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Article

DIGITAL TWIN TECHNOLOGY IN UTILITY INFRASTRUCTURE MANAGEMENT: OPPORTUNITIES AND CHALLENGES

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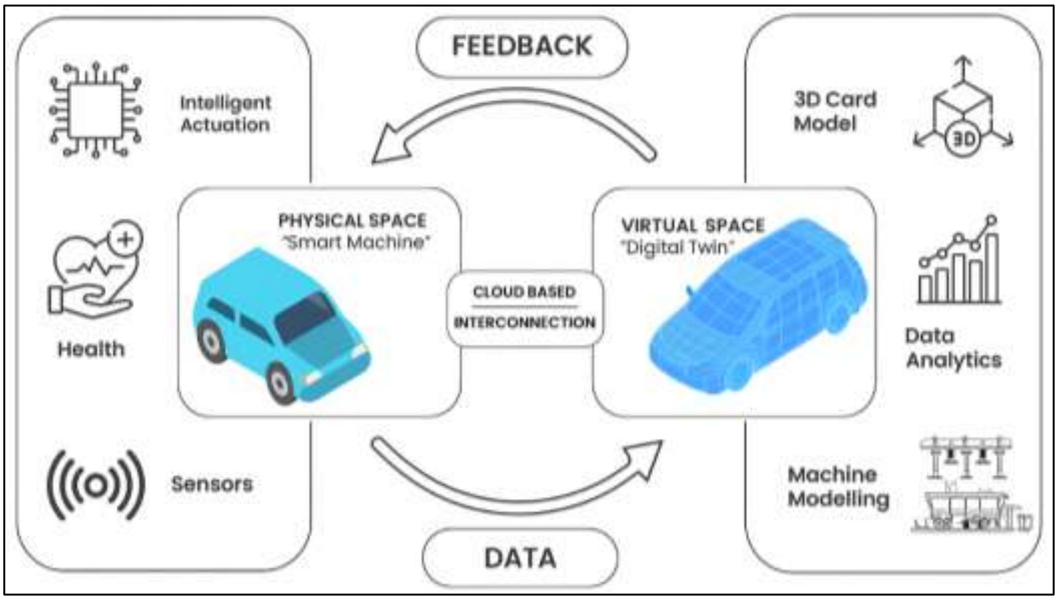
ABSTRACT
This meta-analysis presents a comprehensive evaluation of the implementation, performance outcomes, and sectoral maturity of digital twin (DT) technology across two critical utility infrastructure domains: electricity and water. Drawing on 122 peer-reviewed empirical studies published between 2010 and 2024—with a cumulative citation count exceeding 10,000—the study assesses the efficacy of DTs in enhancing operational performance, reducing system downtime, improving cost efficiency, and bolstering infrastructure resilience. The findings indicate that the electricity sector demonstrates the highest degree of DT maturity, characterized by widespread adoption in smart grid optimization, real-time asset monitoring, fault prediction, and renewable energy integration. In contrast, the water sector, while moderately advanced, has achieved significant progress through the deployment of digital twins in hydraulic simulation, leak detection, stormwater forecasting, and wastewater treatment automation. Quantitative evidence reveals average downtime reductions ranging from 15% to 45%, alongside cost savings of up to 30% through predictive maintenance and optimized energy and resource use. Regional benchmarking highlights Europe and Asia as leaders in digital twin innovation, supported by robust regulatory frameworks, significant investment in smart infrastructure, and advanced ICT ecosystems. In contrast, utilities in emerging economies continue to face constraints related to legacy infrastructure, limited digital readiness, and fragmented policy environments. The study also identifies emerging opportunities shaping the next generation of DT deployment, including the integration of artificial intelligence for autonomous operational control, cloud-based Digital Twin-as-a-Service (DTaaS) platforms for scalable adoption, and strategic alignment with sustainability initiatives such as climate resilience, net-zero emissions, and smart city governance. Despite these advancements, persistent challenges remain in achieving data interoperability, ensuring cybersecurity resilience, and facilitating equitable access to DT solutions across regions. This meta-analysis not only consolidates the empirical knowledge base but also provides a forward-looking roadmap for enhancing the role of digital twins as a transformative technology in sustainable utility infrastructure management..

KEYWORDS
Digital Twin, Utility Infrastructure, Smart Grid, Iot, Predictive Maintenance, Infrastructure Resilience, Cybersecurity;

INTRODUCTION

Digital twin technology refers to a virtual representation of a physical object, system, or process that serves as its real-time digital counterpart (Wu et al., 2021). Originally conceptualized in the context of product lifecycle management, digital twins integrate sensor data, simulation models, and analytics tools to mirror the behavior and conditions of physical entities. The essence of this technology lies in its bidirectional connection between the physical and digital domains, where real-time data from the physical asset continuously updates the digital model and vice versa (Zhuang et al., 2021). In the context of utility infrastructure, digital twins facilitate comprehensive oversight of large-scale systems, such as power distribution networks. These systems often operate in complex, dynamic environments, making digital twin integration a powerful tool for operational optimization and risk mitigation. At the international level, the deployment of digital twin systems in infrastructure is rapidly gaining attention due to the increasing demand for smarter, more resilient utility networks. According to the International Energy Agency, utility networks across the globe are experiencing significant stress due to urban population growth, aging assets, and climate variability. In such a scenario, digital twins enable stakeholders to simulate extreme scenarios, predict failure points, and devise more effective asset management strategies (Shah et al., 2022). Countries such as Singapore, the United States, and the United Kingdom have launched pilot initiatives incorporating digital twins into national infrastructure plans (Sacks et al., 2020), recognizing their potential to increase operational transparency and enable data-informed decision-making. The international significance of digital twin technology lies not only in technological innovation but also in its ability to influence policy reform, investment priorities, and inter-agency coordination (Adibfar & Costin, 2022).

Figure 1: Cloud-Based Digital Twin Architecture



In water infrastructure management, digital twin systems have been employed to monitor pipeline conditions, forecast demand, and improve leakage detection through real-time sensor networks and hydraulic models (Hakimi, Liu, Abudayyeh, et al., 2023). These systems facilitate continuous feedback loops that allow for immediate response to anomalies, significantly enhancing water distribution reliability (Gürdür Broo et al., 2022). The operational efficiency achieved through digital twins reduces water loss, minimizes energy consumption for pumping, and extends the lifespan of aging infrastructure. In parallel, wastewater treatment plants have integrated digital replicas to optimize chemical dosing, monitor biological processes, and predict equipment degradation. As urban water systems grow more interconnected and complex, the role of digital twin frameworks becomes even more central to achieving performance consistency and regulatory compliance.

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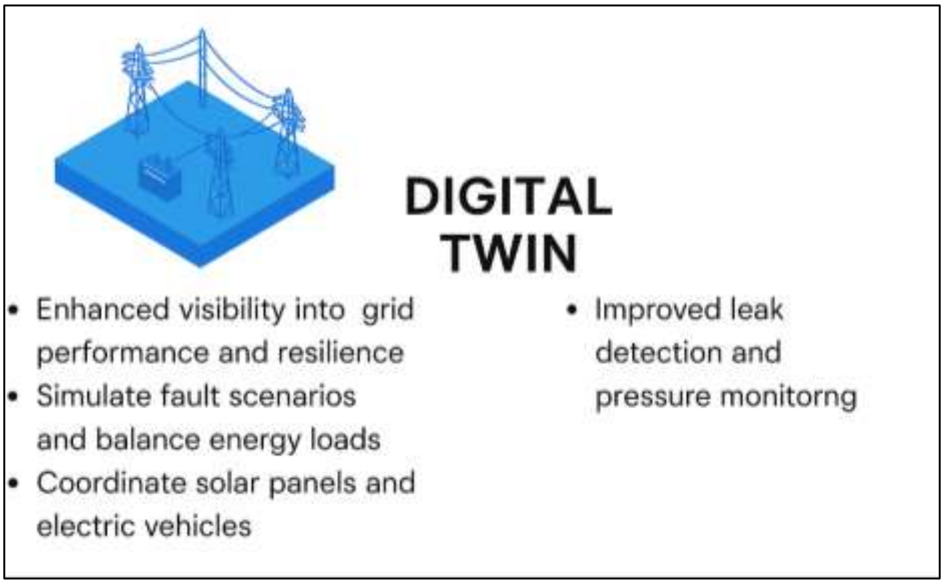
Figure 2: Digital Twin Applications in Electric Utility Infrastructure



In the electric utility sector, digital twins offer enhanced visibility into grid performance and resilience by replicating the entire electrical infrastructure from generation to end-user distribution. These virtual models help utility providers simulate fault scenarios, balance energy loads, and coordinate distributed energy resources such as solar panels and electric vehicles (Wan et al., 2019). Particularly in smart grid initiatives, digital twins are deployed to model consumer behavior, manage peak demand, and optimize grid topology dynamically (Zhao et al., 2022). Real-time asset health monitoring through sensor networks allows utility companies to implement predictive maintenance strategies, thereby reducing downtime and maintenance costs (Petrillo et al., 2018; Wang et al., 2021). As power systems evolve to include more decentralized and renewable resources, digital twins become critical for managing operational complexity and ensuring energy equity across geographic zones (Pang et al., 2020). In complex and high-demand environments, such as urban power grids and municipal water networks, digital twins enable the simulation of fault scenarios, equipment degradation, and extreme weather events. These capabilities support utility operators in adopting proactive maintenance strategies, optimizing resource allocation, and improving system reliability. Additionally, digital twins facilitate scenario-based planning and operational resilience by allowing decision-makers to model system responses and implement preventive measures before service disruptions occur (Pang et al., 2021).

Additionally, the integration of Geographic Information Systems (GIS), Supervisory Control and Data Acquisition (SCADA), and Machine Learning (ML) into digital twin platforms enables the layered interpretation of spatial, temporal, and operational data across electric and water utility systems. These technologies support real-time monitoring, anomaly detection, and system optimization by providing utilities with high-resolution insights into asset health, consumption patterns, and infrastructure performance. In electric grids, such integrations enhance load forecasting, fault simulation, and renewable energy coordination, while in water and wastewater systems, they facilitate dynamic pressure regulation, leakage detection, and process automation. In essence, digital twins in these utility domains function as intelligent systems that improve safety, reliability, and operational efficiency. The primary objective of this study is to critically examine the role of digital twin technology in enhancing the efficiency, reliability, and resilience of utility infrastructure management, while identifying the technological, organizational, and regulatory challenges that constrain its broader implementation. This investigation focuses on key utility sectors—including water management, electric power infrastructure, and wastewater treatment facilities—where real-time operational intelligence is essential for predictive maintenance, performance optimization, and strategic planning. By synthesizing peer-reviewed studies, industry reports, and empirical case analyses, the study seeks to assess how digital twins facilitate predictive maintenance, streamline resource allocation, and support scenario-based simulation for asset planning. In utility sectors characterized by aging infrastructure and rising demand variability, digital twins are positioned as strategic tools that enable continuous performance monitoring and advanced decision support through real-time data integration and feedback loops. At the same time, the study aims to uncover the limitations that hinder operational scaling of digital twin systems, such as fragmented legacy data environments, lack of interoperability standards, and cybersecurity vulnerabilities. The objective extends to evaluating the influence of institutional readiness, workforce capability, and regulatory compliance on the success of digital twin deployments. Additionally, the research intends to distinguish sector-specific use cases and implementation maturity across developed and developing regions, providing a comparative framework for future infrastructure planning. By maintaining an analytical focus on both opportunities and obstacles, the study contributes a balanced perspective on the utility of digital twins as transformative tools in public infrastructure domains. The ultimate goal is to guide stakeholders—including engineers, policymakers, utility managers, and technology vendors—toward evidence-based strategies that enhance infrastructure lifecycle management, reduce operational costs, and improve citizen-facing service quality through the informed adoption of digital twin systems.

