

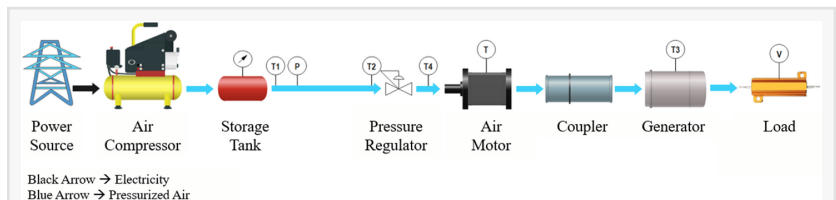
Scientists unveil digital twin tech to slash power losses in energy storage systems

Scientists design advanced digital twin tech that can significantly boost the performance, efficiency, and reliability of renewable energy storage systems.

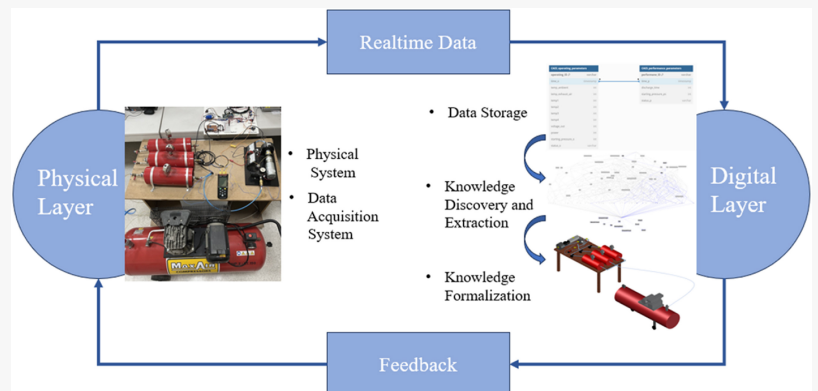
SHARJAH, UNITED ARAB EMIRATES, November 12, 2025 /

EINPresswire.com/ -- Scientists at the University of Sharjah have developed an advanced digital twin technology designed to replicate renewable energy stored in tanks, substantially improving their efficiency and reliability. The team presents the details of their invention, called a data-driven digital twin, in a paper published in the journal Energy.

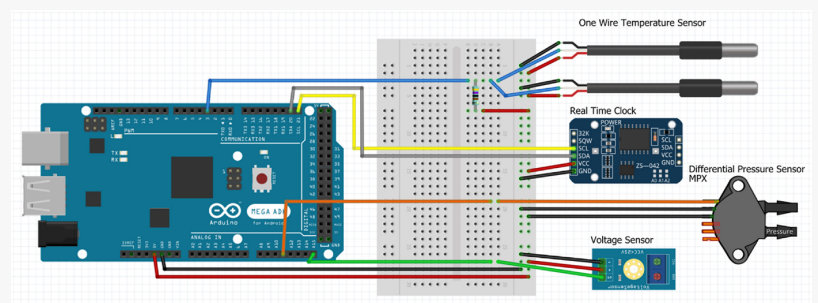
"Our study presents a data-driven digital twin—a virtual replica of a real physical system—designed for Compressed Air Energy Storage (CAES) systems," said lead author Concetta Semeraro, assistant professor in the university's Department of Industrial and Management Engineering. "The digital simulation model uses sensors, statistical analysis, and machine learning (specifically, Relational Concept Analysis) to detect early signs of faults before they become serious."



Components of a CAES system and location of the parameters monitored. Credit: Energy (2025). DOI: <https://doi.org/10.1016/j.energy.2025.138401>



The general architecture of a digital twin on a CAES system. Credit: Energy (2025). DOI: <https://doi.org/10.1016/j.energy.2025.138401>



Arduino sensing system utilized to collect data from the CAES system. Caption: Energy (2025). DOI: <https://doi.org/10.1016/j.energy.2025.138401>

CAES systems offer a sustainable solution for storing surplus renewable energy by compressing air into tanks and later releasing it to generate power on demand. However, their performance

can be compromised by issues such as air leaks, mechanical friction, or generator overloads, reducing efficiency and reliability.

“This work presents the experimental implementation of a digital twin for a CAES system, utilizing a designed sensing system with sensors (positioned) to detect faults by gathering system readings under various conditions,” the authors write.

“Through the invariant patterns developed for the CAES system, it was possible to build a digital twin to predict the three possible system faults: leak fault (F1), Coupling Fault (F2), and Load Fault (F3). Furthermore, this paper successfully identified parameters that could predict and discern the system's health status (HS).”

The authors' virtual model identifies operational data patterns—such as temperature, pressure, and voltage—and stores them in a pattern library. “These patterns form a modular, reusable architecture, meaning that once a pattern is recognized and catalogued, it can be applied or extended to other systems with minimal redesign,” explained Dr. Semeraro.

The study shows that the “versatility of the digital twin's approach suggests its potential application to address various challenges encountered in CAES systems, and the methodology employed holds promise for adaptation to other systems.”

They further point out that their “paper contributes to the proposed methodology of utilizing the modeling patterns concept” by introducing “additional patterns to contribute to the existing digital twin pattern library.”

The researchers report that their newly designed digital twin can continuously mirror the CAES system in real time. Their virtual model, they maintain, is equipped with Arduino-based sensors and has been experimentally validated to ensure accuracy and reliability.

A key takeaway from the study is how the digital twin acts like a smart mirror of its physical energy doppelganger, with the ability to predict potential issues before they happen and constantly monitor the system to detect anomalies in real time.

Another key insight is that the digital twin can function effectively without recourse to big data or expensive computing. Instead, it leverages unsupervised machine learning, meaning it can identify patterns from pre-labelled data, which Dr. Semeraro describes as “a major advantage in industrial environments.”

The scientists affirm that they built and tested a fully operational CAES system to demonstrate that their digital twin can detect leaks and faults in real time. “By preventing failures and optimizing operations, this digital twin helps reduce maintenance costs and increase renewable energy reliability,” emphasized the lead author.

The authors highlight numerous practical implications and real-world applications of their digital twin, noting its potential to significantly enhance energy system performance. By enabling early detection of leaks and mechanical issues, the model helps minimize downtime and prevent costly energy losses.

By applying smart maintenance principles, operators can receive alerts as soon as the system exhibits abnormal behavior, enabling predictive maintenance rather than reactive repairs.

“The system’s architecture is built around modular design patterns—reusable software and data components that can be easily reconfigured or expanded for new systems,” Dr. Semeraro said. “This ensures that improvements in one energy application can be directly transferred to others, dramatically reducing development time and cost.”

The design is modular and reusable, offering system-wide scalability with the possibility of applying the same architecture to other energy systems, such as batteries, turbines, or hydrogen storage units, with minimal recalibration, according to the authors.

“The proposed digital twin methodology integrates real-time data acquisition, data-driven modeling techniques, and patterns library formalization to improve digital twin design and identify potential failures,” the authors note.

The methodology offers a holistic approach combining unsupervised machine learning algorithms with a structured pattern library to enhance the digital twin’s design and adaptability, emphasized Dr. Semeraro.

“Through the invariant patterns developed for the CAES system, it was possible to build a digital twin to predict three possible system faults—leak, coupling, and load faults. The versatility of the digital twin’s approach suggests its potential application to other systems and industries.”

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LEON BARKHO
University Of Sharjah
+971 50 165 4376
[email us here](#)

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