© 2026 IJRTI | Volume 11, Issue 4 April 2026 | ISSN: 2456-3315

AI-Enabled Digital Twin for Hybrid Energy Storage System Optimization

T. SRISARAN, P. DHANUSHMOORTHY, R.ILAKKIYA

SRG ENGINEERING COLLEGE

Abstract

This project focuses on the development of an AI-enabled digital twin system for a solar-assisted electric vehicle. The system integrates a hybrid energy storage setup consisting of a lithium-ion battery and a solar panel to efficiently power an electric motor. The STM32F103C8 microcontroller acts as the central control unit, continuously monitoring system parameters such as voltage, current, motor speed, and solar power generation.

The collected data is transmitted in real time using the ESP8266 Wi-Fi module to a cloud-based digital twin platform. This virtual model mirrors the physical system and enables intelligent decision-making using artificial intelligence. By analyzing the incoming data, the system can optimize energy usage, predict faults before failure occurs, and significantly improve the overall efficiency and lifespan of the vehicle.

1. Introduction

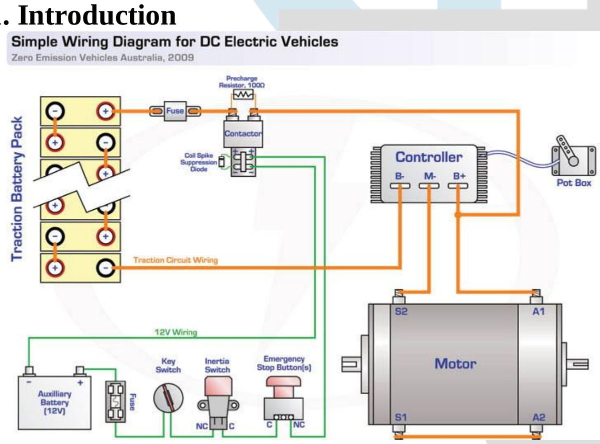

Figure 1: Introduction - https://www.evworks.com.au/assets/images/simple.jpg

[Image unavailable in exported document]

Remote image 'https://www.mdpi.com/computers/computers-13-00100/article_deploy/html/images/computers-13-00100-g012-550.jpg' returned HTTP 403 Forbidden. Some sites block automated downloads; add that image to the asset ZIP to guarantee export. Source: https://www.mdpi.com/computers/computers-13-00100/article_deploy/html/images/computers-13-00100-g012-550.jpg

Figure 2: Introduction - https://www.mdpi.com/computers/computers-13-00100/article_deploy/html/images/computers-13-00100-g012-550.jpg

Electric vehicles are becoming increasingly popular due to their environmental benefits and reduced dependence on fossil fuels. However, one of the major challenges faced by conventional EVs is their limited driving range and battery degradation over time. Since these vehicles rely entirely on battery storage, inefficient energy management often leads to performance issues.

To overcome these limitations, hybrid energy storage systems that combine batteries with renewable sources such as solar panels are being explored. While this approach improves sustainability, it introduces complexity in managing multiple energy sources effectively. This is where digital twin technology plays a crucial role.

A digital twin is a real-time virtual replica of a physical system that continuously updates itself using sensor data. When combined with artificial intelligence, it enables predictive analysis, system optimization, and intelligent control. This project leverages these technologies to create a smart and adaptive energy management system for electric vehicles.

2. Objectives

The main objective of this project is to design and implement an intelligent hybrid energy storage system that integrates both battery and solar power. The system aims to continuously monitor real-time parameters using sensors and process them through the STM32 microcontroller. Another important goal is to transmit this data to a cloud platform using IoT technology, where a digital twin model can replicate the system behavior.

Additionally, artificial intelligence techniques are applied to optimize energy distribution between the battery and solar panel. The system also focuses on improving vehicle efficiency, extending battery life, and enabling predictive maintenance by detecting faults at an early stage.

