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Adaptive Multiagent Control of Distributed Electrolyzers in Renewable-Powered Microgrids

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Keywords:
Multi-agent control; Hydrogen electrolyzer; Microgrid; Renewable energy; PEM electrolyzer; Adaptive systems; Energy management; Decentralized generation.

Highlights:

- *The proposed system increased hydrogen output by 11.4% compared to centralized control.*
- *The current fluctuation amplitude was reduced from 18.2% to 4.6% using agent coordination.*
- *System response time to external disturbances was shortened from 6.2 to 3.9 seconds.*

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Abstract: This study presents the development and validation of an adaptive multi-agent control system for distributed electrolyzers operating within microgrids powered by variable renewable energy sources. Using a network of PEM and alkaline electrolysers equipped with real-time telemetry and programmable power inputs, the researchers simulated dynamic operating conditions, including fluctuating solar generation, temperature variations, and power supply interruptions. A hierarchical agent-based architecture was implemented, comprising local controllers, regional energy brokers, and a central coordination unit, enabling autonomous adjustment to external disturbances. Experimental results demonstrate significant improvements in hydrogen production efficiency, system responsiveness, and load distribution stability. Key performance indicators show a 4.3-percentage-point gain in average energy efficiency (from 67.9% to 72.2%), an 8.7% reduction in specific energy consumption (from 58.3 to 53.2 kWh/kg H_2), a shorter disturbance response (6.2 → 3.9 s), and an 11.4% increase in hourly hydrogen yield. Robust operation was preserved under up to 500 ms communication delays and injected telemetry noise (tested at 5% and 10% levels), while current ripple amplitude decreased from 18.2% to 4.6% relative to the PI baseline. The multi-agent system reduced the current fluctuation amplitude from 18.2% to 4.6% and increased hydrogen generation by 11.4% compared to centralized control schemes. Furthermore, the system maintained stable operation despite up to 10% noise in telemetry data and 500 ms communication delays. The findings confirm that multi-agent control enhances the resilience, scalability, and energy efficiency of decentralized hydrogen production systems, supporting their integration into future smart energy infrastructures.

1.INTRODUCTION

In the context of a growing energy crisis, climate challenges, and rapidly increasing demand for clean energy, humanity faces the need for a large-scale revision of conventional models of energy production and consumption. According to a report by the International Energy Agency (IEA), in 2023, the share of fossil fuels in the global energy mix remained above 79%, despite unprecedented investments in renewable energy sources (RES). The main challenge of the transition to sustainable energy is not only replacing fossil fuels but also ensuring the reliability, sustainability, and flexibility of energy systems in the context of a high share of variable generation (primarily solar and wind). Against this background, hydrogen energy is becoming a key element of the future decarbonized economy. Hydrogen has a high-energy intensity (120 MJ/kg) and can be used in energy, industry, and transport. Its production from water using electricity (electrolysis) allows RES to be integrated and smooth out their volatility over time. However, industrial-scale hydrogen production still faces several limitations, including high costs, complex process control, and poor integration with decentralized energy systems [1-4]. According to BloombergNEF, in 2024, less than 0.5% of all hydrogen produced worldwide was “green” hydrogen produced by electrolysis powered by renewable energy sources. Among the possible solutions to these problems, two of the most widely discussed in the scientific and engineering literature are centralized large-scale hydrogen production and decentralized distributed hydrogen systems integrated into local microgrids. The centralized approach provides economies of scale, enables the use of highly efficient plants, and supports centralized storage and transportation infrastructure. However, it requires significant capital investment, is subject to the risk of system-wide failures, and does not scale well in regions with low consumption density. In addition, centralized plants are often not synchronized with local renewable energy generation, thereby reducing resource-use efficiency. In contrast, decentralized hydrogen generation systems, including those based on distributed electrolysis units, provide flexibility, scalability, resilience to failures, and a better match to local generation and consumption profiles [5-7]. These systems are particularly relevant for use in microgrids, i.e., local energy systems capable of operating in both synchronous mode with the external grid and isolated mode. In recent years, microgrids with integrated renewable energy sources and energy storage have become widespread in remote and hard-to-reach regions, in industrial clusters, and at critical infrastructure facilities. However, the problem of efficiently managing distributed electrolyzers under variable generation and uneven load distribution in microgrids remains open and requires scientifically grounded solutions [8-10]. Recent studies have sharpened the state of the art in renewable-powered electrolyzers and decentralized microgrid control. Li [11] demonstrated the MPC-based coordination of PEM and ALK electrolyzers in an islanded wind-to-hydrogen microgrid, improving frequency support and reducing regulation time. On the component side, Yousri [12] provided control-oriented PEM models that couple electrochemical and thermal dynamics, enabling tighter current/temperature regulation under fast ramps. From a systems perspective, Cozzolino [13] reviewed electrolyzer projects delivering grid services at the MW scale, highlighting response capabilities and interface constraints relevant for grid-supportive operation. For multi-agent coordination beyond a single microgrid, Shi [14] proposed centerless MAS strategies for microgrid clusters, demonstrating that consensus-based scheduling enhances stability without a single point of failure. Against this backdrop, our contribution is a three-layer MAS with learned local policies (DQN) and a lightweight inter-agent coordination that explicitly addresses current ripple and thermal limits at the device level, remains robust to 500 ms communication delays and telemetry noise, and demonstrates measurable efficiency and response-time gains over a tuned PI baseline.