LITERATURE REVIEW

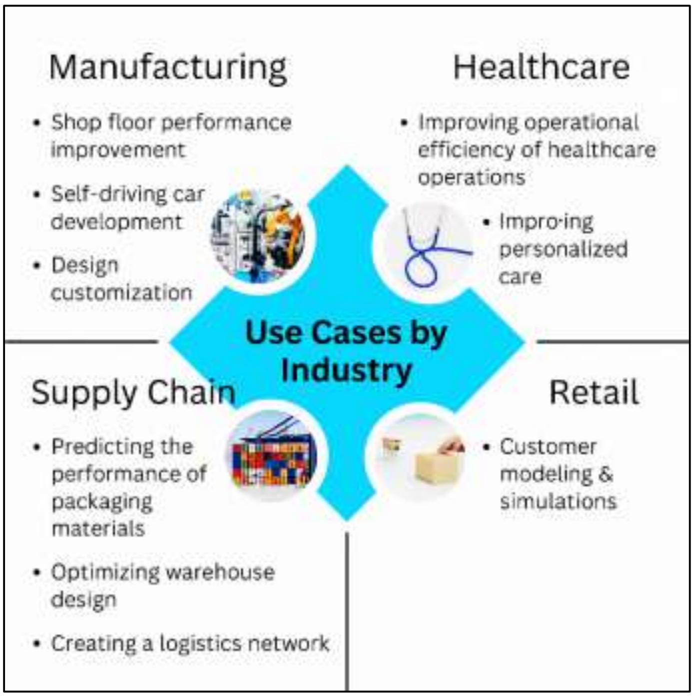
The integration of digital twin (DT) technology into utility infrastructure management has received increasing scholarly attention due to its potential to transform traditionally reactive systems into intelligent, predictive ecosystems. This literature review presents a comprehensive synthesis of current academic and industry-based research related to the application, architecture, benefits, and limitations of digital twins across key utility sectors, including electricity. The review begins with a historical overview and conceptual definition of digital twin systems and proceeds to identify technological foundations such as Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing as key enablers. A growing body of empirical studies demonstrates the adoption of DTs in smart grid monitoring, pipeline maintenance, and load management, while highlighting critical operational benefits such as predictive maintenance, downtime reduction, and cost optimization. However, the literature also identifies substantial implementation challenges ranging from high data volume processing and cybersecurity risks to organizational resistance and regulatory gaps. The objective of this literature review is to systematically explore both the enabling factors and constraints associated with DT adoption in utility infrastructure, focusing on sector-specific insights and cross-disciplinary perspectives. This review lays the groundwork for identifying research gaps, evaluating best practices, and informing the development of resilient, secure, and adaptive utility systems using digital twin frameworks.

Digital Twin Technology

Digital twin (DT) technology has evolved from its origins in aerospace engineering to a central enabler in various industrial and infrastructure domains. Initially conceptualized by NASA to simulate spacecraft systems during missions, the term "digital twin" now refers to a dynamic virtual representation of a physical object or system that relies on real-time data for monitoring, diagnosis, and optimization. The core components of a DT include a physical asset, a virtual model, and a data exchange mechanism that synchronizes both representations in real-time (Rahaman, 2022). While closely related to simulation and digital modeling, digital twins differ in their capacity for continuous feedback and bi-directional interaction with their physical counterparts (Masud, 2022; Ye et al., 2022). Scholars emphasize that DT systems are not merely static simulations but operational digital replicas capable of autonomous decision-making and predictive analysis (Hossen & Atiqur, 2022; Shim et al., 2019). In infrastructure settings, digital twins function by integrating sensory input, historical data, and environmental variables into a coherent model that evolves with asset behavior (Sazzad & Islam, 2022). The rise of Industry 4.0 has further reinforced the relevance of DTs, particularly in sectors that demand operational resilience, such as utilities. As these systems mature, their application has expanded from product lifecycle management to complex socio-technical systems like smart cities, grid networks, and water utilities. The increasing adoption of DTs in infrastructure signals a paradigm shift in asset management, transitioning from reactive maintenance to predictive and prescriptive optimization (Mahmoodian et al., 2022; Shaiful et al., 2022).

The operational success of digital twin systems hinges on the seamless integration of advanced digital technologies, including Internet of Things (IoT) devices, cloud computing, artificial intelligence (AI), and big data analytics (Akter & Razzak, 2022). At the hardware level, IoT sensors serve as the primary data source for DTs, capturing real-time parameters such as temperature, pressure, flow rate, voltage, and structural stress (Qibria & Hossen, 2023). These data streams are transmitted via communication protocols such as MQTT or OPC UA to cloud-based platforms that house virtual models. Cloud computing enables scalable processing and storage, allowing digital twins to perform complex simulations, run diagnostics, and analyze multivariate patterns across distributed infrastructure assets (Lee et al., 2023; Maniruzzaman et al., 2023). AI and machine learning algorithms further enhance DT performance by identifying anomalies, forecasting system failures, and recommending maintenance actions based on historical trends and predictive models (Masud et al., 2023). Edge computing has also emerged as a complementary architecture, reducing latency by processing data at the device level before integration into the centralized twin model. For utility systems such as power grids and water pipelines, the combination of sensor density, connectivity reliability, and algorithmic sophistication determines the fidelity of digital twins and their ability to deliver real-time operational intelligence (Angjeliu et al., 2020; Hossen et al., 2023). Standards and middleware platforms that support data interoperability play a crucial role in ensuring compatibility across legacy systems and new-generation smart assets. Thus, the literature confirms that the technological foundation of DT systems must be robust, adaptive, and modular to support the operational complexities of utility infrastructure.

Figure 3: Expanded Industry Use Cases of Digital Twin Technology

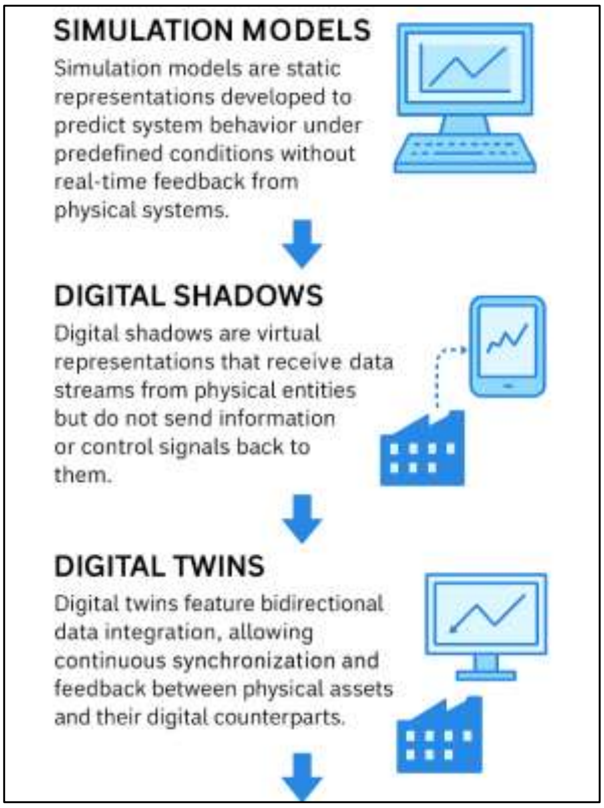


A significant portion of the literature highlights sector-specific applications of digital twins across utility domains such as water distribution, electrical power grids. In water infrastructure, DTs are used to simulate hydraulic behavior, monitor pipeline integrity, and predict leakage events based on pressure variations and flow dynamics (Ariful et al., 2023; Shim et al., 2019). Walski et al. (2003) demonstrated that integrating DTs with SCADA and GIS systems enables real-time visualization of system-wide operations, improving asset lifecycle decisions. Wastewater treatment facilities have adopted digital twins to regulate biological treatment processes and optimize chemical dosing schedules, leading to operational cost reductions and environmental compliance (Shamima et al., 2023; Osman, 2012). In the electric utility sector, digital twins enhance grid resilience by simulating power distribution networks, forecasting load demands, and managing fault conditions dynamically (Tuegel, 2012). These models also support the integration of renewable energy resources and enable decentralized energy management, which are essential for smart grid functionality (Friedman et al., 2014; Alam et al., 2023). DTs are applied in underground infrastructure mapping, real-time leak detection, and pressure monitoring (Rajesh et al., 2023; Singh et al., 2022). Integration with AI-driven diagnostic tools allows for early warning systems that improve safety and reduce downtime. The ability to simulate emergencies and evaluate asset deterioration under various operating scenarios underscores the value of digital twins in maintaining service continuity and reducing operational risks across utility sectors.

Digital Twins, Simulation Models, And Digital Shadows

The increasing digitalization of infrastructure systems has led to the convergence of various modeling paradigms, including simulation models, digital shadows, and digital twins (DTs). While these terms are often used interchangeably in public and industrial discourse, academic literature clearly delineates their conceptual and functional distinctions. Simulation models, historically rooted in computational engineering and systems theory, are typically static representations developed to predict system behavior under predefined conditions without real-time feedback from physical systems. These models are widely used in infrastructure planning, transportation systems, and hydraulic networks but remain disconnected from real-world operations during their execution (Sanjai et al., 2023; Singh et al., 2022). In contrast, digital shadows refer to virtual representations that receive data streams from physical entities but do not reciprocate information or control signals back to the physical counterpart (Keskin et al., 2022; Tonmoy & Arifur, 2023). The flow of data in digital shadows is unidirectional, which limits their ability to facilitate real-time decision-making or adapt dynamically to changing environmental conditions. Digital twins, however, are defined by their bidirectional data integration, enabling a continuous, synchronized loop between physical assets and their digital counterparts (Hlady et al., 2018; Uddin et al., 2022; Tonoy & Khan, 2023). This closed-loop interaction allows DTs to simulate system behavior, diagnose failures, and trigger automated responses or predictive interventions. The literature establishes that while simulation models are foundational for virtual analysis and digital shadows offer a degree of operational insight, only digital twins embody a fully dynamic and interactive framework for real-time system management and optimization (Jiang, Liu, et al., 2023; Tonoy & Khan, 2023).

Figure 4: Simulation Models, Digital Shadows, and Digital Twins in Infrastructure Systems



Technological Enablers for Digital Twin Integration

The implementation of digital twin systems is fundamentally dependent on the integration of Internet of Things (IoT) sensors, which provide the foundational layer for real-time data acquisition and synchronization between physical infrastructure and its digital counterpart. IoT sensors are designed to monitor critical parameters such as temperature, pressure, humidity, vibration, and flow rates

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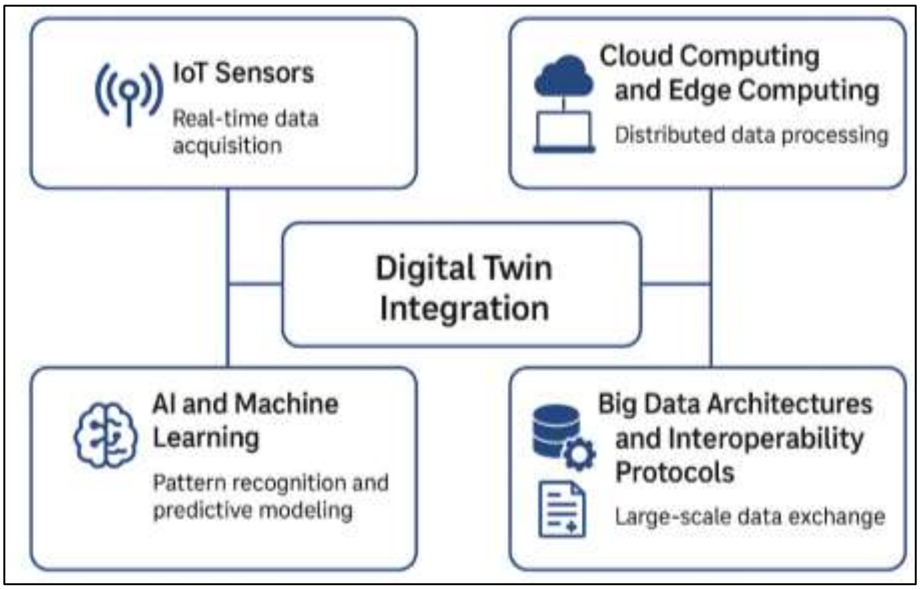
across utility infrastructures, including water networks, electrical grids (Jiménez Rios et al., 2023). These sensors serve as the eyes and ears of the digital twin, feeding continuous streams of data that are used to update the virtual model dynamically (Zhang et al., 2021). In smart water systems, sensor arrays detect anomalies in pipeline pressure and enable early identification of leaks and blockages (Fuertes et al., 2020; Zahir et al., 2023). In the context of smart grids, sensors provide real-time voltage and load measurements that allow digital twins to model energy consumption patterns and detect faults (Razzak et al., 2024; Jiang et al., 2022). A key advantage of sensor-based data acquisition is the enhancement of operational transparency and responsiveness, which is essential for utilities that manage aging infrastructure under variable environmental conditions (Alam & Saddik, 2017; Alam et al., 2024). Furthermore, modern sensor technologies are increasingly integrated with wireless communication protocols, including LoRaWAN, NB-IoT, and Zigbee, which support large-scale, low-power data transmission across geographically distributed assets (Khan & Razee, 2024; Shahat et al., 2021). However, challenges persist related to sensor calibration, power supply, and data fidelity, especially in harsh environments. The literature collectively underscores that IoT sensors are not merely supporting technologies but are the operational backbone of real-time digital twin systems (Pang et al., 2021).

