napoli, 2018). Furthermore, insufficient infrastructure can prevent real-time data collection and processing, which are integral to Power SCADA's operation. Effective solutions require the collaborative efforts of policymakers, manufacturers, operators, consumers, and other stakeholders to ensure engaging, responsive, and adaptable systems that harness the enabling technologies of the IoT, cyber-physical systems, and AI presented earlier. Multi-stakeholder cooperation enables the development of robust networks that improve interaction and engagement, thereby increasing resilience and sustainability. Obstacles to consumer acceptance remain a significant concern. The transition requires large-scale public education to overcome resistance and competing priorities, as consumers frequently hesitate to pre-adopt new technologies for disruptive-scope projects. Smart metering and other strategies further heighten privacy concerns, which must be addressed through regulatory and governance frameworks to reinforce trust, fairness, and responsible innovation (Adebayo et al., 2024).

10.1. Financial Constraints and Technical Limitations

Power SCADA systems are experiencing exponential growth. The systems provide real-time intelligence, which is crucial for modern power grids and plays an essential integrated role in making energy systems

more resilient, innovative, and sustainable. However, obstacles such as financial and technical constraints, underdeveloped market mechanisms, low motivation and consumer engagement, inadequate regulatory and policy frameworks, and lack of coordination among stakeholders could delay adoption and limit the benefits of these systems (A. Brown & Zhou, 2012). Smart grids use Power SCADA to monitor, predict, protect and optimise the balance between local and national demand. Systems must operate at the right level, whether it is a transformer, district, or neighbourhood, and be able to adjust suddenly. Real-time monitoring also enables the prompt assessment of power quality, facilitates forecasting of future conditions, and identifies faults. Financial constraints, technical limitations, and a lack of motivation, particularly at the individual consumer level, hinder the adoption of Power SCADA systems in certain parts of the world. Market mechanisms to address the inherent variability and uncertainty of distributed generation have yet to emerge. On a large scale, some technologies have not yet been adequately proven. There are many obstacles to overcome, including regulatory, policy, and governance challenges, as well as a lack of coordination among stakeholder institutions.

10.2. Public-Private Partnerships and Community Involvement

The adoption of Power SCADA systems in sustainable energy faces multiple challenges. Initially, financial constraints hinder investment, while a lack of expertise and awareness limits further advancement. A fragmented approach also delays development and impedes the integration of SCADA with emerging technologies. Addressing these obstacles necessitates a collaborative strategy. Public-private partnerships, government funding, and community involvement form the foundation of such efforts. Encouraging the implementation of pilot projects contributes to the gradual integration of sustainable SCADA solutions. Public-private partnerships play a crucial role in funding, knowledge sharing, and fostering innovation and efficiency in energy systems. A combined public-private approach further advances the smart grid agenda. Governments possess a wide range of mechanisms for directing sustainable development and guiding specific activities through regulatory frameworks and leadership. In addition to financial and technical partnerships, community involvement remains a pivotal component. Microgrid projects serving local communities offer demonstration sites for renewable generation, storage, and innovative solutions, such as virtual power plants that aggregate communities' resources. As with innovative grid development generally, demand-side participation emerges as an effective means of increasing the resilience, intelligence, and interactivity of energy systems.

11. Conclusion

Power systems are considered the largest, most complex, and most widely automated systems in the world. They include power generation, transmission, distribution and utilisation by industrial plants, commercial entities and households. The Supervisory Control and Data Acquisition (SCADA) system provides power system operators with situational awareness of the system state, enabling them to make prompt decisions and control power system components to maintain security and reliability. When SCADA technology was first introduced, computers served as the central controller, storage, and user interface platform. They received status updates from input devices and User Terminals, while engineers and operators made decisions on corrective actions. However, the communication infrastructure was not sophisticated enough, as it relied on serial and analogue technology. Thus, the devices were generally limited to supervisory control and remote monitoring systems, in which the SCADA centre automatically receives the data. However, the control action must be performed manually (Agrawal et al., 2019). Nevertheless, the journey of the SCADA system from a collection of data systems to the backbone of most operations cannot be overlooked. The evolution of the SCADA system, transitioning from desktop collectables to web-enabled applications, has significantly enhanced data intelligence beyond the SCADA domain. This shift has made the system more

aware and analytical, enabled by increased access to external data from downstream intelligence. Furthermore, state-of-the-art telecommunications and information technology for SCADA systems enhance the system's security, speed, and efficiency. The adoption of the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning, and Cloud data analytics enables real-time intelligence, empowering any system sector to become more efficient and intelligent (Vargas-Salgado et al., 2019).

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

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