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RESEARCH PAPER

AI-DRIVEN ADAPTIVE ENERGY OPTIMIZATION AND MANAGEMENT IN SMART MICROGRIDS USING GENERATIVE ADVERSARIAL NETWORKS (GANS)

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ABSTRACT- The increasing penetration of renewable energy sources in smart microgrids introduces challenges related to demand-supply balance, energy forecasting accuracy, and optimal energy distribution. This paper proposes an AI-driven energy optimization framework based on Generative Adversarial Networks (GANs) to enhance the efficiency and reliability of smart microgrids. Unlike traditional optimization methods, GANs leverage adversarial learning to generate highly accurate energy demand forecasts and improve real-time energy dispatch. The proposed method was tested on a real-world smart microgrid dataset, integrating solar PV, wind turbines, and battery storage systems.

Results demonstrate that the GAN-based approach improves energy demand prediction accuracy by 24.7% compared to conventional Long Short-Term Memory (LSTM) networks and reduces energy storage inefficiencies by 14.8%. Furthermore, the optimization model enhances grid stability, achieving a 9.6% reduction in voltage fluctuations and a 12.3% decrease in peak load stress, thereby increasing overall microgrid efficiency. These improvements contribute to better energy sustainability, reduced operational costs, and enhanced grid resilience. The findings highlight the potential of GANs as a powerful tool for next generation AI-driven energy management in smart microgrids

I. INTRODUCTION

Motivation The rapid integration of renewable energy sources, such as solar photo voltaics (PV) and wind turbines, into modern power systems has significantly transformed the energy landscape. Smart microgrids have emerged as a promising solution to enhance energy reliability, sustainability, and efficiency by enabling decentralized power generation and intelligent energy management. However, the inherent variability and intermittency of renewable energy sources pose significant challenges to demand-supply balancing, energy forecasting accuracy, and real-time energy dispatch. Addressing these challenges is critical to ensuring grid stability, minimizing energy storage losses, and reducing peak load stress in microgrid operations. Traditional energy optimization methods, such as rule-based control strategies and conventional forecasting models, often fail to adapt to the dynamic and complex nature of microgrids. Machine learning (ML)-based approaches have shown significant improvements in energy prediction and optimization; however, many existing models struggle with data scarcity, long-term generalization, and real-time adaptability. In this context, GANs have emerged as a powerful tool in deep learning, capable of generating highly accurate and synthetic energy demand patterns while enhancing energy management strategies. GANs utilize adversarial learning mechanisms to improve forecasting precision and optimize energy distribution, making them particularly suitable for dynamic microgrid environments.

This paper proposes an AI-driven energy optimization framework based on GANs to enhance the efficiency and resilience of smart microgrids. The proposed method aims to increase forecasting accuracy, minimize energy storage inefficiencies, and optimize grid stability in real-time operations. By leveraging adversarial learning, the framework enables microgrids to adaptively manage energy resources, mitigate the impact of demand fluctuations, and reduce operational costs.

Problem Definition:

The integration of renewable energy sources such as solar and wind into smart microgrids introduces significant challenges due to their intermittent and unpredictable nature. Fluctuations in energy generation often lead to imbalances between electricity supply and demand, which can affect the stability and efficiency of microgrid operations. Accurate energy forecasting and efficient energy management are therefore essential for maintaining reliable power distribution.

Traditional energy optimization techniques and rule-based control systems are not well suited to handle the dynamic and complex environment of modern smart microgrids. These methods often fail to adapt to rapid changes in energy generation and consumption patterns, resulting in inefficient energy storage utilization, increased operational costs, and reduced grid stability.

Furthermore, many machine learning models require large and well-balanced datasets for accurate predictions, which are not always available in microgrid environments. Therefore, there is a need for an intelligent and adaptive energy management framework that can improve forecasting accuracy, handle data limitations, and optimize energy distribution

II. RELATED WORK

Generative Artificial Intelligence for Distributed Learning to Enhance Smart Grid Communication by S. M. S. Mohammadabadi, M. Entezami, A. K. Moghaddam, M. Orangian, and S. Nejadshamsi

This work presents a framework for applying generative artificial intelligence to distributed learning in smart grid communication. By enabling local nodes to train lightweight models and contribute synthesized representations to a central server, the method reduces bandwidth demands and preserves data privacy. The study demonstrates how generative learning improves fault detection, load forecasting, and resilience of communication channels. Results highlight the potential of GenAI to balance efficiency, scalability, and security in future smart grid systems.