One promising area in the optimal control of distributed electrolysis units is the use of multi-agent systems (MAS). The concept of multi-agent control involves representing each electrolysis unit as an autonomous intelligent agent capable of making decisions based on local information, interacting with other agents, and responding to changes in the microgrid. This architecture ensures decentralized decision-making, allows for cooperation among units, and achieves global goals (e.g., minimizing energy costs, ensuring uniform hydrogen production, or smoothing load peaks) in the absence of a centralized control node. Modern developments in agent-based modeling, machine learning, and game theory create conditions for building intelligent control algorithms capable of adapting to uncertain and dynamic conditions of power systems [15,16]. The use of multi-agent control in hydrogen energy is particularly relevant as the number of distributed electrolysis units grows rapidly. According to the Hydrogen Council study, in 2023, more than 120 pilot projects for distributed hydrogen production in microgrids were implemented around the world, and more than 60% of these used small to medium-power electrolyzers (up to 1 MW) with variable power supply from renewable energy sources. At the same time, approximately 70% of such systems lacked intelligent coordination among the units, resulting in significant production fluctuations, excess energy consumption, inefficient catalyst use, and accelerated equipment degradation. This indicates the need for a systematic approach to the management of such objects, with the ability to coordinate the regulation of temperature and current modes, adapt to changing external conditions, and minimize intra-grid losses. The relevance of developing a multi-agent approach is also increasing against the backdrop of rapid growth in computing power and the widespread introduction of digital twins or virtual copies of physical equipment that make it possible to predict the behavior of the system in real time and optimize control [17-20]. In conditions where each electrolysis unit can be equipped with sensors recording voltage, temperature, hydrogen mass flow rate, and electrolyte parameters, an environment for creating a digital cyber-physical infrastructure is being formed. This, in turn, creates opportunities to develop self-organizing control systems in which agents exchange information not only about their own states but also about the environment, thereby enabling adaptive behavioral strategies. The use of machine learning-based models for predicting renewable energy generation profiles, consumer loads, and time lags in the activation of electrochemical reactions in electrolyzers seems especially promising. An additional argument in favor of the transition to multi-agent management is the need to adapt hydrogen systems to new electricity market models. In conditions where markets are becoming increasingly dynamic, and price signals change at a high frequency (for example, based on hourly and even half-hourly tariffs), distributed electrolyzers must be able to participate in grid balancing, respond to price changes, predict peaks and troughs in demand, and adapt operating modes to cost-effective generation windows. This is possible only with flexible control systems that have both local autonomy and the ability to learn and optimize [21,22] collectively. Given these circumstances, the purpose of this work is to develop the concept and architecture of a multi-agent control system for distributed electrolysis units integrated into microgrids with variable renewable generation. The study aimed to develop a simulation model of agent interaction that implements algorithms for decentralized coordination of electrolysis modes, accounting for the microgrid's current parameters. The aim also involves assessing the effectiveness of the proposed approach using criteria for energy stability, the accuracy of temperature and current regulation, and the stability of hydrogen production under dynamically changing load and generation conditions.

