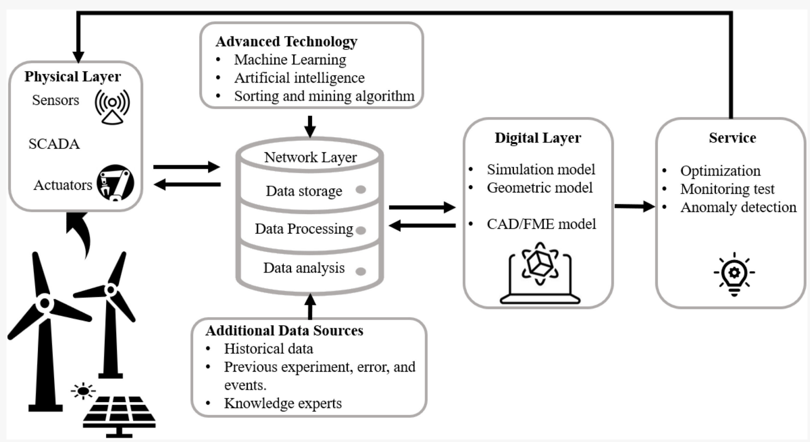
How digital twins can accelerate the global transition from fossil fuels to clean energy

Once limitations are overcome, digital twins could solve the urgent challenge of shifting from fossil fuels to renewable energy sources.

SHARJAH, EMIRATE OF SHARJAH, UNITED ARAB EMIRATES, July 28, 2025 /EINPresswire.com/ -- As the world grapples with the urgent need to reduce carbon emissions and combat climate change, researchers at the University of Sharjah are turning to a cutting-edge technology that could reshape the future of energy: AI-powered digital twins.



The structure of a digital twin. Credit: Energy Nexus (2025). DOI: https://doi.org/10.1016/j.nexus.2025.100415

According to the researchers, these digital replicas of the physical world have the potential to transform the generation, management, and optimization of energy across diverse clean energy platforms, accelerating the transition away from fossil fuels, which environmental scientists associate with global warming.

Digital twins' ability to replicate and interact with complex systems has made them a cornerstone of innovation across industries, driving improvements in efficiency, cost reduction, and the development of novel solutions.

However, the scientists caution that current digital twin models still face notable limitations that restrict their full potential in harnessing energy from sources such as wind, solar, geothermal, hydroelectric, and biomass.

“Digital twins are highly effective in optimizing renewable energy systems,” the researchers write in the journal Energy Nexus. “Yet, each energy source presents unique challenges—ranging from data variability and environmental conditions to system complexity—that can limit the performance of digital twin technologies, despite their considerable promise in improving energy generation and management.” (https://doi.org/10.1016/j.nexus.2025.100415)

In their study, the authors conducted an extensive review of existing literature on the application of digital twins in renewable energy systems. They examined various contexts, functions, lifecycles, and architectural frameworks to understand how digital twins are currently being utilized and where gaps remain.

To extract meaningful insights, the researchers employed advanced text mining techniques, leveraging artificial intelligence, machine learning, and natural language processing. This scientifically rigorous approach enabled them to analyze large volumes of raw data and uncover structured patterns, concepts, and emerging trends.

From this in-depth analysis, the authors drew several key conclusions. They identified research gaps, proposed new directions, and outlined the challenges that must be addressed to fully harness the potential of digital twin technology in the renewable energy sector.

Following a detailed discussion on the integration of digital twins across various renewable energy applications, the authors summarized their most significant findings across five major energy sources: wind, solar, geothermal, hydroelectric, and biomass. Each source presents unique opportunities and challenges, and the study offers a comprehensive overview of how digital twins can be tailored to optimize performance in each domain.

The study reveals that digital twins offer significant advantages across various renewable energy systems:

Wind Energy: Digital twins can predict unknown parameters and correct inaccurate measurements, enhancing system reliability and performance.

Solar Energy: They help identify key factors that influence efficiency and output power, enabling better system design and optimization.

Geothermal Energy: Digital twins can simulate the entire operational process—particularly drilling—facilitating cost analysis and reducing both time and expenses.

Hydroelectric Energy: The AI-driven models simulate system dynamics to identify influencing factors. In older hydro plants, they are used to mitigate the impact of worker fatigue on productivity.

Biomass Energy: Digital twins improve performance and management by offering deep insights into operational processes and plant configurations.

But the authors’ contribution to the field stands out in highlighting critical limitations in the application of digital twin technology across these energy sources. Their analysis underscores the need for more robust models that can address specific challenges unique to each renewable energy system.

The authors identify several limitations in the application of digital twins across different renewable energy systems:

Wind Energy: Digital twins face challenges in accurately modeling and monitoring environmental conditions. They struggle to simulate critical factors such as blade erosion, gearbox degradation, and electrical system performance—particularly in aging turbines.

Solar Energy: Despite their potential, digital twins still fall short in reliably predicting long-term performance. They have difficulty tracking panel degradation and accounting for environmental influences over time, which affects their accuracy and usefulness.

Geothermal Energy: A major obstacle is the lack of high-quality data, which hampers the ability of digital twins to simulate geological uncertainties and subsurface conditions. The technology also faces complexity in modeling the long-term behavior of geothermal systems, including heat transfer and fluid flow dynamics.

Hydroelectric energy: Applied to hydroelectric projects, digital twins face challenges in accurately modeling water flow variability and in capturing environmental and ecological constraints. These limitations reduce their effectiveness in optimizing system performance and sustainability.

biomass energy: When used with biomass energy systems, digital twins still struggle to simulate the entire production supply chain. They fall short in providing precise models for biological processes, biomass conversion, and the complex biochemical and thermochemical reactions involved.

The authors emphasize the broader implications of these shortcomings for the renewable energy sector. To address these challenges, they offer a set of guidelines and a research roadmap aimed at helping scientists enhance the reliability and precision of digital twin technologies.

Their recommendations focus on improving data collection methods, advancing modeling techniques, and expanding computational capabilities to ensure digital twins can deliver trustworthy insights for decision-making and system optimization.

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