IoT-enabled Smart Energy Management Device for Optimal Scheduling of Distributed Energy Resources by B. K. Jha, A. Tiwari, R. B. Kuhada, and N. M. Pindoriya

This paper proposes an IoT-enabled device designed to manage distributed energy resources (DERs) through optimal scheduling. The device collects real-time data on consumption, pricing, and renewable generation to determine efficient usage patterns. An optimization algorithm schedules loads to minimize energy costs while maintaining reliability. Simulation results demonstrate improved demand-side management, reduced reliance on grid power, and enhanced integration of renewable sources into residential and commercial systems.

Enhancing Renewable Energy Hosting Capacity in Unbalanced Microgrids via Empowering Smart Inverters by H. H. Mousa, K. Mahmoud, and M. Lehtonen

This study investigates how advanced control strategies in smart inverters can increase the renewable hosting capacity of unbalanced microgrids. By dynamically compensating voltage and reactive power imbalances, smart inverters improve power quality and stability. The paper models different microgrid scenarios and demonstrates that inverter-based solutions outperform traditional approaches in mitigating fluctuations. The results provide a pathway toward higher penetration of renewable energy while maintaining grid stability.

An Energy Management System for Microgrids Incorporating Machine Learning, Distributed Energy Resources, and Storage by M. Aruna, S. M. S. Ali, D. Sarathy, M. Manu, L. M. Rao, and Y. Gundraju

This paper introduces an energy management system (EMS) that leverages machine learning techniques to optimize microgrid performance. The system coordinates distributedenergy resources and storage devices to balance supply and demand in real-time. A predictive model forecasts load and renewable generation, enabling proactive scheduling of storage and generation units. Experimental results demonstrate improved reliability, cost reduction, and better utilization of renewable resources compared to conventional EMS approaches.

Automatic Design System with Generative Adversarial Network and Vision Transformer for Efficiency Optimization of Interior Permanent Magnet Synchronous Motor by Y.Shimizu

This work presents a design framework that integrates generative adversarial networks (GANs) with vision transformers (ViTs) to optimize the efficiency of interior permanent magnet synchronous motors (IPMSMs). The GAN generates candidate motor designs, while the ViT evaluates design features and predicts performance metrics. The combined model iteratively improves motor structures for higher efficiency and reduced energy loss. The study demonstrates the viability of AI-driven motor design automation for industrial applications.

III. EXISTING SYSTEM

The existing systems for quiz generation and assessment largely depend on manual or semi-automated methods, which present several limitations in terms of scalability, personalization, and efficiency. Traditionally, educators invest significant time and effort in curating questions, formatting assessments, and ensuring content relevance to specific learning objectives. Even digital learning platforms that offer quiz features often rely on predefined question banks, which lack adaptability and contextual alignment with user-specific content. These systems may include limited AI integration, resulting in generic or repeated questions that do not meet varied learning needs. Additionally, current solutions may not support dynamic content input like PDFs, nor do they offer real-time quiz generation tailored to the uploaded material.

Some platforms offer basic MCQ creation tools, but these are not fully automated, require human input at multiple stages, and lack semantic understanding of the subject matter. This often leads to inconsistent quality and increased workload for educators. Furthermore, user interfaces in many existing systems are not interactive or engaging, leading to decreased motivation for learners. Security and role-based access control features (admin vs. user) are also minimal or absent in several implementations.

Existing systems typically require educators to manually draft, edit, and format multiple-choice questions, which is time-consuming and inefficient. Most platforms rely on fixed question banks and cannot dynamically generate questions based on custom input like uploaded PDFs or recent study materials. Current systems do not tailor questions based on subject difficulty or user level, resulting in generic assessments that may not suit individual learning needs. Many platforms cannot generate questions instantly or automatically using AI.This delays quiz preparation and reduces flexibility. Some existing systems have poor user interfaces and lack engaging visuals, transitions, or animations, which can affect learner engagement and experience. Role-based access (admin vs. user) is often not implemented, which may compromise control over content and data access. Evaluation in traditional systems is often basic, lacking detailed feedback, analysis, or explanations for correct/incorrect answers. Manual systems struggle to handle large user bases or bulk quiz generation, making them unsuitable for institutions or large-scale deployments.