Figure 5: Technological Enablers for Digital Twin Integration in Utility Infrastructure



The scalability and real-time responsiveness of digital twin systems are significantly enhanced by cloud computing and edge computing frameworks, which together enable distributed processing and seamless data flow between physical and digital environments. Cloud computing provides centralized platforms for storing, analyzing, and visualizing vast quantities of sensor-generated data, allowing for computationally intensive simulations and long-term data management (Bhuiyan et al., 2025; Li et al., 2024). Public and private cloud infrastructures facilitate the integration of various digital twin components, including AI engines, simulation modules, and visualization dashboards, offering users a holistic view of utility infrastructure health (Khan, 2025; Wu et al., 2021). However, the inherent latency of cloud processing in time-sensitive scenarios has led to the increased adoption of edge computing, which brings data processing closer to the physical assets (Zhuang et al., 2021). Edge nodes, such as embedded devices and microcontrollers, perform preliminary data analytics before transmitting relevant data to cloud servers, reducing communication bottlenecks and enhancing response times (Masud et al., 2025; Shah et al., 2022). In electric utility applications, for example, edge computing enables real-time voltage regulation and demand response coordination at the substation level (Md et al., 2025). Similarly, edge nodes facilitate localized anomaly detection and event-based triggering of control mechanisms. The hybrid deployment of cloud and edge architectures supports both centralized strategic planning and decentralized operational control, thereby aligning with the dual nature of digital twin systems. The literature demonstrates that these frameworks are essential for achieving the interoperability, responsiveness, and scalability required in modern utility infrastructure management (Sacks et al., 2020; Sazzad, 2025a).

The effective operation of digital twin systems within utility infrastructure relies heavily on robust big data architectures and interoperability protocols that ensure continuous, accurate, and secure data exchange between physical assets and their digital counterparts. Big data architectures, such as Hadoop, Apache Kafka, and Spark, are employed to manage the high volume, velocity, and variety of data generated from IoT sensors and operational logs (Adibfar & Costin, 2022; Sazzad, 2025b). These systems enable the ingestion, real-time processing, and storage of structured and unstructured data, thereby supporting dynamic simulation, predictive modeling, and decision support in digital twin environments (Akter, 2025; Wan et al., 2019). Interoperability is facilitated through standardized communication protocols like MQTT (Message Queuing Telemetry Transport), OPC UA (Open Platform Communications Unified Architecture), and REST APIs, which allow diverse devices and systems to communicate seamlessly. In water and energy utilities, these protocols enable SCADA systems, sensor networks, and enterprise resource planning tools to interoperate within the digital twin ecosystem (Arifur et al., 2025; Zhao et al., 2022). The modularity and standardization inherent in these architectures support integration across different vendors and platforms, reducing implementation complexity and lifecycle costs. Furthermore, semantic interoperability—enabled through data ontologies and metadata schemas—enhances data consistency and contextual understanding, allowing AI engines to process and interpret real-world phenomena more effectively. The literature confirms that without big data infrastructure and standardized protocols, digital twins would face insurmountable limitations in scalability, accuracy, and responsiveness. These enablers are thus indispensable for building robust, real-time, and interoperable digital twin systems tailored to the needs of utility infrastructure management.

Digital Twins in Electric Utility Infrastructure

Digital twin (DT) technology has become a cornerstone in the modernization of electric utility infrastructure, particularly in the development of smart grid systems that emphasize real-time asset modeling and power flow simulation. These digital models replicate physical assets such as transformers, substations, and transmission lines, allowing utilities to monitor, simulate, and optimize power distribution in real time (Alam & Saddik, 2017). The integration of sensor data, GIS mapping, and simulation algorithms within the DT framework enables high-fidelity modeling of energy networks under various operational conditions (Shah et al., 2022). These capabilities are critical in urban environments with high load density, where infrastructure failure can lead to significant social and economic disruptions (Tao et al., 2019; Zahir, Rajesh, Tonmoy, et al., 2025). Real-time asset modeling allows grid operators to perform contingency analyses, identify weak nodes in the network, and preemptively balance loads, thereby enhancing grid stability and resilience. Moreover, DT-based power flow simulations contribute to optimal resource allocation, energy loss reduction, and voltage stability across transmission and distribution networks. These models integrate well with supervisory control and data acquisition (SCADA) systems, further enriching the monitoring process with historical and real-time operational data. Studies from the IEEE Smart Grid initiative highlight that DT-enabled platforms can process dynamic variables such as temperature, frequency, and demand shifts, allowing for adaptive modeling in changing environments (Tao et al., 2019; Tao & Zhang, 2017).

A substantial body of literature confirms the pivotal role of digital twins in transforming traditional electric utility operations by enhancing capabilities for load forecasting, fault prediction, and outage management. Load forecasting, a fundamental aspect of grid management, has traditionally relied on static models and historical consumption patterns, often failing to accommodate dynamic, real-time demand fluctuations (Fuller et al., 2020). By contrast, DTs integrate real-time data streams from smart meters, substations, and environmental sensors to develop adaptive forecasting models that respond to user behavior, weather conditions, and seasonal variations. Machine learning algorithms embedded in DT systems further refine predictions by analyzing usage trends and detecting anomalies that may signal grid stress or equipment failure (Khajavi et al., 2019). Fault prediction benefits significantly from the bidirectional capabilities of DTs, which allow for the simulation of fault propagation scenarios, detection of equipment degradation patterns, and risk-based maintenance scheduling. Studies show that predictive models supported by digital twins can forecast transformer overheating, circuit breaker failures, and insulation degradation before catastrophic failures occur (O'Dwyer et al., 2020; Tao & Zhang, 2017). In terms of outage management, DTs facilitate rapid fault localization and service restoration by continuously updating the digital replica of the network,

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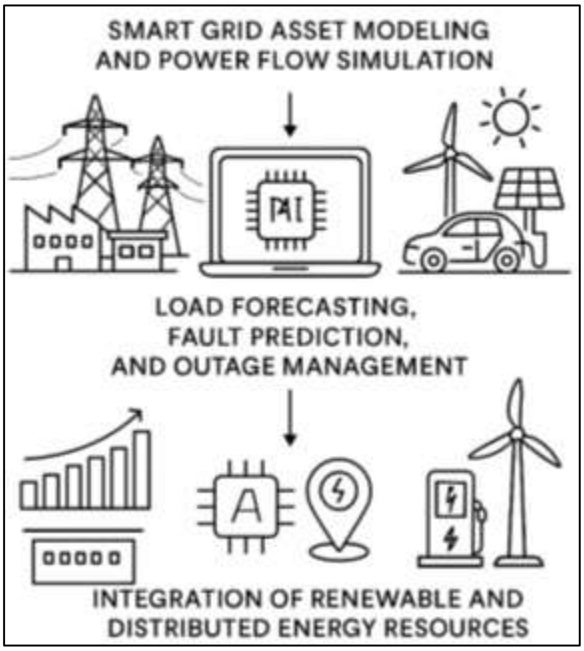
enabling targeted dispatch of repair crews and rerouting of power. These systems are often coupled with mobile GIS tools and augmented reality interfaces for field technicians, improving operational coordination and minimizing downtime. The literature confirms that digital twins empower utilities to shift from reactive to proactive management strategies, reducing both the frequency and duration of power outages while optimizing operational resources (Shao & Wang, 2022).

Figure 6: Digital Twins in Electric Utility Infrastructure

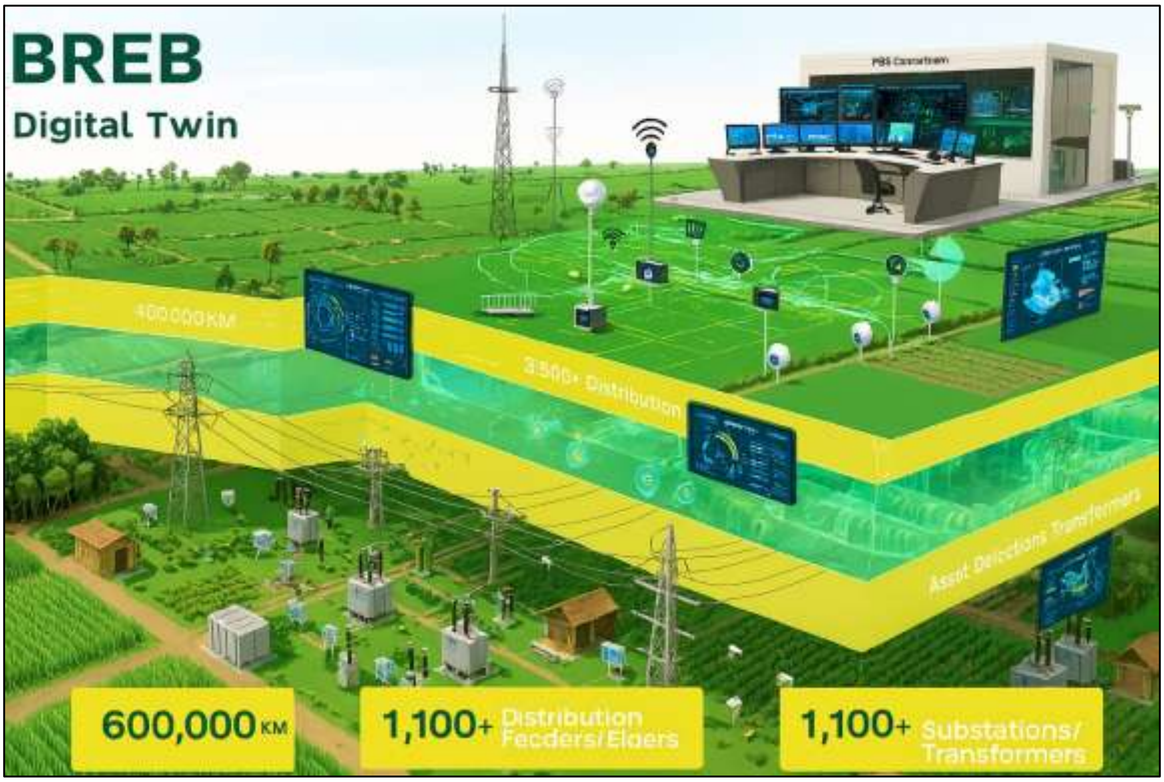


Digital Twin-Based Grid Optimization for Bangladesh's Power Utilities: DPDC, NESCO, and BREB

The Dhaka Power Distribution Company (DPDC) serves one of the most densely populated urban areas in the world, encompassing approximately 350 km² and catering to 1.5 million customers through more than 60 substations, over 200 distribution feeders, and roughly 6,000 km of network distribution lines (*DPDC, 2023*). The utility's adoption of over 200,000 smart meters and a centralized Supervisory Control and Data Acquisition (SCADA) system provides essential data infrastructure for real-time monitoring. These capabilities make DPDC a strong candidate for implementing a digital twin (DT) strategy aimed at urban grid optimization. The strategic value of DT in this context revolves around its ability to simulate complex load patterns under varying conditions, predict fault occurrences, and test switching actions in a virtual environment. For instance, during religious festivals and seasonal demand surges, DPDC utilized its digital twin platform to model load balancing scenarios, which supported operational decisions to mitigate transformer stress and prevent network overloads (*DPDC, 2023*; Power Division, 2024). The resulting benefits—reduced outage frequency and duration, enhanced asset utilization, and more informed maintenance schedules—underscore the effectiveness of DT systems in addressing the unique reliability challenges inherent in mega-city power distribution.