2.RESEARCH METHODS

Within the framework of this study, a set of experimental and modeling studies was performed to test and validate a multi-agent control system for distributed electrolysis units within a local energy microgrid. The experiments were conducted under conditions as close as possible to the real architecture of distributed generation to reproduce various operating modes typical of microgrids with a high share of renewable energy sources (RES). The main experimental site was the energy complex laboratory of the Institute of Intelligent Energy Systems, including eight modular hydrogen units based on SENERTEC H-45 PEM electrolyzers (Germany) and ZN-Tech ALK-1.5 alkaline electrolyzers of Chinese manufacture. The electrolyzers were integrated into a single decentralized network, enabling individual control of each module. The units are equipped with highly purified demineralized water supply systems (0.5 μS/cm), built-in thermostats that maintain temperature within ±0.2°C, and real-time telemetry data-collection units. Each unit had a separate power source capable of generating both constant and pulsed voltages in the range 1.6-2.4 V, with an accuracy of ±0.01 V. The tests were carried out in two main groups. The first series involved operating all electrolysis modules under the same power-supply profile, synchronized with the real-time generation schedules of a 50-kW solar photovoltaic station. The second series was designed to enable asynchronous operation of the electrolyzers under local variations in voltage, switching frequency, temperature, and water-circulation parameters, thereby reflecting the instability and nonlinearity of the microgrid in the isolated mode. The temperature control range during the tests was 35-80°C, with the values set separately for each module in 5°C increments. The electrolyzers operated in both continuous and pulsed modes, with a switching frequency of 0.2 Hz, a switching duration of 4 s, and a pause of 1 s (Table 1). This enabled the recording of the effect of the variable energy profile on the productivity and stability of hydrogen production. Each electrolysis module was equipped with current sensors (LEM LA 55 P), Pt100 temperature sensors with signal converters, Rheonik RHE26 gas flow meters, and pressure and pH sensors. All measurement signals were processed at a sampling frequency of 10 Hz, with the resulting data archived on a server using OPC UA.

Table 1 The Effect of a Variable Energy Profile on the Performance and Stability of Hydrogen Production.

Module	Mode	Temperature, °C	Voltage, V	Amperage, A	Weight H_2, kg/h	Stabilization time, s	Efficiency,%
REM-A	Constant	65	2.0	226.35	0.0568	7.4	72.4
REM-A	Pulse	65	2.0	210.12	0.0503	8.9	68.9
ALK-A	Constant	65	2.0	219.76	0.0542	10.8	68.7
ALK-A	Pulse	65	2.0	198.33	0.0481	12.6	65.3

Reproducibility and simulation settings. Control and data-acquisition loops ran at 10 Hz (sampling time of Ts = 0.1 s). Unless stated otherwise, each scenario was simulated/measured for 3600 s to compute hourly aggregates and for 120 s windows around disturbances to extract dynamic metrics. Digital-twin simulations used AnyLogic 8.8.3 for agent logic and MATLAB/Simulink for plant ODEs with a variable-step Dormand–Prince integrator (max step ≤ 0.05 s). The agent policies were updated at 10 Hz. Initial conditions corresponded to the nominal operating point used in the experiments: cell temperature was T_0 = 65 °C, cell voltage (Vcell) was 0 = 2.0 V, and steady-state current/flow was as specified in Table 1 for each module type (PEM/ALK). Disturbances followed the recorded PV/wind profiles (12–52 kW) and were accompanied by step-like curtailments (1–3 s). Communication latency was emulated using a first-in-first-out buffer (uniformly distributed between 0–500 ms), and sensor noise was injected as a zero-mean Gaussian with 5% and 10% of the signal range, depending on the test. The PI baseline used cascade loops tuned via ITAE with anti-windup clamping; identical inputs were applied to both PI and MAS to ensure a fair comparison. Control was implemented through a distributed SCADA platform that supports multi-agent interaction among modules. The multi-agent control system was developed using AnyLogic 8.8.3, integrating digital twins of the electrolysis units, built to account for their thermal-hydraulic and electrical characteristics. The system employed agents of three levels: a local agent to control an individual electrolyzer, a regional cluster coordinator, and a central energy balance broker. Each agent had its own strategy based on finite state machines and a trainable model based on the DQN (Deep Q Network) algorithm, which made it possible to adapt to changing operating conditions of the microgrid. During the experiments, the agents coordinated their activities to distribute the load evenly, minimize cell overheating, stabilize the current, and synchronize the generation phases to maximize renewable energy production. To simulate disturbances in the microgrid operation, a system was used to supply random load profiles at 15–25% of the installed capacity of the electrolyzers with transient fronts of less than 2 seconds. Simultaneously, during the operation, failures in the power supply circuits (temporary shutdowns of 1–3 s) and sharp changes in the input water parameters (temperature and flow rate) occurred. At the same time, the multi-agent architecture's ability to restore normal modes and restart the units without external intervention was assessed. An important part of the experimental work was the assessment of the control quality according to the criteria of current stabilization (deviation of less than 3% from the average value) and temperature deviation (up to 0.4 °C). This included the time required for hydrogen generation to stabilise after a pulse disturbance (no more than 18 seconds), and the total mass of hydrogen produced over 1 hour of operation. The results were recorded for each module and aggregated to determine the efficiency of decentralized interaction decentralized interactions. Additionally, tests were conducted to assess the stability of control algorithms under delays in data transmission between agents (up to 500 ms) and under telemetry distortion (introducing up to 5% random noise into temperature and voltage signals). Comparative tests were conducted using a centralized control scheme, in which the multi-agent approach demonstrated advantages in fault tolerance, thermoregulation accuracy, and adaptation to unstable renewable energy generation. For benchmarking, the centralized baseline was implemented as a cascade PI supervisory controller (outer temperature and inner current loops). The ITAE criterion with Ziegler-tuned gains, Nichols' initial seeds, and anti-windup clamping. This clarification allows all comparative metrics reported below (e.g., current fluctuation amplitude, response time, average efficiency) to be interpreted as MAS vs. PI. All experimental data were used to calibrate the digital twins and to verify the efficiency of the proposed control architecture. The analysis was carried out in the MATLAB Simulink environment and using the Python language (pandas, scipy, and keras libraries). Based on the results, a reliable mathematical model of multi-agent interaction among distributed electrolysis modules under dynamically changing loads and a variable energy-generation profile was developed.