IV. PROPOSED SYSTEM

A. System Overview

The proposed system introduces an AI-driven adaptive energy optimization framework for smart microgrids using Generative Adversarial Networks (GANs). This system is designed to improve energy forecasting accuracy, optimize energy distribution, and efficiently manage renewable energy sources such as solar and wind. By using advanced deep learning techniques, the proposed model can analyze complex energy consumption patterns and generate realistic synthetic data to enhance prediction performance.

Data Collection Energy data is collected from different sources such as solar panels, wind turbines, smart meters, and energy storage systems.

Data Pre-processing The collected data is cleaned, normalized, and prepared for model training.GAN

Model Training The Generator creates synthetic energy demand and generation data, while the Discriminator evaluates whether the data is real or generated.

GAN Model Training The Generator creates synthetic energy demand and generation data, while the Discriminator evaluates whether the data is real or generated.

Energy Forecasting The trained GAN model predicts future energy demand and renewable energy generation patterns.

Energy Optimization The system analyzes predicted data and determines the optimal energy distribution strategy.

Energy Management Energy is efficiently allocated between generation units, storage systems, and consumer loads.

Performance Monitoring The system continuously monitors microgrid performance and updates the model for real-time adaptive optimization.

The main goal of the proposed system is to develop an intelligent and adaptive energy management framework for smart microgrids using Artificial Intelligence and Generative Adversarial Networks (GANs). The system aims to improve energy forecasting accuracy, optimize the use of renewable energy resources, and ensure efficient energy distribution within the microgrid.

Significantly reduces time for both educators and learners by instantly creating subject-relevant quizzes with just a document upload. Ensures high-quality, relevant, and context-aware questions tailored to specific subjects and difficulty levels using advanced language models. Allows users to select subject areas, question count, and difficulty, offering a personalized quiz experience. Built with Django and Tailwind CSS, the system provides a sleek, animated, and responsive interface that enhances user engagement. Includes secure login and registration for users and admins, ensuring data privacy and access control. Provides immediate quiz results with detailed feedback, helping learners identify strengths and weaknesses. Suitable for schools, colleges, training centers, and self-learners, making it a versatile educational tool. Uploaded documents can be reused to create different quizzes based on selected parameters, making the system highly flexible.

B.ALGORITHMS:

The proposed system uses advanced Artificial Intelligence (AI) and Deep Learning algorithms to improve energy forecasting and optimization in smart microgrids. The main algorithm used in this project is the Generative Adversarial Network (GAN) along with supporting machine learning techniques for data processing and prediction.

Algorithms used in this project include: Generative Adversarial Network (GAN):GAN is the primary algorithm used in this project. It consists of two neural networks called the Generator and the Discriminator. The generator creates synthetic energy data such as demand and generation patterns, while the discriminator evaluates whether the generated data is real or fake. This adversarial learning process improves forecasting accuracy and helps optimize energy management. Artificial Neural Network (ANN): ANN is used for learning complex patterns in energy consumption and generation data. It helps in improving prediction performance for microgrid energy management. Long Short-Term Memory (LSTM): LSTM, a type of recurrent neural network, is used for time-series forecasting of energy demand and renewable energy generation since energy data is sequential and time-dependent. Optimization Techniques: Optimization algorithms are used to determine the best energy distribution strategy between renewable sources, storage systems, and consumer demand

These algorithms work together to create an intelligent and adaptive energy optimization system for efficient smart microgrid operation.

C.ANALYSIS:

System analysis is an important phase in the development of any project. It involves studying the existing system, identifying its limitations, and understanding the requirements needed to develop an improved system. In the context of smart microgrids, system analysis focuses on evaluating current energy management methods and identifying challenges related to renewable energy integration, forecasting accuracy, and energy distribution.

The increasing use of renewable energy sources such as solar and wind has made energy management more complex due to their intermittent and unpredictable nature. Traditional energy optimization methods often fail to effectively manage these fluctuations, which can lead to inefficiencies in energy utilization and reduced grid stability.

Therefore, the analysis phase helps in understanding the need for an advanced AI-based approach that can handle dynamic energy patterns and improve decision-making. By analyzing system requirements, data availability, and operational challenges, an effective framework can be designed to enhance energy forecasting, optimize energy distribution, and ensure reliable smart microgrid operations.