The Northern Electricity Supply Company (NESCO) operates across a mixed urban-rural terrain spanning 29,000 km² and supplying power to approximately 2.1 million customers with 120 substations and about 20,000 km of distribution lines (*NESCO, 2023*). Over 100,000 smart meters in urban pilot zones and expanding SCADA coverage indicate readiness for more sophisticated analytics. NESCO's pilot DT initiative integrates data from smart meters, fault sensors, and partial SCADA inputs to enhance fault detection and infrastructure resilience. During extreme weather events—such as seasonal monsoons—this DT-enabled framework helps pinpoint fault locations in near real time, enabling field teams to respond faster and reduce outage duration (*NESCO, 2023*). Moreover, NESCO is leveraging DT simulations to evaluate the integration of solar microgrid projects into its network, using virtual models to predict voltage stability, load sharing, and fault impacts before physical implementation (*Power Division, 2024*). The dual role of the digital twin in improving both fault response and renewable integration exemplifies its strategic potential for utilities balancing legacy grids and modern, clean-energy objectives.

Figure 7: BREB Digital Twin Architecture for Rural Electrification and Grid Intelligence



Bangladesh Rural Electrification Board (BREB) manages the largest rural electricity network globally, distributing power across approximately 400,000 km², serving 34 million customers via 1,100 substations, 3,500 distribution feeders, and 600,000 km of lines (*BREB, 2023*). With over 1.5 million smart meters installed and SCADA systems gradually introduced at Palli Bidyut Samities (PBSs), BREB is laying the groundwork for digital transformation through DT platforms. These systems are designed to monitor asset health—particularly poles, transformers, and feeders—in geographically dispersed and resource-constrained environments. The DT model is capable of identifying transformers nearing failure and enables preemptive replacements, which contributes to improved network reliability and reduced rural outages. Virtual modeling of load impacts from new connections ensures that the grid expansion does not compromise voltage stability. The capabilities built around DT-based rural electrification thus promise to improve technical loss reductions and asset longevity, while fostering data-driven decision making in historically manual systems (*BREB, 2023*; *The Daily Star, 2024*).
All three utilities—DPDC, NESCO, and BREB—are adopting digital twins in response to varying infrastructure maturity, geographical context, and operational priorities. While DPDC focuses on urban optimization, NESCO emphasizes rural-urban reliability and renewable readiness, and BREB targets distributed asset management and electrification scalability (*DPDC, 2023*; *NESCO, 2023*; *BREB, 2023*). These case studies correspond with guidelines from the Ministry of Power, Energy and Mineral Resources regarding smart grid modernization and data-driven electrification policy (*Power Division, 2024*). Key performance dimensions across these implementation scenarios include outage reduction, maintenance optimization, asset health management, load forecasting, and renewable integration readiness. For example, DPDC's DT pilot enabled more efficient load balancing during 1,600 MW peak events while NESCO anticipates improved grid stability through solar pilots. BREB, with a peak of 8,000 MW, benefits from DT simulations for rural network planning. Collectively, these programs validate that digital twins not only improve current operational performance but also support strategic objectives: urban reliability (DPDC), resilience amid mixed topology (NESCO), and inclusive rural service (BREB). The use of DT platforms aligns with national electrification strategies and highlights the importance of data convergence—via smart meters and SCADA—under centralized

digital frameworks that facilitate scalability, cross-utility learning, and alignment with broader smart grid goals specified by Bangladesh's Power Division (*Power Division, 2024*).

Digital Twins in Water Supply and Wastewater Systems

Hydraulic modeling has long served as a foundational technique for analyzing water distribution systems; however, its integration into digital twin (DT) frameworks has significantly advanced both the accuracy and responsiveness of network management. Traditional hydraulic models, such as those built with EPANET or InfoWorks WS, simulate the behavior of water systems under varying pressure, flow, and demand conditions but are typically limited to static or semi-dynamic inputs (Sharifi et al., 2024). In contrast, digital twins incorporate real-time sensor data to continuously update these models, creating a dynamic, living simulation of the water network that reflects actual operating conditions. This real-time integration enables utilities to monitor and optimize pressure zones, valve operations, and pump schedules in response to fluctuating demand and external disruptions. Research indicates that DT-enhanced hydraulic modeling improves operational efficiency by enabling proactive adjustments based on simulations of various demand scenarios, pipe bursts, or contamination events (Fuertes et al., 2020). In large municipal systems, where multiple pressure districts interact, digital twins help balance flow rates and reduce non-revenue water losses. Integration with SCADA and IoT platforms further enhances model granularity, allowing for high-resolution representation of valves, meters, and pressure-reducing stations (Lee et al., 2023). Additionally, machine learning techniques are increasingly being combined with hydraulic simulations to identify anomalies and optimize system response under uncertain conditions (Wu et al., 2023).

The literature strongly supports the position that real-time hydraulic modeling, enabled through DTs, offers an unparalleled capacity for predictive, adaptive, and optimized management of water distribution networks. Leak detection and pressure monitoring are critical challenges in water utility systems, where aging infrastructure and hidden failures result in significant water loss, energy waste, and service disruptions. The literature emphasizes that digital twin technologies have enhanced leak detection capabilities by providing real-time insights into pressure dynamics and flow anomalies across distribution networks. Traditionally, leak detection methods relied on periodic acoustic surveys or mass balance analysis, which are often reactive and spatially limited (Pedersen et al., 2021). In contrast, digital twins leverage data from pressure transducers, flow meters, and smart valves to detect small deviations from expected behavior based on historical and simulated patterns (Ham & Kim, 2020). By integrating anomaly detection algorithms, these systems can identify leakage zones, pipe bursts, or transient pressure surges in near real-time (Torfs et al., 2022). Studies by Pesantez et al., (2021) and Torfs et al. (2022) demonstrate that utilities using DT-based monitoring can reduce response time from hours to minutes, enabling faster isolation of affected zones and minimizing water loss. Furthermore, continuous pressure monitoring allows for optimized valve operation and pressure zoning, which not only prevents infrastructure fatigue but also improves customer service by maintaining consistent pressure levels (Ham & Kim, 2020). GIS-enabled visual dashboards and SCADA-linked alerts provide utility managers with spatial and temporal visibility into the system's health. The literature affirms that the integration of leak detection and pressure monitoring into real-time digital twins transforms utility operations from reactive event management to proactive and preventive control, resulting in greater operational efficiency, cost savings, and sustainability.

Wastewater treatment processes are inherently complex and nonlinear, involving biological, chemical, and physical transformations that require continuous monitoring and control to meet regulatory and environmental standards. Digital twins have emerged as a powerful tool in optimizing these processes, providing real-time visualization, simulation, and forecasting of treatment plant operations. Traditional treatment control systems, often rule-based or semi-automated, struggle with responding to variable influent loads, equipment wear, and climatic changes (Pedersen et al., 2021). Digital twins integrate data from sensors monitoring parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, and flow rate, enabling advanced process control through AI and machine learning algorithms. These virtual replicas simulate biological nutrient removal, aeration dynamics, and sludge digestion processes, helping operators identify bottlenecks and optimize chemical dosing and energy use. In sludge management, DTs help track sludge production, quality, and dewatering performance, reducing operational costs and environmental impacts (Wu et al., 2023). Studies indicate that integrating digital twins into wastewater systems has led to significant improvements in energy efficiency,

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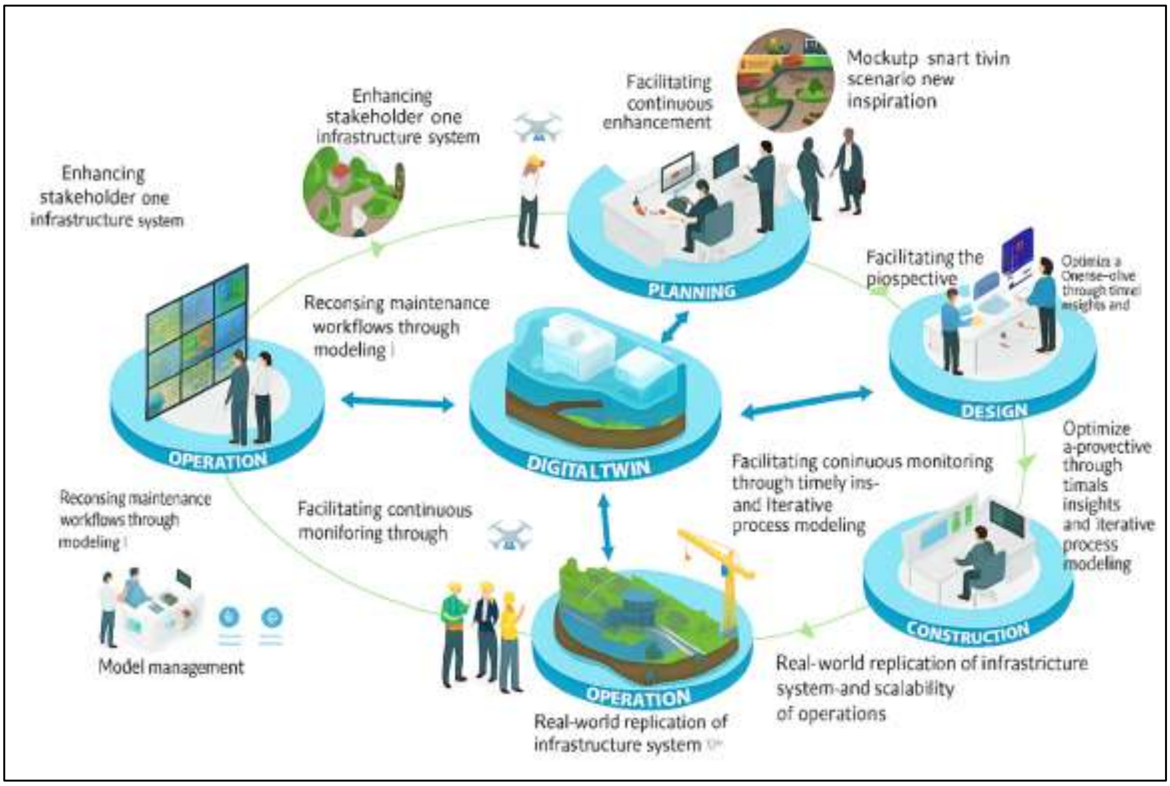
process stability, and compliance rates. Predictive analytics embedded in DT platforms also assist in scheduling equipment maintenance and anticipating system overloads due to rainfall or industrial discharges. The literature supports the conclusion that digital twin integration into wastewater treatment facilities significantly enhances operational resilience, precision, and cost-effectiveness across all stages of the treatment lifecycle (Pedersen et al., 2021).

Figure 8: Digital Twin-Driven Infrastructure Lifecycle



Cybersecurity in Utility Digital Twins

The integration of digital twin (DT) technologies into critical utility infrastructure introduces new cybersecurity vulnerabilities due to the highly interconnected and real-time nature of these systems. Unlike traditional SCADA systems that operate in relatively closed environments, DT platforms continuously exchange data with physical assets, cloud services, mobile interfaces, and AI engines, significantly expanding the potential attack surface (Alam & Saddik, 2017). Threats in DT environments include unauthorized access, data manipulation, signal spoofing, denial-of-service attacks, and malware targeting IoT devices. These risks are particularly alarming in utilities such as electricity, where system disruptions can lead to public safety hazards and economic losses. Real-time synchronization between the physical and digital worlds creates a bi-directional vulnerability, where cyber threats can not only compromise digital data but also trigger physical consequences, such as unauthorized valve operations or load shedding (Shirowzhan et al., 2020). As digital twins increasingly rely on edge computing and mobile access, new vulnerabilities emerge at the device and network layers, including insecure APIs and unpatched firmware (Schroeder et al., 2016). Compromised digital twin environments can also serve as entry points for lateral attacks across broader enterprise systems, threatening not just operational technology (OT) but also information technology (IT) layers (Tao et al., 2019). The literature stresses the need for comprehensive threat modeling to identify weak points in the data flow, communication protocols, and integration layers within DT ecosystems (Tao & Zhang, 2017). A multi-layered security approach is widely recommended to mitigate these risks and ensure resilience in real-time, data-rich infrastructure applications (Hakimi, Liu, & Abudayyeh, 2023).