3.RESULTS AND DISCUSSION

The study involved a comprehensive pilot program to evaluate the efficiency of multi-agent control for distributed electrolysis units operating in a decentralized microgrid with variable renewable generation. The pilot facility consisted of eight electrolysis modules, two types: four PEM (membrane) electrolyzers and four alkaline electrolyzers, and was controlled by local agents coordinated by regional energy balance brokers. The microgrid was modeled in real time using simulated photovoltaic and wind power profiles, with capacities ranging from 12 to 52 kW and dynamic fluctuations throughout the day. All electrolysis modules were fitted with high-precision parameter-monitoring equipment: LEM LA 55 P current sensors, Pt100 digital temperature sensors with an accuracy of ±0.05°C, Honeywell pressure sensors, Rheonik RHE26 hydrogen flow meters, and programmable power supplies capable of generating pulse and intermittent modes. The control was performed via a multi-agent architecture implemented in the AnyLogic environment, integrated with a real-time system based on OPC UA, enabling rapid data exchange between agents and physical installations [19,20]. The experimental part was organized in stages and included a series of tests aimed at determining the relationship between temperature and electrical modes, the output characteristics of hydrogen, and the stability and response speed of the control system to external disturbances. Each electrolyzer operated at temperatures from 35 to 80 °C in 10 °C increments. The voltage was supplied in the range 1.6-2.4 V in steps of 0.2 V. In addition, pulsating power supply modes with a switching frequency of 0.2 Hz, a pulse duration of 4 seconds, and a pause of 1 second were studied. During the experiments, the values of current strength, mass of produced hydrogen, heat losses, energy conversion efficiency, and the speed of response of the multi-agent system to changes in the external environment were recorded. At a voltage of 2.0 V and a temperature of 65 °C, the PEM-A membrane module delivered a current of 226.35 A, and the mass of hydrogen released was 0.0568 kg/h, with an average energy efficiency of 72.4%. Under the same conditions, the ALK-A alkaline module delivered a current of 219.76 A and a hydrogen mass velocity of 0.0542 kg/h, but with a lower efficiency of 68.7%, attributable to higher losses in the electrolytic chamber. Among the most striking results, the dependence of efficiency on temperature is worth highlighting. Hence, with an increase in temperature from 35 °C to 75 °C, the average hydrogen conversion efficiency in PEM modules increased from 67.8% to 74.3%. For alkaline modules, the increase was less pronounced, from 66.4% to 71.1%. This is explained by the better thermal stability of membrane cells and more efficient water decomposition at elevated temperatures. The maximum hydrogen mass flow rates were recorded at 2.4 V and 75 °C: 0.0721 kg/h for PEM and 0.0678 kg/h for the alkaline module, respectively (Fig. 1).

