


# Chapter 4


## AI-Driven Twin Framework for Intelligent Condition Monitoring and Predictive Maintenance in Grid-Integrated Wind Turbines: Advanced ML Models for Real Time Asset Optimization

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### **ABSTRACT**

*The exponential development of wind power requires a high level of operational efficiency, reliability, and grid integration. The chapter presents a four-layer AI-powered digital twin architecture of grid-integrated wind turbines, which includes multi-sensors networks, IoT-based data acquisition (MQTT, LoRaWAN, 5G), hybrid physics and deep learning modeling, and autonomous decision-making. Machine learning models such as CNNs, RNNs, attention-based models and ensemble genetic models allow real-time condition monitoring and predictive maintenance*

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*with 99.72% accuracy in fault detection and predicting fault in 1-56 days. The conversion of reactive to predictive strategies generate 11-50% O&M savings, 60% reduction of inspections and 85% expedited repairs, and maximum asset lifespan. Critical infrastructure is secured by secure gateways, encryption, and blockchain. Field deployments demonstrate 25 of downtime and 40 of emergency repair cost decreases, greater capacity factors, and improved sustainability.*

## **INTRODUCTION**

### **The Global Wind Energy Context and the Imperative for Transformation**

The wind energy is turning out to be one of the most significant pillars of global shift towards the decarbonisation and the energy systems that are sustainable. In 2024, the world is projected to have more than 1,050 gigawatts (GW) of wind power installed capacity, an unprecedented pattern of quad-fold growth in the last 20 years. Such growth not only represents the coming-of-age of technology but it also represents a desperate acknowledgment that renewable energy is the magic key to helping weasel out disastrous climate change, as well as to satisfy legally mandated emission-cutting obligations. The International Energy Agency (IEA) suggests that wind energy needs to grow and reach over 2,000 GW by 2030 in a way that is compatible with net-zero carbon directions, which would necessitate an almost a doubling in the number of installed capacities in the next five years (International Energy Agency (IEA), 2023) (Intergovernmental Panel on Climate Change (IPCC), 2022). The unprecedented upward trend of wind energy brings forth impressive opportunities and operational challenges in the most challenging format ever. Contemporary wind turbines are now very complicated electro-mechanical structures; stand-alone offshore systems are now over 15 megawatts (MW) installed capacity and have rotor scaffolds over 220 meters in diameter. Such machines are used in highly variable conditions, including variable wind velocities, temperatures between -40°C and +60° C permeating seawater, salt-spray corrosion of offshore units, and complicated turbulent flow states and caused by adjacent turbines (Kühn & Muskulus, 2022)(Worden et al., 2021). At the same time, wind turbines will have to combine harmoniously with electrical grids themselves in downturn to high levels of distributed renewable resources, and thus build dynamic conditions of operation never before documented in the history of grid operations. The wind farm operational environment has experienced a paradigm. Early turbines were used in the 1980s and 1990s and they were pegged in relatively isolated clusters where the requirement of interconnection with the grid was not much. Modern turbines are actively involved

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