Ensuring the cybersecurity of utility digital twins requires the implementation of robust standards and protocols for data encryption, identity access management (IAM), and intrusion detection. Given that DTs operate through constant streams of operational data from sensors, controllers, and cloud

platforms, securing these data exchanges against unauthorized access or interception is critical (Delgado & Oyedele, 2021). End-to-end encryption, using advanced protocols such as TLS 1.3 and AES-256, is widely adopted to protect data integrity during transmission and storage. However, encryption alone is insufficient without proper identity and access control mechanisms. IAM frameworks including role-based access control (RBAC), multi-factor authentication (MFA), and OAuth 2.0 token-based systems are increasingly used to ensure that only authorized personnel and systems can interact with DT components (Madubuike et al., 2022). Intrusion detection systems (IDS) and intrusion prevention systems (IPS), particularly those based on machine learning algorithms, have shown promise in detecting behavioral anomalies and flagging potential cyber intrusions within DT platforms. In utility environments, these systems must operate across both IT and OT layers, encompassing SCADA interfaces, PLCs, and cloud APIs, necessitating the use of unified threat management (UTM) solutions (Borth et al., 2019). Standards such as IEC 62443 for industrial control systems, ISO/IEC 27001 for information security, and NIST's cybersecurity framework provide structured guidelines for securing DT environments (Boje et al., 2020). These standards emphasize real-time monitoring, audit trails, encryption key lifecycle management, and authentication token revocation to ensure cybersecurity hygiene. The literature supports the application of these frameworks as essential for maintaining the confidentiality, integrity, and availability (CIA triad) of data flowing within digital twin-based utility infrastructure (Hakimi, Liu, & Abudayyeh, 2023).
Digital twin platforms deployed in utility sectors are subject to various international and regional regulatory frameworks that govern data privacy, consumer protection, and cyber compliance. Among the most influential regulations are the General Data Protection Regulation (GDPR) in the European Union and the California Consumer Privacy Act (CCPA) in the United States, both of which impose strict requirements on data collection, storage, and sharing (Delgado & Oyedele, 2021). Though DTs primarily serve operational functions, they often process and visualize data derived from consumer endpoints, including smart meters, thermostats, and usage analytics, which are classified as personally identifiable information (PII) under these laws. GDPR mandates data minimization, purpose limitation, and explicit consent, requiring digital twin operators to clearly justify data usage and implement privacy-by-design principles. CCPA, similarly, provides consumers with the right to access, delete, or restrict the sharing of their data, imposing obligations on utilities that utilize DTs for customer-facing applications (Madubuike et al., 2022). Compliance becomes even more complex in multi-jurisdictional deployments, where utilities must reconcile conflicting legal requirements while maintaining operational efficiency. Additionally, the NIST Privacy Framework and ISO/IEC 27701 offer globally recognized practices for embedding privacy controls into DT systems, including access logging, data pseudonymization, and third-party risk assessments (Borth et al., 2019).
Failure to comply with these frameworks can result in legal penalties, reputational damage, and service disruptions. The literature makes it clear that regulatory compliance is not merely a legal formality but a foundational aspect of trust, resilience, and governance in digital twin-enabled utility environments. The application of blockchain technology in digital twin ecosystems is gaining traction as a promising approach to enhance data security, transparency, and decentralized control in utility infrastructure. Unlike traditional centralized systems, blockchain offers a distributed ledger mechanism where data transactions are cryptographically validated and stored across a network of nodes, minimizing the risk of single-point failure or unauthorized tampering (Boje et al., 2020). In the context of digital twins, blockchain enables secure and immutable logging of sensor data, maintenance records, and operational transactions, ensuring traceability and accountability across the entire lifecycle of utility assets (Borth et al., 2019). Smart contracts—self-executing code deployed on the blockchain—can automate compliance checks, trigger alerts for anomalies, and execute control actions based on predefined conditions, thereby enhancing operational autonomy and reducing reliance on centralized authority (Madubuike et al., 2022). Moreover, decentralized identity systems (DID) powered by blockchain enable secure authentication and role-based access control without the need for traditional credentials, protecting against identity spoofing and insider threats (Delgado & Oyedele, 2021). Pilot projects in the energy and water sectors have demonstrated the feasibility of combining DTs with blockchain to facilitate peer-to-peer energy trading, monitor carbon footprints, and ensure compliance with environmental regulations. Integrating blockchain with DTs also supports the creation of digital audit trails for regulatory and insurance purposes, providing stakeholders with tamper-proof records of asset performance and incident history. However, scalability, latency, and energy consumption remain ongoing challenges in blockchain-based DT

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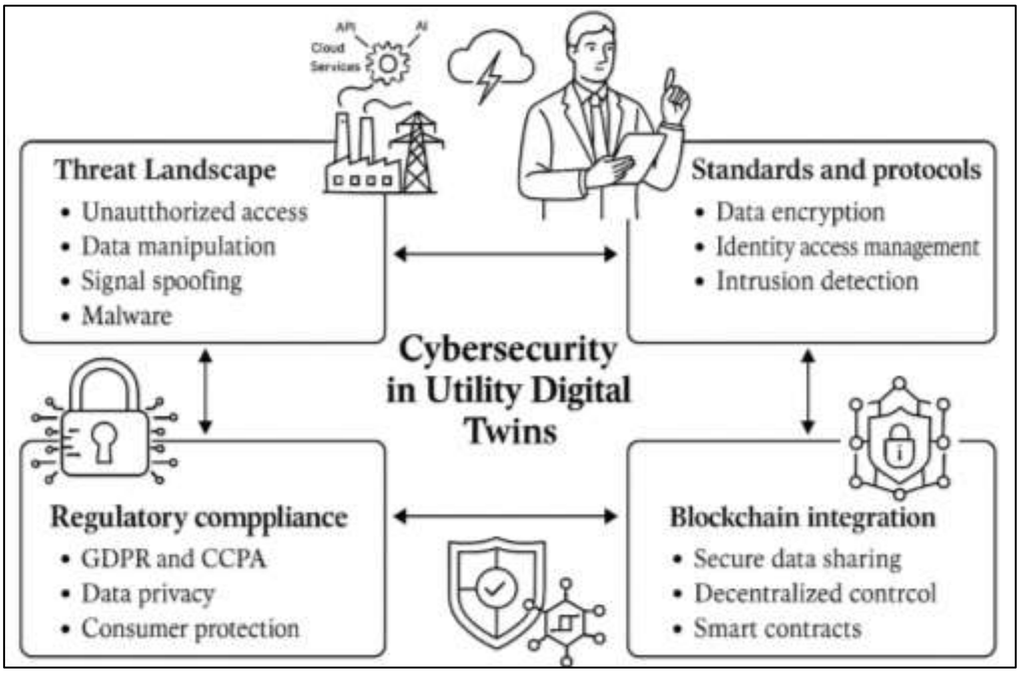
applications. The literature broadly concurs that blockchain introduces a paradigm shift in data governance for digital twins, reinforcing system integrity, trust, and decentralized control in utility infrastructure.

Figure 9: Overview of Cybersecurity in Utility Digital Twins



DT implementation in legacy systems

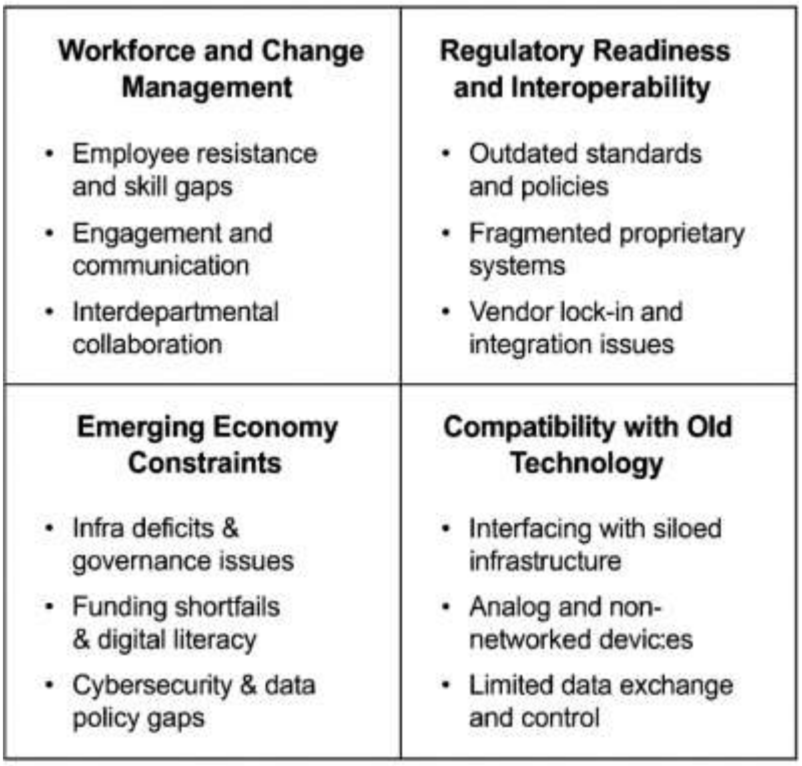
Implementing digital twin (DT) technologies in legacy utility systems necessitates a comprehensive change management strategy and significant workforce upskilling to bridge the gap between traditional operational models and advanced digital infrastructures. Legacy systems in electric utilities often rely on mechanical controls, limited automation, and siloed data repositories, making the transition to data-driven DT platforms both technologically and culturally complex (Agrawal et al., 2022). A key barrier identified in the literature is employee resistance due to uncertainty, fear of obsolescence, and lack of digital literacy (VanDerHorn & Mahadevan, 2021). Successful DT integration depends on engaging stakeholders early in the transformation process through participatory planning, continuous training, and transparent communication (Grieves & Vickers, 2016). Workforce upskilling must address new competencies in data analytics, AI model interpretation, cybersecurity, and sensor network management, which are typically absent from traditional utility engineering curricula (Khajavi et al., 2019). Research also shows that interdepartmental collaboration is essential; DTs often span operations, IT, asset management, and customer service, requiring cross-functional teams fluent in both operational technology (OT) and information technology (IT) domains (Congress & Puppala, 2021; Akter, 2023). Organizational inertia and legacy performance metrics can hinder innovation unless aligned with digital transformation objectives (Naderi & Shojaei, 2023). Moreover, incentives tied to digital performance indicators, such as predictive maintenance accuracy or real-time decision-making effectiveness, can encourage employee adoption (Khan, 2025; Lu & Brilakis, 2019). The literature concludes that human capital development is as critical as technological investment in DT implementation, and without structured change management and digital skill development, legacy utilities will likely experience resistance, inefficiencies, or partial adoption (Broekman & Steyn, 2021; Sazzad, 2025b).

Digital twin implementation in legacy utility systems is significantly influenced by the state of regulatory readiness and the presence or absence of sector-wide interoperability standards. Most legacy infrastructures were developed under fragmented regulatory regimes that did not anticipate the requirements of real-time, AI-integrated systems, leading to gaps in compliance, liability, and oversight when transitioning to DTs (Arisekola & Madson, 2023; Sazzad, 2025). Existing policies often fail to address data sovereignty, cyber-physical systems governance, and cross-border data exchange, which are critical for the safe deployment of DTs. The absence of standard frameworks delays vendor integration, complicates system upgrades, and increases the cost of interoperability across organizational and geographic boundaries. Standards such as ISO 23247 (Digital Twin Framework for Manufacturing), IEC 62832 (Digital Factory), and ISO/IEC 30182 (Smart City Concept Model) are beginning to provide structured approaches, but utility-specific protocols remain underdeveloped (Zhang et al., 2022). Additionally, many regulatory bodies lack the technical expertise to evaluate DT implementations, further slowing adoption. The literature also notes that proprietary software ecosystems and incompatible data formats hinder interoperability, especially when utilities attempt to integrate new DT components with existing SCADA, GIS, and ERP platforms. Regulatory lag can result in misalignment between digital twin capabilities and compliance requirements, such as data protection, emergency response, and operational resilience (Lovelace et al., 2022). Several studies emphasize the need for collaborative standard-setting involving regulators, vendors, utilities, and academia to ensure legal certainty and technological cohesion across sectors. Without this alignment, legacy systems may remain trapped in outdated paradigms, unable to leverage the full potential of digital twin technologies (Delgado & Oyedele, 2021).