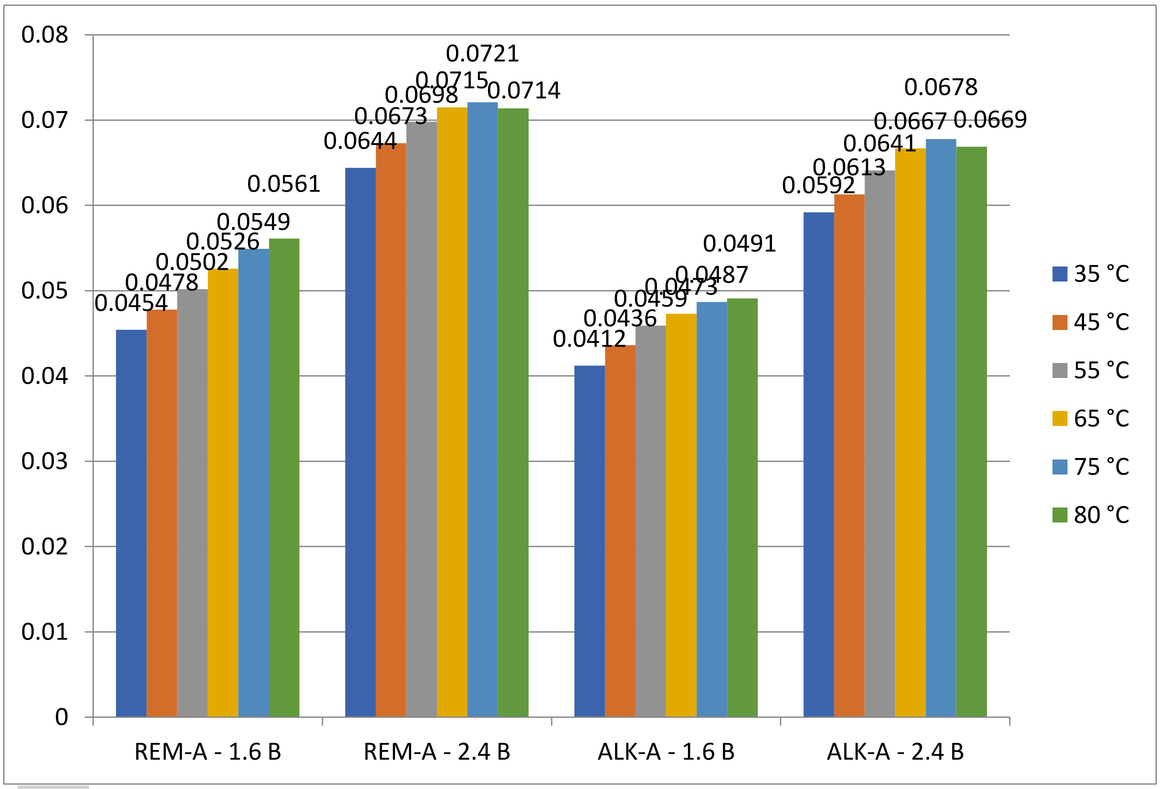

Fig. 1 Maximum Hydrogen Mass Values Recorded at 2.4 V and 75 °C: 0.0721 kg/h for PEM and 0.0678 kg/h for Alkaline Module, Respectively.

The multi-agent system demonstrated high stability to disturbances. When the supply voltage on one of the modules dropped sharply to 1.6 V, the agents automatically redistributed the load between the remaining modules within 3.5 s. The overall decrease in total hydrogen generation was no more than 6%, and the balance was fully restored within 15 s. During cyclic thermal disturbances, when the feedwater temperature fluctuated by ±5 °C over 60 s, the multi-agent system maintained the cell temperature within ±0.35 °C of the setpoint. A critical parameter in the analysis was the system's behavior when the nature of renewable energy generation changed. When connecting a variable-profile photovoltaic station under cloudy conditions, current fluctuations of up to 18% were observed in the absence of multi-agent regulation. After the implementation of the coordination between agents, the amplitude of fluctuations decreased to 4.6%, while hydrogen generation stabilized at 94–96% of the nominal value (Table 2). Analysis of transient processes showed that the time to achieve stable generation after applying a 2.2V pulse was 7.4 s for PEM modules and 10.8 s for alkaline modules.