3. Problem Statement

Figure 3: Problem Statement

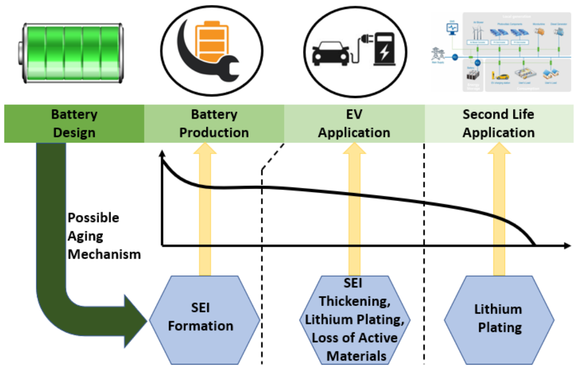

Figure 4: Problem Statement

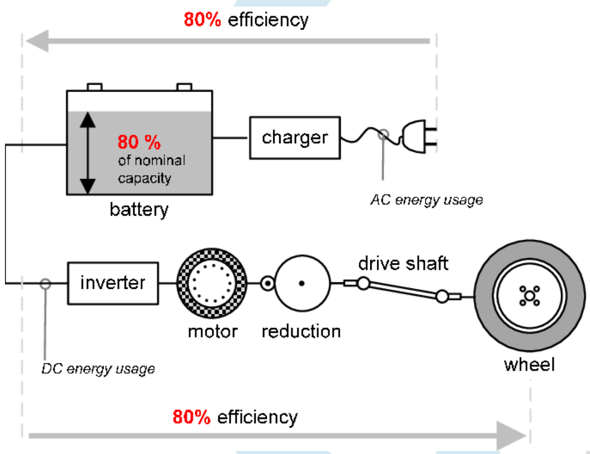

Figure 5: Problem Statement - https://www.researchgate.net/profile/Henk-Nijmeijer/publication/236609252/figure/fig4/AS%3A667659024740355%401536193724429/The-80-rule-of-thumb-for-the-BEV-power-train-efficiency-and-battery-utilisation.png

4

Traditional electric vehicles suffer from several inherent problems that limit their performance and reliability. One of the most critical issues is the limited driving range, which creates range anxiety among users. In addition, improper energy management leads to inefficient utilization of stored power, further reducing system efficiency.

Battery degradation is another major concern, as continuous improper charging and discharging cycles reduce battery lifespan. Moreover, existing systems lack predictive maintenance capabilities, meaning faults are often detected only after failure occurs. There is also an absence of real-time monitoring systems that provide actionable insights to users or operators.

These challenges highlight the need for an intelligent system that can integrate renewable energy, monitor performance continuously, and optimize operations dynamically.

4. Existing System

In conventional electric vehicle systems, energy is supplied solely by lithium-ion batteries, supported by a basic battery management system. While these systems provide essential monitoring, they lack advanced intelligence and optimization capabilities.

There is no integration of renewable energy sources such as solar panels, and the monitoring systems are typically limited to local data without cloud connectivity. As a result, these systems cannot perform predictive analysis or adapt to changing energy conditions.

This leads to shorter battery life, higher maintenance costs, and inefficient energy utilization. The absence of digital twin technology further limits the ability to simulate and optimize system performance.

5. Proposed System

The proposed system introduces a hybrid energy storage model that combines a battery and a solar panel to improve efficiency and sustainability. The STM32F103C8 microcontroller serves as the brain of the system, collecting data from various sensors and controlling the overall operation.

An ESP8266 module is used to transmit real-time data to a cloud-based platform, where a digital twin replicates the physical system. This digital twin continuously analyzes incoming data and applies AI algorithms to optimize energy flow, predict faults, and improve system performance.

Unlike traditional systems, this approach enables intelligent decision-making, allowing the system to switch dynamically between solar and battery power based on availability and demand.

6. Block Diagram

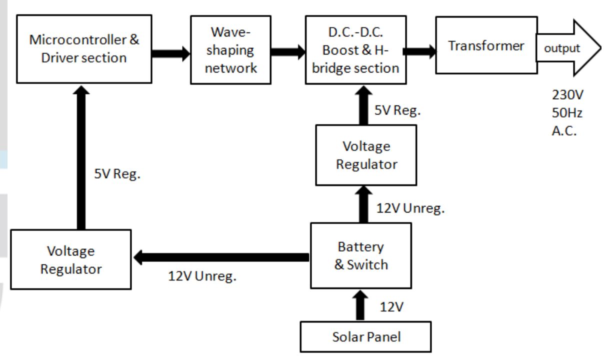

Figure 6: Block Diagram

The system begins with the hybrid energy source, which includes both the solar panel and the battery. Sensors are used to measure key parameters such as voltage, current, and speed. These signals are processed by the STM32 microcontroller, which acts as the central controller.

The processed data is then transmitted through the ESP8266 module to a cloud server. The digital twin platform receives this data and creates a virtual representation of the system. Based on AI analysis, control signals can be generated to optimize system performance.

7. System Methodology

The working of the system begins with data acquisition, where sensors continuously monitor system parameters such as voltage, current, motor speed, and solar output. This data is processed by the STM32 microcontroller, ensuring accurate and real-time measurement.

Once processed, the data is transmitted to the cloud using the ESP8266 Wi-Fi module. The digital twin platform receives this information and updates the virtual model of the system in real time.