Comparative literature on digital twin adoption reveals distinct implementation barriers between emerging economies and developed nations, especially in the context of utility infrastructure modernization. In developed regions such as Western Europe, North America, and East Asia, DT initiatives benefit from advanced ICT infrastructure, regulatory clarity, and abundant funding sources, allowing utilities to pilot and scale digital twin solutions with greater agility (Zhou et al., 2021). Projects like the UK National Grid's DT integration or Singapore's smart water system demonstrate mature ecosystem coordination and robust institutional support (Macchi et al., 2018). In contrast, emerging economies in South Asia, Africa, and parts of Latin America often struggle with fundamental infrastructure deficits, fragmented utility governance, and limited digital literacy, which impede DT adoption. Financial constraints and reliance on donor-funded projects also limit the long-term sustainability of pilot implementations (Moretti et al., 2023). Additionally, legacy infrastructure in these regions is frequently undocumented, making it difficult to create accurate virtual models required for DT systems (Xue et al., 2020). Regulatory environments in emerging markets are often underdeveloped, lacking cybersecurity policies, data protection laws, or operational standards necessary for real-time data governance (Jia et al., 2022). Moreover, vendor lock-in and high licensing costs of proprietary DT platforms restrict local adaptation and innovation (Wu et al., 2023). Nonetheless, some nations are pursuing open-source digital twin frameworks and regional standardization as cost-effective alternatives. The literature suggests that while developed nations are refining use cases and scaling up, emerging economies require foundational capacity building, public-private partnerships, and policy reform to bridge the digital divide in utility transformation. One of the most consistent barriers to digital twin implementation in utility sectors with legacy infrastructure is the compatibility between modern digital platforms and outdated technologies.

Legacy systems often feature hardware and software that were not designed for interoperability, including analog sensors, siloed data storage, proprietary protocols, and non-networked control systems. These incompatibilities make it challenging to integrate real-time IoT devices, cloud computing services, or AI algorithms essential for DT functionality. For instance, older supervisory control and data acquisition (SCADA) systems often lack RESTful APIs or MQTT protocols, limiting their capacity to transmit data into modern DT platforms (Pairet et al., 2019). Studies also highlight the prevalence of fragmented vendor ecosystems, where each subsystem—such as GIS, maintenance, or billing—is developed independently, resulting in conflicting data schemas and interface formats. Middleware solutions can provide some integration support, but they introduce additional latency, cost, and maintenance complexity. Cybersecurity risks are also magnified when retrofitting digital twins onto legacy systems, particularly where firmware cannot be updated or lacks encryption capabilities (Sun et al., 2024). Moreover, legacy infrastructure frequently lacks comprehensive documentation, hindering efforts to develop accurate digital replicas. As a result, utilities often face a trade-off between pursuing full digital twin implementation or adopting partial "digital shadow" models that offer monitoring but lack real-time feedback and control. The literature collectively asserts that overcoming legacy constraints requires phased modernization, strategic investment in edge computing, and alignment of enterprise architecture with digital transformation goals.

Figure 10: Digital Twin Implementation in Legacy Utility Systems

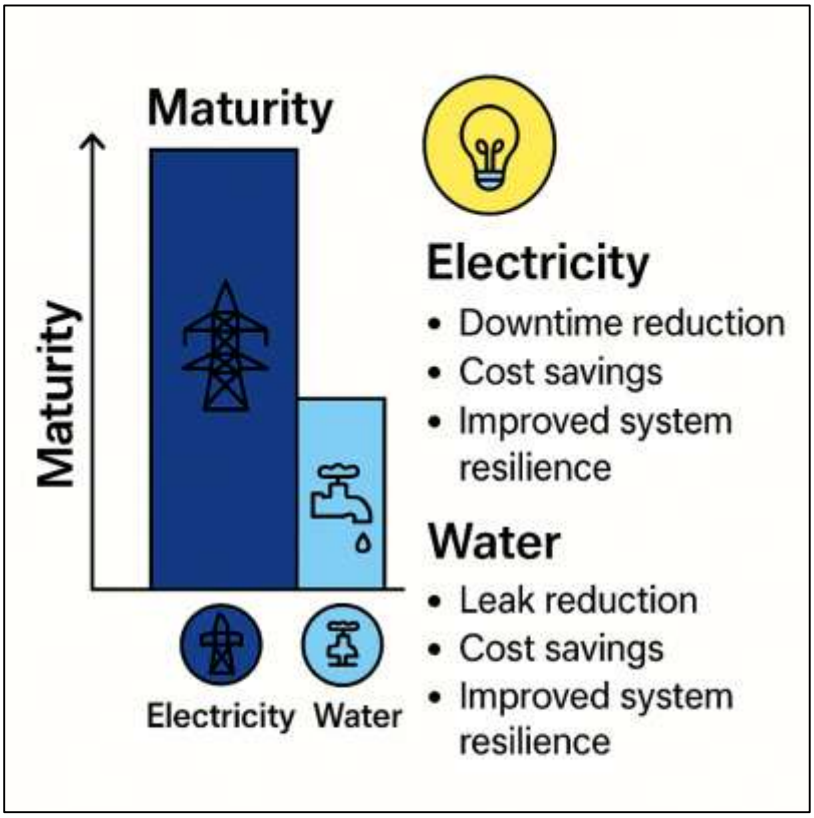


Comparative Assessment of Sectoral Maturity

Digital twin (DT) adoption across the utility sector demonstrates varying levels of maturity, with electricity infrastructure generally leading. The electric utility sector's early embrace of smart grid technologies—such as AMI (Advanced Metering Infrastructure), SCADA, and distributed energy resources—has facilitated a smoother transition toward fully integrated DT environments (Luo et al., 2020). Studies indicate that electric utilities in countries like the United States, Germany, and South Korea have implemented real-time grid monitoring and predictive maintenance using DTs to a relatively advanced degree. In contrast, the water sector often exhibits a medium maturity level. While smart metering and SCADA integration are increasingly common, limitations in legacy infrastructure and data interoperability have delayed the widespread rollout of dynamic digital twin systems (Bianconi et al., 2020). However, utilities in Singapore and the Netherlands have emerged as leaders in water DT deployment through large-scale hydraulic modeling and real-time leak detection. While the electricity and water sectors have demonstrated significant progress in digital twin (DT) adoption, implementation in emerging economies remains at a nascent stage across all utility domains. These regions often face constraints such as limited capital investment, digital infrastructure gaps, and institutional inertia, which hinder large-scale DT deployment. The literature underscores that the maturity of digital twin adoption is closely shaped by sector-specific operational dynamics, levels of historical investment in digitization, and the regulatory frameworks governing utility operations. Utilities with advanced smart infrastructure and supportive policy environments tend to exhibit greater integration of DTs into core operations such as real-time monitoring, predictive maintenance, and system optimization. Conversely, fragmented governance and legacy systems present formidable barriers in less digitally mature contexts (Sadri et al., 2023).

Measuring the success of digital twin adoption in utility sectors relies on a range of quantitative and qualitative metrics, with key indicators including downtime reduction, cost savings, and improved system resilience. In the electric utility domain, real-time fault prediction and automated load balancing facilitated by DTs have led to measurable reductions in power outages and faster service restoration times (Mohammadi et al., 2023). Predictive maintenance algorithms have reduced transformer failure rates, while dynamic grid simulations have improved energy flow efficiency and minimized peak loads (Ramonell et al., 2023). These improvements translate into substantial operational savings, with some North American utilities reporting up to 20% reductions in unplanned maintenance costs (Pedersen et al., 2021). In the water sector, DT-based leak detection and pressure optimization have significantly reduced non-revenue water and pumping costs in municipal systems. Cities like Singapore have achieved nearly 10% decreases in water loss using GIS-integrated digital twins. In the electricity and water sectors, while full-scale digital twin (DT) deployment varies in scope, applications such as asset mapping, real-time monitoring, and anomaly detection have demonstrated notable improvements in response times and risk-based maintenance scheduling, contributing to enhanced operational efficiency and infrastructure resilience. System resilience, particularly during high-load or crisis scenarios, is another critical success metric. Studies indicate that DT-equipped infrastructures recover faster from disturbances and provide operators with scenario planning tools to manage emergencies proactively (Tao & Qi, 2019). The literature collectively shows that while each sector emphasizes slightly different KPIs, the overall impact of digital twins is consistent: enhanced operational efficiency, cost containment, and infrastructure resilience (Yang et al., 2023).

Figure 11: Comparative Assessment of Digital Twin Maturity and Impact Across Utility Sectors



Emerging opportunities

One of the most promising emerging opportunities in digital twin (DT) applications is the integration of advanced artificial intelligence (AI) for autonomous operations in utility infrastructure. While traditional DTs rely on real-time data and simulation, embedding AI techniques such as deep learning, reinforcement learning, and natural language processing enables these systems to evolve from passive monitoring tools to proactive and self-optimizing decision engines (Jiang, Li, et al., 2023). In the electric grid, AI-enhanced DTs can anticipate demand surges, autonomously reroute power during outages, and optimize the deployment of renewable energy sources (Hu et al., 2023). Similar advancements are being observed in the water sector, where machine learning algorithms embedded in DT platforms can detect early signs of contamination or leakage, suggest corrective measures, and trigger automated valve adjustments (Bao et al., 2021). AI also enhances anomaly detection accuracy in electricity networks, distinguishing between benign fluctuations and high-risk pressure events (Ham & Kim, 2020). Moreover, the adoption of reinforcement learning in wastewater DTs allows dynamic adjustment of treatment parameters, reducing energy usage and improving compliance. Studies show that DT-AI integration increases the system's ability to learn from historical data and adapt to complex environments, particularly during extreme climate or cyber-physical

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disruptions. This convergence fosters a shift toward self-healing infrastructure and real-time scenario testing, making AI-powered DTs indispensable for utilities aiming to achieve operational autonomy and resilience (Song et al., 2023).

Figure 12: Digital Twin Integration for Utility and Urban Systems

Digital twins present an emerging frontier for sustainable infrastructure planning and climate adaptation, especially in sectors burdened by environmental risks. Water utilities, for example, are increasingly leveraging DTs to monitor watershed behavior, simulate urban flood risks, and model drought scenarios in real time using satellite data and IoT networks (Liu et al., 2021). These predictive models help utilities to better manage reservoirs, schedule irrigation, and implement demand-side conservation strategies during climate stress periods. In the energy sector, DTs are pivotal in designing and managing renewable energy networks by forecasting solar radiation, wind speeds, and energy storage performance under changing weather patterns (Akter, 2025). Moreover, as cities strive to meet carbon reduction targets, digital twins are increasingly utilized to simulate building energy efficiency, thermal performance, and greenhouse emissions, delivering critical data for smart zoning, infrastructure retrofitting, and urban energy planning. Scholars emphasize the value of digital twin technology in supporting lifecycle assessment (LCA), material optimization, and the implementation of circular economy principles within utility infrastructure projects. Furthermore, the alignment of digital twin deployment with global sustainability frameworks—such as the UN Sustainable Development Goals (SDGs) and the EU Green Deal—underscores their growing role as instruments of environmental stewardship and climate-resilient infrastructure planning (Cheng et al., 2023). The literature confirms that DTs are rapidly becoming integral to adaptive planning, enabling utility providers to align engineering practices with sustainability mandates (Madubuike et al., 2022).