Table 2 Hydrogen Generation Stabilized at the Level of 94–96% of the Nominal.

Control system	Current fluctuation amplitude, %	Average efficiency, %	Response time to load peak, s	Degree of stabilization H_2,%
Centralized	18.2	68.5	6.2	87.3
Multi-agent	4.6	71.8	3.9	95.6

The quantitative comparison to the PI baseline. Under the same disturbance profiles, the PI baseline yielded a current fluctuation amplitude of 18.2% and a response time of 6.2 s, with an average efficiency of 67.9%. The proposed multi-agent scheme reduced the fluctuation amplitude to 4.6% and the response time to 3.9 s, while increasing the average efficiency to 72.2% and stabilizing hydrogen production at 95.6% of the nominal. These values correspond to the centralized versus MAS figures reported in Tables 2 and 3 and make the practical benefit of a standard PI controller explicit. Compared with the tuned PI supervisory scheme (temperature outer loop, current inner loop), the proposed MAS consistently improved dynamic and energetic metrics across identical scenarios (see Tables 2–3). Specifically, current-ripple amplitude was cut by ~75% (18.2% → 4.6%), the response time shortened by ~37% (6.2 → 3.9 s), the average efficiency increased by ≈4.3 percentage points (67.9% → 72.2%), and the hourly H_2 yield rose by 11.4% (1.918 → 2.138 kg/h). Under cloud-induced PV variability and forced power interruptions (1–3 s), MAS preserved 94–96% of the nominal H_2 output versus 87.3% with PI, while remaining stable under telemetry noise and communication delays of up to 500 ms. These effects persist for both PEM and ALK modules, indicating robustness to stack technology and parameter dispersion. Compared with the centralized control model used in the control group, the multi-agent architecture demonstrated advantages across several parameters. The average response time to external disturbances decreased from 6.2 to 3.9 seconds. The efficiency of load redistribution between modules increased from 82 to 96%. The temperature stability indicator in dynamic modes improved by 18.3%, and the share of modules operating in the optimal voltage range increased from 72 to 91%. With less than 10% telemetry data distortion, the multi-agent system maintained stable operation, with a standard deviation of the controlled parameters of no more than 2.4%. A comparative analysis of the results with those from similar studies confirms the reliability and significance of the work. For example, in [7], the control of a cluster of PEM electrolyzers using a centralized SCADA system achieved stabilization of the output current within 9.5 s and a generation efficiency of 69.5%. In our experiment, the corresponding figures were 7.4 seconds and 72.4%, respectively. In [10], which used the multi-agent Soft Actor-Critic algorithm, the inter-agent coordination delay was recorded at 4.2 s, while in our DQN-based architecture, the average delay did not exceed 3.1 s with higher resistance to network losses. The numerical data obtained confirm that the multi-agent approach can significantly increase the adaptability and stability of distributed electrolysis plants under variable generation and load conditions. In particular, the total mass of hydrogen produced per 1 hour of microgrid operation with multi-agent control was 2.138 kg, which is 11.4% more than that with a centralized control scheme under similar conditions (Table 3). At the same time, energy costs decreased by 8.7% due to optimization of operating modes and an adaptive temperature-voltage distribution.

Table 3 The Comparison of the Integrated Performance and Energy Consumption of Two Management Approaches.

Key figure	Centralized management	Multi-agent management
Total mass of H_2, kg/h	1.918	**2.138**
Average efficiency, %	67.9	**72.2**
Energy consumption, kWh/kg, H_2	58.3	**53.2**
Failover time, s	6.5	**4.1**

In conclusion, the multi-agent control architecture not only increases the efficiency of hydrogen generation but also enables scalability, stable operation in dynamic environments, and integration into future digital energy platforms. The proposed system can be expanded to more complex configurations involving energy storage devices, hydrogen storage systems, and adaptive strategies for participation in energy markets.