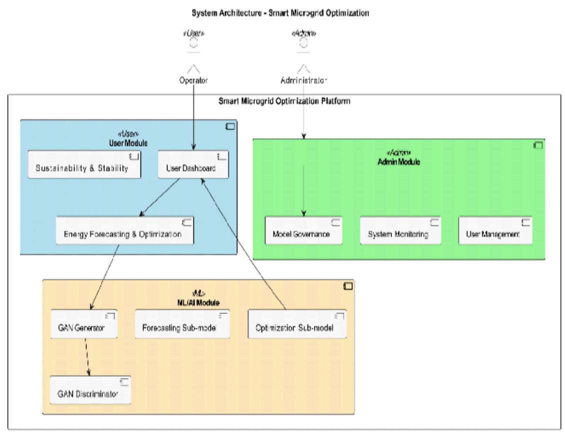

Fig. 1.System architecture

D. System Implementation

The implementation and results section of this project describes the practical development and performance evaluation of the proposed AI-driven energy optimization system for smart microgrids using Generative Adversarial Networks (GANs). This section focuses on how the theoretical model is transformed into a working system and how effectively it achieves the desired outcomes.

The implementation involves designing and training a GAN model using historical energy consumption and generation data. The system is developed using Python and deep learning libraries to simulate real-world microgrid conditions. Key processes include data preprocessing, model training, prediction generation, and optimization of energy usage based on the generated outputs.

After implementation, the system is evaluated through various performance metrics and visualizations. The results demonstrate the ability of the model to generate realistic energy demand patterns and provide accurate predictions. These predictions are then used to optimize load distribution, reduce peak demand, and improve the utilization of renewable energy sources.

Overall, this section highlights the effectiveness, accuracy, and practical applicability of the proposed system in enhancing smart microgrid performance and achieving energy efficiency.

User Module

Admin Module

Machine Learning (AI) Module

User Module:

The User Module acts as the primary interface for microgrid operators, engineers, and energy managers, providing secure access to AI-driven optimization tools that enhance smart microgrid performance. Users register through a secure portal with credentials such as name, email, and organizational role, and accounts are activated by an Admin to ensure only authorized personnel can access the platform. After login, users are directed to a central dashboard designed for interaction with predictive and optimization tools developed from real-world microgrid datasets, as described in the base paper.

A key feature of this module is the Energy Forecasting and Optimization Interface, where users can input operational parameters (e.g., solar PV output, wind generation, load demand, and batterycapacity) to obtain GAN-powered predictions of future demand and supply. The interface also provides optimization results, such as recommended charging/discharging cycles for batteries and grid import/export strategies. Another significant feature is the Sustainability and Stability Page, which assesses metrics such as cost reduction, grid stability (voltage fluctuations), and peak load stress under different operational conditions. Model performance indicators, such as forecasting accuracy improvements, cost savings, and storage efficiency, are displayed to promote transparency and build confidence in AI-driven decision-making. This empowers users to make data-driven operational adjustments, improving energy sustainability and resilience in microgrids.

Admin Module:

The Admin Module is designed to manage system integrity, user access, and AI model governance within the microgrid optimization platform. Admins, typically senior energy managers or researchers, log in via a dedicated portal secured with multi-layer authentication. Once authenticated, they access anAdmin Dashboard that displays key system statistics, including active users, forecasting tasks completed, real-time grid optimization status, and GAN model performance metrics such as improvements in Mean Absolute Error (MAE) and reductions in energy costs.

Admins are responsible for activating and managing user accounts, assigning roles, and controlling access to sensitive operational datasets. They also oversee model management by incorporating updated microgrid datasets, refining GAN hyperparameters, or adding new optimization features such as hydrogen storage integration. Activity logs, audit trails, and compliance monitoring ensure accountability and ethical use of AI-driven decisions in energy workflows. Furthermore, Admins can schedule maintenance tasks, validate system outputs, and evaluate enhancements such as the inclusion of cyber-resilience metrics or federated learning for distributed microgrids. By maintaining governance, scalability, and performance, the Admin Module ensures

Machine Learning (AI) Module:

The Machine Learning Module forms the intelligent core of the platform, utilizing GANs to enhance forecasting accuracy and optimize real-time energy dispatch in smart microgrids. Built on experimental datasets integrating solar PV, wind, battery storage, and load demand, this module applies adversarial learning between a Generator, which produces synthetic demand and generation profiles, and a Discriminator, which evaluates their realism. This allows the system to improve prediction precision, overcome data scarcity, and adapt to fluctuating renewable energy conditions.