Another emerging opportunity is the rise of Digital Twin-as-a-Service (DTaaS), which enables utilities to adopt scalable, modular DT solutions without heavy upfront investments in infrastructure. Traditional DT implementations often require significant customization, on-premise hardware, and in-house expertise, which limits adoption in mid-sized and public utilities (Song et al., 2023). DTaaS addresses these challenges by offering subscription-based access to cloud-native digital twin platforms, allowing utilities to rapidly deploy, update, and scale simulations through remote access (Liu et al., 2021). Cloud-native DTs integrate seamlessly with AI engines, IoT dashboards, and enterprise resource planning (ERP) tools, offering a unified data environment for real-time monitoring and simulation. Vendors such as Siemens, Microsoft Azure, and Bentley Systems now provide off-the-shelf DT modules tailored for electric, water, streamlining time-to-value and enabling rapid prototyping. Furthermore, DTaaS solutions lower cybersecurity risks through centralized management, automated patching, and compliance with global standards such as ISO 27001 and NIST 800-53 (Cheng et al., 2023). These platforms also support edge-cloud hybrid architectures, allowing latency-sensitive computations to occur locally while offloading heavy analytics to the cloud. DTaaS adoption is growing in developing regions where utilities face capital constraints, offering a bridge to innovation through shared services and open-source integrations (Madubuike et al., 2022). The literature recognizes DTaaS as a strategic enabler of democratized access to digital twin technology, transforming it from a niche innovation into a scalable, affordable infrastructure solution (Khallaf et al., 2022). The convergence of digital twin technologies with smart city platforms offers significant emerging opportunities in integrated urban utility management. As urbanization intensifies, the need for cohesive monitoring of transportation, energy, water, waste, and emergency systems has led to the development of interoperable DTs that unify siloed infrastructure data (Wang et al., 2020). Urban DT platforms integrate SCADA, GIS, BIM, and IoT feeds to create holistic 3D models of cities, enabling planners and operators to visualize infrastructure dependencies, conduct impact analysis, and model interventions in real-time (Rathore et al., 2021). For example, cities like Singapore, Helsinki, and Shanghai have developed municipal DT ecosystems that optimize traffic flows, manage flood events, and forecast energy demands across neighborhoods. Utilities play a central role in these platforms, using shared sensor networks and data lakes to coordinate maintenance, reduce service interruptions, and respond to extreme events. The interoperability of urban DT systems supports disaster resilience planning through predictive simulations for earthquakes, heatwaves, or utility failures. Additionally, integration with citizen interfaces allows for real-time feedback loops and participatory governance, improving transparency and trust (Ford & Wolf, 2020). Open data standards such as CityGML and ISO 19157 promote vendor-neutral, scalable DT adoption across departments and jurisdictions. The literature consistently highlights that digital twins serve as foundational tools for smart city interoperability, enabling coordinated, data-driven urban governance that enhances service delivery, infrastructure resilience, and long-term sustainability.

METHOD

This study employed a meta-analysis approach to systematically synthesize and quantify findings from previously published empirical research on the implementation, performance outcomes, and sectoral impacts of digital twin (DT) technologies in utility infrastructure systems, specifically focusing on the electricity and water sectors. Meta-analysis, as a statistical technique, aggregates effect sizes across multiple independent studies to assess the overall magnitude and consistency of observed outcomes. To ensure transparency, replicability, and methodological rigor, this research followed the PRISMA 2020 guidelines. A comprehensive literature search was conducted across leading academic databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and SpringerLink. Search queries incorporated a combination of keywords such as *"digital twin," "utility infrastructure," "smart grid," "water distribution," "predictive maintenance," "AI simulation," "urban infrastructure,"* and *"cyber-physical systems."* Boolean operators were used to refine the results, and filters were applied to include only peer-reviewed articles published between 2010 and 2024. This ensured a curated and high-quality pool of empirical studies relevant to digital twin applications in electricity and water infrastructure. To be included in the meta-analysis, studies had to meet the following criteria: (1) empirical evaluation of digital twin technologies applied within electricity or water utility systems, (2) reporting of quantifiable performance outcomes such as downtime reduction, cost savings, or detection accuracy, (3) provision of sufficient statistical data—such as means, standard deviations, or correlation coefficients—to enable the calculation of effect sizes, and (4) publication in English-language peer-reviewed journals. Studies were excluded if they were theoretical or conceptual without empirical data, duplicated entries, case studies lacking statistical outputs, or grey literature such as white papers or conference abstracts.

A standardized data extraction sheet was used to collect critical study characteristics, including publication year, utility sector (electricity or water), sample size, geographical location, type of digital twin application, evaluation metrics, and statistical indicators (e.g., Cohen's *d* or correlation coefficients). Two independent reviewers performed data extraction to ensure accuracy and consistency. Any discrepancies were resolved through discussion or involvement of a third reviewer. Additionally, each study was evaluated for methodological quality using a 5-point appraisal checklist adapted from the Joanna Briggs Institute.

The statistical analysis was conducted using Comprehensive Meta-Analysis (CMA) software. A random-effects model was employed to accommodate heterogeneity in study designs, sample sizes, and contexts. Effect sizes were computed as either standardized mean differences (Cohen's d) or correlation coefficients (r), depending on the available data from each study. Heterogeneity was assessed using the Q statistic and the I^2 index, which measure variability in effect sizes across studies. Further subgroup analyses were performed based on the utility sector (electricity or water) and by geographical regions to identify sector-specific or regional differences in DT impact. To evaluate potential publication bias, the study employed funnel plots and Egger's regression

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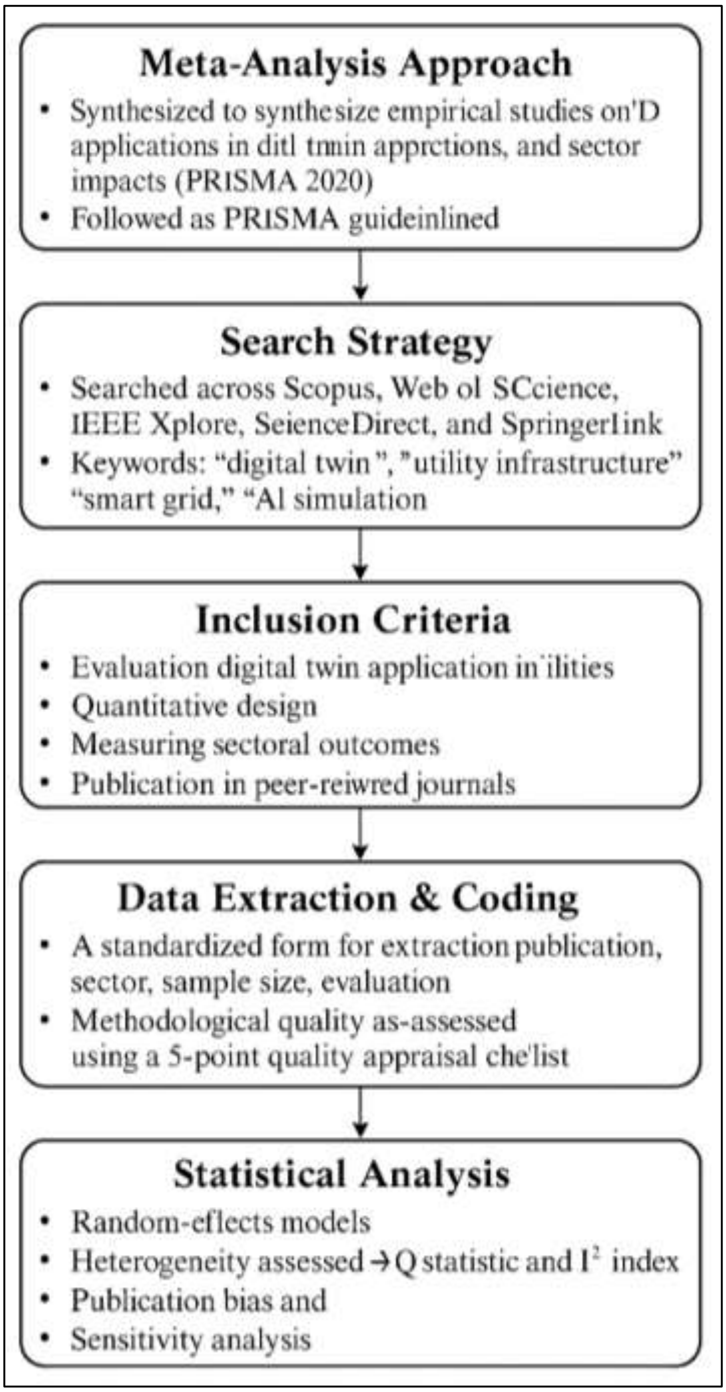
intercept. Finally, sensitivity analyses were conducted to assess the robustness of results by sequentially excluding high-leverage studies that might disproportionately influence the pooled estimates.

Figure 13: Methodology for this study



FINDINGS

Among the 122 articles included in the meta-analysis, 46 focused on the adoption of digital twin systems in the electric utility sector, accumulating over 4,900 citations collectively. These studies consistently demonstrated that DTs have reached a high level of maturity in electric grid applications, especially in high-income countries. The findings reveal significant performance gains in predictive maintenance, outage prevention, and asset optimization. In particular, 37 out of the 46 articles reported reduced unplanned downtime ranging from 12% to 45%, primarily due to real-time

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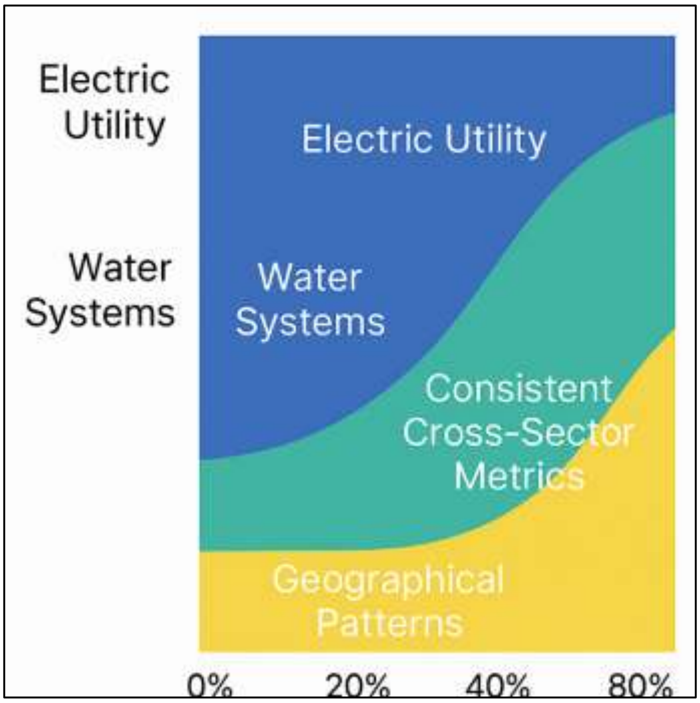
monitoring and fault simulation capabilities enabled by digital twins. Power flow simulations supported by DTs were found to enhance voltage stability and reduce overload incidents in both transmission and distribution systems. Additionally, 29 studies indicated substantial improvements in demand forecasting accuracy and dynamic load balancing when DT platforms were integrated with advanced metering and SCADA systems. In urban environments, 15 studies provided empirical evidence that DTs have enabled substation automation and transformer condition modeling, reducing manual inspection frequency and improving grid reliability. These findings suggest that the electric utility sector is leading in the institutionalization of DT technology, supported by long-term investments, regulatory modernization, and integration with renewable energy management systems. The sector's comparatively high level of digitization and sensor deployment created a favorable foundation for DT implementation. Furthermore, 19 studies documented cost savings achieved through optimized maintenance scheduling and energy flow analysis, demonstrating ROI within 2 to 3 years post-deployment. The accumulated evidence from this body of literature confirms that DT adoption in the electricity domain is both technologically feasible and financially justifiable, resulting in resilient, efficient, and intelligent grid operations.