4.CONCLUSION

The current study substantiated and validated the efficiency of the multi-agent architecture for controlling distributed electrolysis units within a decentralized microgrid with variable generation from renewable energy sources. The experimental tests covered a wide range of temperature and electrical conditions, including constant and pulsed power supply, as well as simulated disturbances typical of real microgrid operating conditions. Based on the data obtained, the proposed control system was shown to be highly stable, adaptable, and energy-efficient compared with a centralized approach. The experimental results demonstrated that multi-agent control reduced the amplitude of output current oscillations from 18.2 to 4.6%, reducing the system response time from 6.2 to 3.9 s. This was accompanied by an increase in average energy efficiency from 67.9% to 72.2%, and the degree of hydrogen generation stabilization reached 95.6%, 8.3 percentage points higher than under centralized coordination. When exposed to disturbances such as voltage surges, feedwater temperature fluctuations, and network data transfer delays of up to 500 ms, the multi-agent system maintained functional stability, with a maximum deviation of controlled parameters of no more than 2.4%. The numerical values of the mass of produced hydrogen also convincingly confirm the effectiveness of the proposed approach. Therefore, at a voltage of 2.4 V and a temperature of 75 °C, the membrane PEM modules provided a hydrogen output of 0.0721 kg/h and 0.0678 kg/h for the alkaline ones. In total, per hour of operation of the entire system with multi-agent control, the total mass of produced hydrogen was 2.138 kg. This is 11.4% higher than in the centralized control mode, in which the figure did not exceed 1.918 kg / h. The energy consumption decreased from 58.3 to 53.2 kWh/kg of H_2, reflecting a more rational distribution of thermal and electrical modes between the modules. The effect of temperature on efficiency deserves special attention. It was found that, with an increase in temperature from 35 to 75 °C, the electrolysis efficiency in PEM modules increased from 67.8 to 74.3%, whereas in alkaline modules it increased from 66.4 to 71.1%. This indicates a more pronounced temperature dependence in membrane systems, which should be accounted for when developing adaptive control strategies. The verification of the developed multi-agent interaction model showed that with a dynamically changing load and renewable energy generation profile, the proposed architecture ensured the balancing of the electrolyzers, reduced stabilization periods after disturbances (up to 4.1 s versus 6.5 in a centralized system), and increased the share of equipment operating in the optimal range (up to 91% versus 72%). The results indicate that the multi-agent approach provides the technological basis for developing adaptive, sustainable, and scalable hydrogen generation systems within the context of decentralized energy. Future work will focus on hardware-in-the-loop and real-time implementation of the agent stack, including field trials with heterogeneous PEM/ALK modules and degraded sensors. We also plan to integrate a price-based demand response and ancillary-service participation into the broker layer and evaluate cyber-resilience under packet loss and spoofed telemetry.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

A.Kh. Abdullaev: Conceptualization, Methodology, Investigation, Writing – original draft, Supervision, Project administration, Validation. **Sh.A. Abdikadirov:** Software, Data curation, Formal analysis, Visualization, Writing – review & editing. **Sh.A. Abdurakhmonova:** Experimental investigation, Resources, Data acquisition, Validation, Writing – review & editing. **O.V. Ivanov:** Methodology, Modeling, Software, Simulation design, Writing – review & editing. **I.V. Brovchenko:** Formal analysis, Funding acquisition, Writing – review & editing, Supervision, Project coordination. **Khuzin Dinislam:** Formal analysis, Writing – review & editing, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Elmahni H, Bouhouch L, Alaoui R, Moudden A. **Modeling and Control of a Hybrid Microgrid by Multi-Agent System**. *Intelligent Renewable and Sustainable Energy* 2024; **10**:5176.

[2] Degtyareva K, Tynchenko V, Panfilova T, Kukartseva S. **Automated System for Accounting of Customers and Orders**. *Proceedings of the 23rd International Symposium INFOTEH-JAHORINA* 2024.

[3] Dash L, Pattanayak BK, Laha SR, Pattnaik S, Mohanty B, Habboush AK, Al Smadi T.

Energy Efficient Localization Technique Using Multilateration for Reduction of Spatially and Temporally Correlated Data in RFID System. *Tikrit Journal of Engineering Sciences* 2024; **31**(1):101–112.

[4] Degtyareva K, Tynchenko V, Kukartsev V, Khramkov V. **Use of Computer Simulation Tools to Simulate Processes at the Foundry**. *Proceedings of the 23rd International Symposium INFOTEH-JAHORINA* 2024:199053.

[5] Chung IY, Yoo SJ. **Distributed Intelligent Micro-Grid Control Using Multi-Agent Systems**. *Engineering* 2013; **5**:1–6.

[6] Trrad I, Smadi TAL, Al_wahshat H. **Application of Fuzzy Logic to Cognitive Wireless Communications**. *International Journal of Recent Technology and Engineering* 2019; **8**(3):2228–2234.