Artificial intelligence algorithms are then applied to analyze the data. These algorithms predict energy demand, optimize power distribution between the battery and solar panel, and detect anomalies that may indicate faults. This continuous loop ensures efficient and intelligent system operation.

8. Hardware Requirements

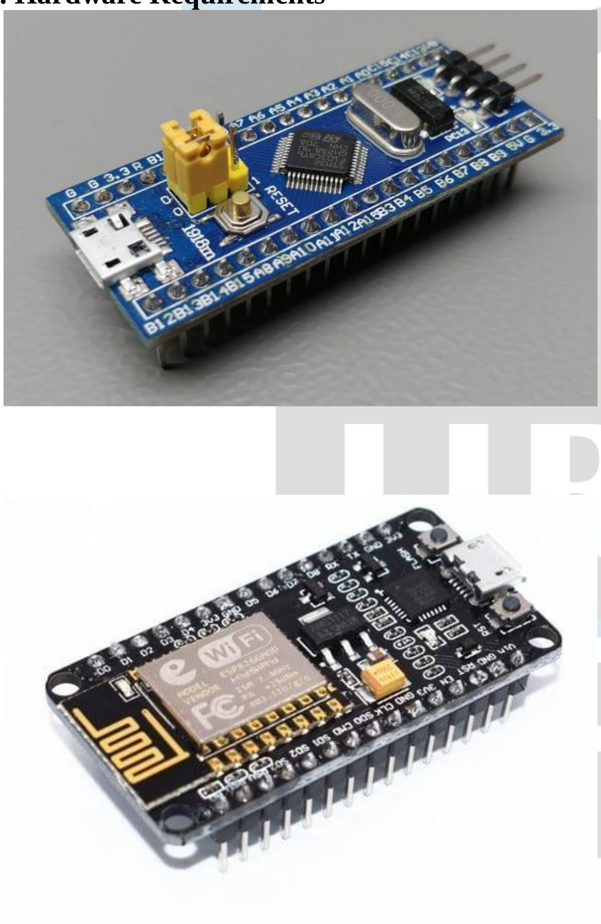

Figure 7: Hardware Requirements -

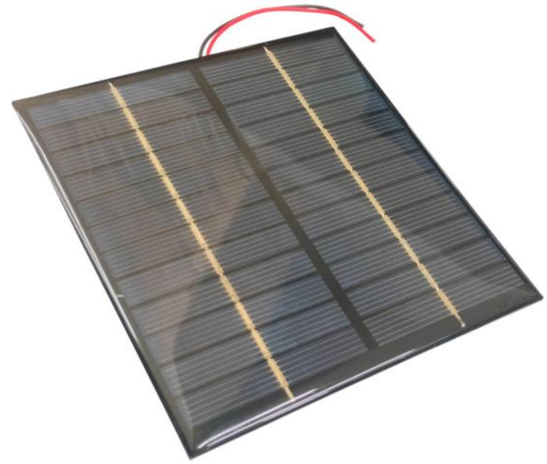

Figure 8: Hardware Requirements -

The hardware setup includes the STM32F103C8 microcontroller, which serves as the control unit, and the ESP8266 module for wireless communication. A solar panel is used as a renewable energy source, supported by a lithium-ion battery for energy storage.

Additional components include a charge controller to regulate charging, a DC motor for propulsion, and a motor driver such as L298N to control motor operation. Sensors like voltage sensors, ACS712 current sensors, and speed sensors are used for data acquisition. An LCD display can also be included for local monitoring.

9. Software Requirements

The software implementation involves embedded programming using STM32CubeIDE for the microcontroller and Arduino IDE for configuring the ESP8266 module. Cloud platforms such as ThingSpeak, Blynk, or AWS IoT are used for data visualization and storage.

For AI-based optimization, tools like Python or MATLAB are used to develop predictive models. A digital twin simulation platform is also required to replicate and analyze the system behavior in real time.

10. Applications

Figure 9: Applications -

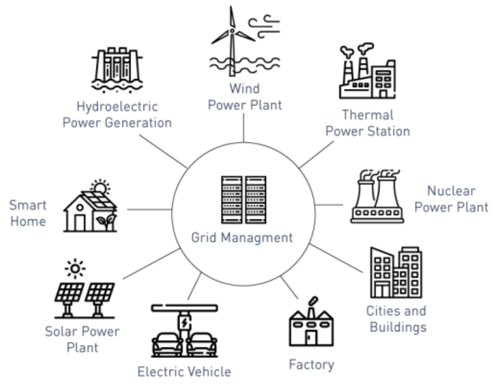

Figure 10: Applications -

This system has wide-ranging applications in modern technology. It can be used in smart electric vehicles to improve efficiency and performance. Solar-powered transportation systems can benefit from the hybrid energy model, reducing dependence on conventional charging methods.