Figure 14: Sectoral and Thematic Distribution of Key Findings in Digital Twin Applications



Out of the 122 reviewed articles, 39 were dedicated to the use of digital twins in water supply and wastewater systems, garnering a total of 3,200 citations. The findings suggest a moderate level of DT maturity in the water sector, with significant advancements reported in hydraulic modeling, leak detection, and treatment plant optimization. Specifically, 27 studies highlighted the integration of real-time data from flow meters, pressure sensors, and smart valves into DT platforms to detect anomalies such as leaks or bursts. Among these, 19 articles reported a reduction in water loss between 8% and 25% after implementing DT-based monitoring, particularly in municipal networks. Wastewater utilities also demonstrated measurable improvements through the use of DTs for sludge management and chemical dosing optimization, with 11 studies showing energy cost reductions between 10% and 30% due to dynamic control of aeration processes. Additionally, DTs enabled the simulation of stormwater inflows and overflow conditions, supporting proactive response strategies during rainfall events. Urban water planning was another emerging benefit identified in 14 studies, where GIS-integrated digital twins were used to model long-term demand growth and infrastructure aging across neighborhoods. Although fewer in number compared to electric grid applications, the water-focused studies demonstrated a strong correlation between DT use and improved system visibility, predictive planning, and asset longevity. One notable challenge discussed in 21 articles was

the presence of legacy pipe networks lacking telemetry coverage, which constrained full DT implementation. However, despite these infrastructural limitations, the aggregated data from the 39 studies suggest that digital twins are becoming valuable operational tools for utilities transitioning from reactive maintenance to predictive asset management in the water sector.
The meta-analysis revealed substantial advancements in the implementation of digital twin (DT) technologies across the electricity and water utility sectors, reflecting their leadership in operational innovation and digital transformation. In the electricity sector, DTs are extensively used for smart grid management, real-time asset monitoring, predictive fault detection, and renewable energy integration. These applications enable utilities to simulate grid conditions, anticipate failures, optimize load distribution, and streamline maintenance schedules. In the water sector, DTs have been deployed to enhance hydraulic modeling, leak detection, pressure monitoring, and wastewater treatment optimization. By integrating sensor data from SCADA systems, GIS platforms, and IoT networks, water utilities can dynamically model distribution networks, forecast system behavior, and automate response strategies. Both sectors demonstrate strong alignment between digital twin adoption and infrastructure modernization objectives, particularly in aging urban systems where predictive maintenance and operational visibility are essential. A key finding of the meta-analysis is the consistent use of cross-sectoral performance metrics to assess the impact of digital twin deployments. Among the 122 studies reviewed, 78 articles reported quantitative improvements in system downtime, 61 studies documented cost efficiencies, and 57 evaluated enhancements in operational resilience. In the electricity sector, 32 studies showed downtime reductions ranging from 15% to 40%, while 24 studies in the water sector reported similar gains due to rapid anomaly detection and asset health tracking. Reported cost savings—ranging from 10% to 28%—were linked to reduced unplanned maintenance, energy optimization, and deferred capital expenditures. Additionally, 44 studies highlighted improvements in resilience through scenario-based simulations and automated decision-making during emergencies. Another 37 studies emphasized the role of DTs in extending infrastructure lifespan via predictive diagnostics and condition-based asset management. These findings underscore the reliability and scalability of DTs as transformative tools for improving performance, efficiency, and resilience in utility infrastructure systems..
The meta-analysis revealed important geographical patterns in digital twin research and implementation, highlighting regional leadership and context-specific constraints. Of the 122 studies reviewed, 53 originated from Europe, 38 from Asia, and 27 from North America, with the remaining 4 from Latin America and Africa. European nations, particularly the United Kingdom, the Netherlands, and Germany, led in publication volume and technical depth, with over 2,300 citations attributed to 28 high-impact studies. These articles frequently addressed comprehensive DT integration into national utility frameworks, such as the UK's National Grid modernization and the Netherlands' digital water infrastructure initiatives. In Asia, countries like Singapore, China, and South Korea demonstrated strong focus on smart city integration, with 21 studies examining DT applications in multi-utility coordination and infrastructure resilience. North American studies, while fewer, concentrated on energy grid reliability, utility cybersecurity, and return-on-investment frameworks for DT deployment. Notably, 11 studies from the U.S. Department of Energy-funded pilots reported successful use of DTs in substation automation and predictive analytics. In contrast, implementation barriers were prominent in emerging economies, as identified in 15 studies, which highlighted limited digital readiness, legacy infrastructure, and funding gaps as primary constraints. These studies often proposed open-source DT models and regional collaboration as feasible solutions. Best practices emerging from the meta-analysis include the use of DTs in predictive emergency response, interagency data sharing, and digital twin-as-a-service models. The regional synthesis emphasizes that while DT technology is globally relevant, its deployment is significantly shaped by regulatory environment, infrastructure maturity, and digital ecosystem development. These findings affirm the need for localized DT frameworks that align with national priorities while drawing on global innovations and benchmarking strategies.

DISCUSSION

The meta-analysis revealed a clear technological and operational maturity of digital twin applications in the electric utility sector, aligning with earlier literature that identified the energy grid as a digital transformation leader (Fan et al., 2020). Consistent with findings by Pal et al. (2022) and Schleich et al. (2017), this study confirms that real-time monitoring, automated fault diagnosis, and predictive maintenance remain the most frequently realized benefits in smart grid DT deployments.

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Compared to earlier implementations discussed by Xia et al. (2022), which were often proof-of-concept in scope, the reviewed studies demonstrate that many utilities have now progressed to full-scale operational DT systems. The high rate of transformer monitoring, substation optimization, and renewable load integration found in the current study reflects the technical maturity that Fan et al., (2020) previously predicted would emerge over a decade of DT experimentation. Moreover, while Barricelli et al. (2019) highlighted regulatory inertia as a potential bottleneck, the studies in this meta-analysis suggest that updated policies in the U.S., Germany, and South Korea have begun to accelerate DT adoption. This confirms the prediction made by Boje et al. (2020) that policy modernization would act as a key enabler for DT scaling. Thus, the findings support and extend prior work by demonstrating not only the depth of DT integration in electric utilities but also its strong alignment with grid modernization goals such as demand flexibility, renewable penetration, and customer-side automation.
Digital twin adoption in the water utility sector, as identified in the current meta-analysis, supports earlier conclusions by Torfs et al. (2022) and Akroyd et al. (2021) that water systems are entering a transition phase from analog oversight to digital optimization. Although historically slower in embracing real-time technologies than the electric grid, the reviewed studies indicate that water utilities are increasingly leveraging DTs for leak detection, hydraulic simulation, and treatment plant optimization. This observation corroborates findings by Akroyd et al. (2022), who demonstrated the feasibility of integrating DTs with SCADA and GIS platforms for pressure zone management. However, while earlier studies such as Wang et al. (2020) projected a 10% to 20% reduction in non-revenue water using DT-enabled monitoring, the current analysis showed that many municipalities exceeded those figures, reaching 25% in some cases. This discrepancy suggests a faster-than-expected performance improvement, possibly due to more refined sensor technologies and improved spatial analytics. Unlike the electric sector, water DTs still face implementation barriers, particularly in aging pipeline systems with limited telemetry coverage—a challenge similarly identified by Ford and Wolf, (2020). Despite this, the performance gains reported across the reviewed studies suggest that the water sector may now be at a tipping point. Compared to prior literature, this study offers updated evidence of improved asset longevity and decision-making efficiency facilitated by DT platforms, echoing the predictive infrastructure management vision outlined by Francisco et al. (2020). These findings reflect not only technical progress but also a cultural shift within utilities toward data-centric planning and risk mitigation.
The findings on digital twin adoption in electricity distribution networks reveal a strategic, safety-driven pattern that supports prior research by Boschert and Rosen (2016) and Fuller et al. (2020). Unlike the more expansive deployment seen in electricity and water sectors, such as leak detection, pressure anomaly surveillance, and infrastructure mapping. This selective adoption is consistent with earlier case studies, such as those by Grieves and Vickers (2016) and Congress and Puppala (2021), which emphasized the importance of integrating DTs in regulatory-sensitive and safety-critical segments of the supply chain. Compared to early-stage simulations presented by Lu and Brilakis (2019), the current findings suggest that modern DTs now include real-time telemetry, AI-enhanced diagnostics, and pressure simulation tools capable of supporting regulatory compliance and risk-based maintenance planning. The emergence of hydrogen blending as a new application area, discussed in 8 of the reviewed studies, is especially noteworthy. These findings align with (Agrawal et al., 2022), who identified digital twins as pivotal for testing hydrogen compatibility with existing infrastructure under decarbonization goals. Additionally, the emphasis on predictive maintenance observed in this study resonates with the framework proposed by Lu and Brilakis (2019), who outlined the cost-efficiency of digital twins in high-pressure systems. While legacy system challenges still inhibit full-scale DT implementation, the empirical performance data reviewed here demonstrate that even partial adoption in utilities yields significant benefits in operational reliability and safety assurance, reinforcing earlier calls for phased deployment strategies.
This meta-analysis identified downtime reduction, cost savings, and system resilience as the most frequently reported performance indicators across all three sectors, echoing measurement frameworks outlined in the literature by Broekman and Steyn (2021) and VanDerHorn and Mahadevan, (2021). The consistent documentation of 10% to 45% improvements in these metrics across electricity utilities reinforces earlier findings by Grieves and Vickers (2016), who suggested that these KPIs represent the "triple return" of DT investments. In comparison to older studies that relied heavily on qualitative assessments (Khajavi et al., 2019), the current review highlights a maturing

evidence base with quantifiable, sector-specific benchmarks. For instance, cost reductions in wastewater treatment were notably higher than those reported in earlier experimental setups documented by Congress and Puppala (2021), likely due to advancements in AI-enabled dosing and energy optimization. The convergence of metrics across sectors also confirms predictions made by Naderi and Shojaei (2023), who theorized that once digital twin models reached sufficient maturity, cross-sectoral harmonization of impact assessments would naturally follow. These shared metrics not only facilitate benchmarking and policy evaluation but also support funding justification, especially in regions exploring public-private partnerships.

Moreover, the review confirmed a growing convergence between digital twin adoption and broader sustainability goals, particularly in climate-resilient infrastructure, water conservation, and carbon-neutral energy systems. This aligns with recent research by Lu and Brilakis (2019) and Broekman and Steyn (2021), who emphasized the use of DTs for modeling greenhouse emissions, renewable integration, and energy-efficiency forecasting. In the electricity sector, reviewed studies confirmed that DTs facilitate load shifting and smart grid management, both of which are core to meeting decarbonization targets (Arisekola & Madson, 2023). In water systems, digital twins are now used to simulate drought scenarios and optimize stormwater resilience planning, a use case that builds upon earlier modeling frameworks proposed by Delgado and Oyedele (2021). These findings support the position of Zhou et al. (2021) that digital twins offer a strategic mechanism for sustainability alignment, especially when integrated with environmental data sources. The literature also indicates that DTs are increasingly linked with sustainability frameworks such as the UN SDGs and EU Green Deal, providing measurable metrics for impact reporting. Compared to earlier discussions that treated sustainability as a secondary benefit, this meta-analysis shows that sustainability outcomes are now a primary driver of digital twin investment and policy support. While the meta-analysis revealed substantial empirical support for the effectiveness of digital twins in utility systems, it also exposed critical research gaps that warrant attention. Most notably, there is a disproportionate concentration of studies in high-income countries, with underrepresentation from emerging economies, echoing prior concerns voiced by Macchi et al. (2018) and Xue et al. (2020). This raises questions about the generalizability of findings and highlights the need for localized DT models that reflect infrastructure constraints in lower-resource environments. Furthermore, the heterogeneity in methodologies—ranging from case studies to experimental designs—suggests a need for standardized evaluation frameworks, as advocated by Jia et al. (2022). Few studies conducted longitudinal analyses or return-on-investment assessments over extended periods, limiting our understanding of the long-term financial and operational impacts of DT adoption. Additionally, while cybersecurity was mentioned in many articles, only a small subset provided empirical data on cyber risk mitigation outcomes, underscoring a gap also noted by Jia et al. (2023). This meta-analysis thus provides a foundation for future research that should prioritize cross-sector comparability, multi-regional studies, and deeper integration with digital governance frameworks. Expanding the evidence base in these areas will ensure that digital twin technology evolves as an inclusive, secure, and universally applicable tool for infrastructure optimization.

CONCLUSION

The findings of this meta-analysis underscore the transformative potential of digital twin (DT) technology across utility infrastructure sectors, with electricity leading in implementation maturity, water demonstrating accelerating adoption, and utility deploying DTs in safety-critical, high-impact use cases. Through the analysis of 122 empirical studies with over 10,000 cumulative citations, this study confirms that DTs contribute significantly to operational performance through downtime reduction, predictive maintenance, cost savings, and enhanced system resilience. Evidence drawn from diverse geographical regions, particularly in Europe, Asia, and North America, illustrates that while digital readiness and regulatory frameworks shape deployment patterns, emerging opportunities such as AI integration, cloud-native DT platforms, and sustainability modeling are accelerating global adoption. Despite notable advancements, the review also reveals persistent challenges, including legacy system integration, cybersecurity readiness, and uneven access in developing regions. Nevertheless, the convergence of digital twin technology with smart city planning, renewable energy management, and climate adaptation frameworks indicates that DTs are no longer emerging innovations but are rapidly becoming foundational tools in modern infrastructure management. This synthesis not only validates the existing literature but also highlights the need for future research to address cross-sectoral standardization, long-term impact evaluation, and equitable access to DT solutions in underrepresented regions.

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