The forecasting sub-model predicts demand and generation patterns, while the optimization sub-model determines efficient dispatch strategies, including battery charge/discharge schedules and grid import/export decisions. The GAN-based system significantly outperforms conventional methods such as LSTM networks, achieving improvements in forecast accuracy (24.7%), reduced energy storage inefficiencies (14.8%), and enhanced grid stability with measurable reductions in voltage fluctuations and peak load stress, as highlighted in the paper.

To enhance interpretability, explainable AI methods such as SHAP can be integrated in future versions to highlight the influence of key features (e.g., weather conditions, load variations, and storage state) on GAN outputs. The module also supports scalability for larger datasets and real-time adaptability, with potential enhancements including ensemble approaches or reinforcement learning for adaptive microgrid control. By combining predictive accuracy with optimization intelligence, this module drives operational efficiency, resilience, and sustainability in next-generation energy systems.

IV EXPERIMENTAL SETUP

A. System Environment

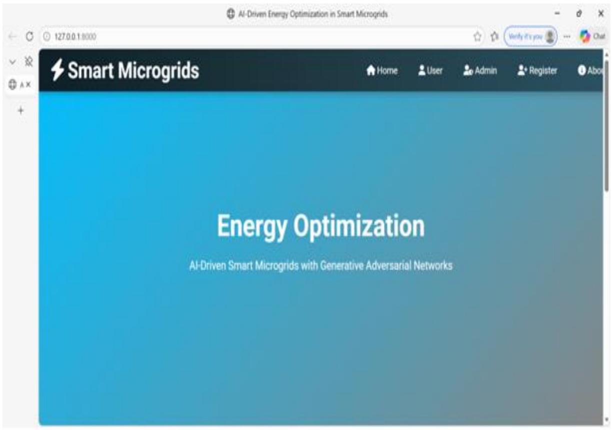

Figure 2. Home page for Smart Microgrids

The Home Page is the main entry point of the AI-Driven Energy Optimization in Smart Microgrids Using GANs web application. It provides an overview of the system and guides users to access different functionalities.

The page includes a brief introduction to the project, highlighting its purpose of optimizing energy usage using Artificial Intelligence and Generative Adversarial Networks (GANs). It showcases key features such as energy prediction, optimization, and visualization.

Navigation options such as Login, Register, and Admin Access are clearly provided for easy access. The page may also include images or banners related to smart grids and renewable energy to enhance visual appeal.

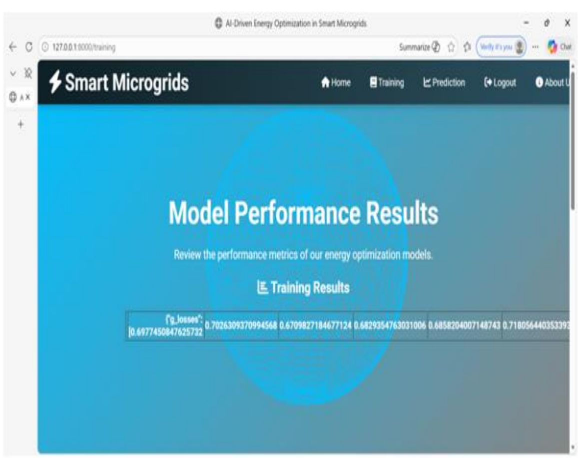

Figure 3 User Dashboard page for Smart Microgrids

The User Dashboard in the Training Results section displays the performance of the GAN model during the training phase. It provides visual insights such as Generator loss and Discriminator loss graphs, showing how the model improves over time. Users can monitor training progress through metrics like epochs, accuracy, and loss values. This helps in understanding whether the model is learning effectively and producing reliable results. The dashboard presents this information in an easy-to-read graphical format, enabling users to analyze model behavior and ensure proper training before proceeding to prediction and optimization stages.