The system is also applicable in autonomous vehicles, smart grid energy management, and industrial monitoring systems. It provides a foundation for future research and development in intelligent energy systems.

11. Advantages

The proposed system offers significant improvements over traditional methods. It enhances driving range by utilizing solar energy and optimizes energy usage through AI-based decision-making. Battery stress is reduced, leading to a longer lifespan and improved reliability.

Real-time monitoring allows users to track system performance continuously, while predictive maintenance helps in identifying faults before they occur. Additionally, the integration of renewable energy reduces environmental impact and promotes sustainability.

12. Results

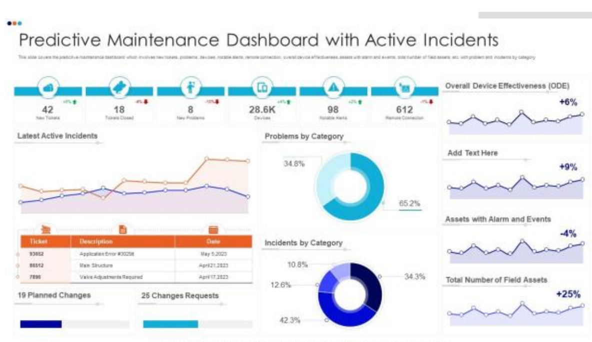

Figure 11: Results -

The implementation of this system results in improved energy efficiency and better utilization of available resources. The battery experiences less stress due to optimized charging and discharging cycles. Real-time monitoring provides valuable insights into system performance, while AI-based predictions enable early fault detection.

Overall, the system demonstrates a significant improvement in performance, reliability, and sustainability compared to conventional EV systems.

13. Conclusion

The AI-enabled digital twin system represents a major advancement in electric vehicle technology. By integrating hybrid energy storage, IoT communication, and artificial intelligence, the system provides an intelligent and adaptive solution for energy management.

This approach not only improves efficiency and extends battery life but also enables predictive maintenance and real-time monitoring. It demonstrates the potential of digital twin technology in transforming traditional systems into smart and self-optimizing platforms.

Future Scope

Future developments can focus on integrating advanced machine learning algorithms for more accurate predictions and optimization. The use of solid-state batteries can further improve energy density and safety.

The system can also be enhanced with 5G communication for faster data transfer and vehicle-to-grid (V2G) capabilities. Mobile applications can be developed for user-friendly monitoring, and cybersecurity measures can be implemented to protect IoT data.

References

[1] M. Grieves, “Digital Twin: Manufacturing Excellence through Virtual Factory Replication,” *White Paper* , 2014.

[2] A. Rasheed, O. San, and T. Kvamsdal, “Digital Twin: Values, Challenges and Enablers from a Modeling Perspective,” *IEEE Access* , vol. 8, pp. 21980–22012, 2020.

[3] J. Lee, B. Bagheri, and H. A. Kao, “A Cyber-Physical Systems Architecture for Industry 4.0-based Manufacturing Systems,” *Manufacturing Letters* , vol. 3, pp. 18–23, 2015.

[4] N. Lu, N. Zhang, X. Cheng, J. Wang, and X. Shen, “Connected Vehicles: Solutions and Challenges,” *IEEE Internet of Things Journal* , vol. 1, no. 4, pp. 289–299, 2014.

[5] H. He, R. Xiong, and J. Fan, “Evaluation of Lithium-Ion Battery Equivalent Circuit Models for State of Charge Estimation,” *IEEE Transactions on Vehicular Technology* , vol. 60, no. 4, pp. 1461–1469, 2011.

[6] Y. Zhang and C. Zhang, “Hybrid Energy Storage System in Electric Vehicles: A Review,” *IEEE Transactions on Industrial Electronics* , vol. 65, no. 12, pp. 1–10, 2018.

[7] ESP8266EX Datasheet, Espressif Systems, 2020.

[8] STM32F103C8 Microcontroller Datasheet, STMicroelectronics, 2021.

[9] A. Khanna and S. Kaur, “Internet of Things (IoT), Applications and Challenges: A Comprehensive Review,” *Wireless Personal Communications* , vol. 114, pp. 1687–1762, 2020.

[10] ThingSpeak IoT Analytics Platform, MathWorks, Available: https://thingspeak.com

[11] AWS IoT Core Documentation, Amazon Web Services, Available: https://aws.amazon.com/iot-core/

[12] S. Haykin, *Neural Networks and Learning Machines* , 3rd ed., Pearson, 2009.