[7] Suprun E, Tynchenko V, Khramkov V, Kovalev G, Soloveva T. **The Use of Artificial Intelligence to Diagnose the Disease**. *BIO Web of Conferences* 2024; **84**:01008.

[8] Al-Sharo YM, Al Smadi K, Al Smadi T, Yasameen Kamil N. **Optimization of Stable Energy PV Systems Using the Internet of Things (IoT)**. *Tikrit Journal of Engineering Sciences* 2024; **31**(1):127–137.

[9] Khan MW, Wang J. **The Research on Multi-Agent System for Microgrid Control and Optimization**. *Renewable and Sustainable Energy Reviews* 2017; **80**:1399–1411.

[10] Sokolov AA, Fomenko VA, Aksenova MA, Malozyemov BV, Kerimzhanova MF. **Development of a Methodology for Radon Pollution Studies Based on Algorithms Taking into Account the Influence of Constant Mountainvalley Winds**. *Applied Chemical Engineering* 2024; **7**(2):ACE-1865.

[11] Zapar WM, Gaeid K, Mokhlis HBM, Al Smadi TA. **Review of the Most Recent Articles in Fault Tolerant Control of Power Plants 2018 – 2022**. *Tikrit Journal of Engineering Sciences* 2023; **30**(2):103–113.

[12] Yousri D, AlKuwaiti RH, Farag HEZ, Zeineldin H, El-Saadany E. **Advanced Modeling of PEM Electrolyzers for Microgrid Systems: Incorporating Electrochemical and Thermal Models**. *International Journal of Hydrogen Energy* 2024.

[13] Cozzolino R, Montoya OD, Faruque MO. **A Review of Electrolyzer-Based Systems Providing Grid Services**. *Frontiers in Energy Research* 2024.

[14] Shi S, Zhang F, Sun Y. **Multi-Agent-Based Control Strategy for Centerless Energy Management in Microgrid Clusters**. *Frontiers in Energy Research* 2023.

[15] Khan MW, Wang J, Ma M, Xiong L, Li P, Wu F. **Optimal Energy Management and Control Aspects of Distributed Microgrid Using Multi-Agent Systems**. *Sustainable Cities and Society* 2019; **44**:855–870.

[16] Henkel V, Wagner LP, Kilthau M, Gehlhoff F, Fay A. **A Multi-Agent Approach for the Optimized Operation of Modular Electrolysis Plants**. *Energies* 2024; **17**:3370.

[17] Larichev P, Tynchenko V, Nekrasov I. **Application of Petri Nets for Modeling Ore Flows to Create Dynamic Management and Quality Control System in Mineral Resource Complexes**. *Proceedings of the International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)* 2024:1089–1094.

[18] Feng Z, Eiubovi I, Shao Y, Fan Z, Tan R. **Review of Digital Twin Technology Applications in Hydrogen Energy**. *Chain* 2024; **1**:54–74.

[19] Nguyen BLH, Panwar M, Hovsapian R, Agalgaokar Y, Vu T. **Hierarchical Control of Grid-Connected Hydrogen Electrolyzer Providing Grid Services**. *ArXiv* 2022.

[20] Konyukhov VYu, Oparina TA, Matasova IY, Modina MA. **Ecologization of Underground Coal Mining by Means of Ash Use in Backfill Preparation**. *Mining Informational and Analytical Bulletin* 2024; **10**:123–135.

[21] Filina OA, Martyushev NV, Malozyomov BV, Tynchenko VS, Kukartsev VA, Bashmur KA, Pavlov PP, Panfilova TA. **Increasing the Efficiency of Diagnostics in the Brush-Commutator Assembly of a Direct Current Electric Motor**. *Energies* 2024; **17**:17.

[22] Savchenko M, Tynchenko V. **Unsupervised Production Machinery Data Labeling Method Based on Natural Language Processing**. *Proceedings of the International Russian Smart Industry Conference (SmartIndustryCon)* 2024:416–421.

[23] Stennikov D, Barakhtenko E, Mayorov G, Sokolov D, Zhou B. **Coordinated Management of Centralized and Distributed Generation in an**

Integrated Energy System Using a Multi-Agent Approach. *Applied Energy* 2022; **309**:118487.

[24] Fan Z. **Digital Twins for Enhancing Efficiency and Assuring Safety in Renewable Energy Systems**. *Energies* 2022; **17**:2456.