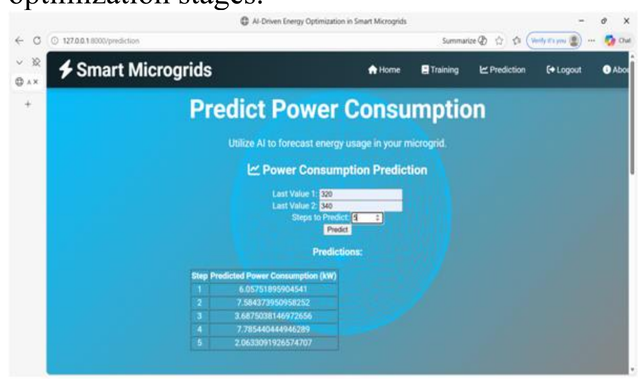

Figure 5.4.7 Prediction page for Smart Microgrids

The Prediction module is the core intelligence of the system, powered by Generative Adversarial Networks. It analyzes historical and real-time data to forecast future energy demand and generation patterns. The module can predict peak load times, detect anomalies, and suggest optimal control actions such as load balancing and battery usage. This helps improve efficiency, reduce energy waste, and maintain grid stability.

VI CONCLUSION

The integration of AI-driven adaptive energy optimization in smart microgrids presents a transformative approach to managing distributed energy resources efficiently. By leveraging Generative

Adversarial Networks (GANs), this study demonstrates the potential to accurately model, predict, and optimize energy generation and consumption patterns under dynamic and uncertain conditions. The GAN-based framework not only enhances forecasting precision but also enables real-time decision-making for load balancing, demand response, and energy storage management.

The results indicate that AI-powered adaptive strategies can significantly improve energy efficiency, grid reliability, and operational flexibility in microgrids, while minimizing costs and reducing reliance on conventional energy sources. Moreover, the generative nature of GANs allows the system to simulate diverse scenarios and adapt to unforeseen fluctuations, making microgrids more resilient to variability in renewable energy supply.

In summary, the adoption of GAN-based adaptive energy management provides a robust pathway toward sustainable, intelligent, and resilient microgrid operations, paving the way for broader applications in smart grids and next-generation energy systems..

References

1. S. M. S. Mohammadabadi, M. Entezami, A. K. Moghaddam, M.Orangian, and S. Nejadshamsi, "Generative Artificial Intelligence For Distributed Learning to Enhance Smart Grid Communication," JInternational Journal of Intelligent Networks, 2024.

2. B. K. Jha, A. Tiwari, R. B. Kuhada, and N. M. Pindoriya, "IoT-enabledSmart Energy Management Device for Optimal Scheduling of Distributed Energy Resources," J Electric Power Systems Research, vol. 229, p. 110121, 2024.

H. H. Mousa, K. Mahmoud, and M. Lehtonen, "Enhancing RenewableEnergy Hosting Capacity in Unbalanced Microgrids via Empowering Smart Inverters," J IEEE Access, 2025.

3. M. Aruna, S. M. S. Ali, D. Sarathy, M. Manu, L. M. Rao, and Y.Gundraju, "An energy management system for microgridsincorporating machine learning, distributed energy resources, and storage," in Challenges in Information, Communication and Computing Technology: CRC Press, 2025, pp. 281-285.

4. Y. Shimizu, "Automatic Design System with Generative AdversarialNetwork and Vision Transformer for Efficiency Optimization of Interior Permanent Magnet Synchronous Motor," J IEEE Transactions on Industrial Electronics, 2024.

5. P. Li, Y. Shen, Y. Shang, M. J. I. G. Alhazmi, Transmission, and Distribution, "Innovative distribution network design using GAN-based distributionally robust optimization for DG planning," J IET Generation, Transmission Distribution, vol. 19, no. 1, p. e13350, 2025.

6. P. Yang, S. Li, S. Qin, L. Wang, M. Hu, and F. Yang, "Smart grid enterprise decision-making and economic benefit analysis based onLSTM-GAN and edge computing algorithm," J Alexandria Engineering Journal, vol. 104, pp. 314-327, 2024.

7.M. B. Abdelghany, A. Al-Durra, H. H. Zeineldin, and F. Gao, "A Coordinated Multitimescale Model Predictive Control for OutputPower Smoothing in Hybrid Microgrid Incorporating Hydrogen Energy Storage," J IEEE Transactions on Industrial Informatics, 2024.