Chapter 1
Digital Twin-Driven Green Energy Systems:
Real-Time Optimization for Smart, Sustainable Infrastructure

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ABSTRACT

This chapter explores the transformative role of Digital Twin (DT) technology in optimizing green energy systems for net-zero goals. DTs serve as dynamic virtual replicas of physical energy assets such as wind turbines, solar panels, and EV infrastructure integrated with IoT, AI, and edge computing for real-time monitoring, predictive maintenance, and autonomous control. The chapter outlines DT architecture, sector-wise applications, and performance improvements with real-world case studies, including Siemens' wind farms and smart city EV networks. Key advancements include up to 40% enhancement in efficiency and 22% reduction in downtime. The integration of blockchain ensures data security and decentralized governance. Ethical, regulatory, and deployment challenges are discussed, along with future research directions in AI-driven autonomy and interoperability. This chapter concludes that DTs are central to developing resilient, intelligent, and sustainable energy ecosystems aligned with global climate targets.

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INTRODUCTION

The need of the entire world to reach net-zero carbon emission requires smart, dynamic and renewable energy systems. This being one such changing landscape, it is in this environment that Digital Twin (DT) technology has claimed to be a life changing solution that has the capability of providing predictive control and real-time optimization through renewable energy infrastructures(González-Herbón et al., 2024). A digital twin is a dynamic digital construction that reflects the state, behavior, and performance of physical system in real-time using data, Artificial Intelligence (AI) as well as high-performance computing(Chandhana et al., 2023). Misalignment of physical assets with the digital version of the assets, in this case, wind turbines, solar panels, energy storage units, and smart buildings, allows the stakeholders to model actions, identify areas of inefficiency, anticipate failure and improve performance, before it is too late. Visualization is not the only area in which DTs can have potential, with data-driven decisions made possible by the use of DTs helping to improve energy efficiency, resilience, and reliability and cut carbon footprints(Solman et al., 2022). This chapter deep dives into the actual architecture of digital twins systems including such fundamental components as sensor integration, real-time data streaming, AI-powered analytics, and edge-cloud computing. It also addresses the use of green energy not only in real-world sectors, but also those in specific domains, including solar PV, wind energy, micro-grids, EV infrastructure, and smart cities.(Barricelli et al., 2019a) The consistent combination of IoT, edge computing, and blockchain also enables DTs to create a future-secure and sustainable, and scalable energy ecosystem.

DIGITAL TWIN ARCHITECTURE FOR SUSTAINABLE ENERGY SYSTEMS

The premise of a digital twin-powered green energy system is in its sound architecture and stratified development. In essence, sensor integration is used to measure physical properties of energy resources (including temperature, pressure, voltage, and vibration) of turbines, batteries and solar panels, among others. Such sensors transmit live data streams into the cloud/edge computer models. The AI and machine learning algorithms are run on these platforms which can recognize patterns and anomalies, and perform predictive analysis. Intelligent visualization dashboards translate intelligence into friendly and actionable operator and stakeholder visualization, (Stadtmann et al., 2023). The architecture should enable interoperability and scalability and can be integrated with various systems, ranging between a smart building to EV charging stations. Hybrid cloud-edge structures are central to the

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