Energy Reports 16 (2026) 109905

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Coordinated energy management of integrated multi-carrier microgrids using attention-enhanced MADDPG

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ARTICLE INFO

Keywords:
Multi-carrier microgrid
Attention-enhanced multi-agent deep deterministic policy gradient
Centralized training and decentralized execution
Multi energy system
Multi-agent deep reinforcement learning

ABSTRACT

The increasing penetration of renewable energy and the strong interdependence among electricity, gas, heat, and cooling networks make the real-time operation of integrated multi-carrier microgrids (IMCMGs) increasingly complex, particularly under renewable generation and demand uncertainties. To address these challenges, this study proposes an attention-enhanced multi-agent deep deterministic policy gradient (AMADDPG) framework for coordinated energy management. The proposed framework adopts a centralized training and decentralized execution (CTDE) paradigm, while an attention mechanism embedded in the critic network identifies the most relevant inter-agent and inter-carrier interactions, thereby improving coordination and learning stability. Simulation results over a three-IMCMG test system demonstrate that the proposed framework achieves reliable multi-carrier energy coordination and robust operational constraint satisfaction under bounded renewable-generation deviations. Across the evaluated operating scenarios, AMADDPG achieves total operating cost reductions of 54.12%, 45.78%, and 14.31% compared with stochastic programming via particle swarm optimization (SP(PSO)), centralized DDPG, and standard MADDPG, respectively. Furthermore, integrating electrical energy storage (EES) under dynamic electricity pricing reduces the daily operating cost from 246018.051 to 243909.732 (an absolute saving of 2108.319, or 0.86%), reflecting the operational value of storage-enabled load shifting. These results highlight the effectiveness and cost efficiency of the proposed learning-based dispatch framework for modern multi-energy systems.

1. Introduction

The transition toward low-carbon energy systems has increased the need for coordinated operation of heterogeneous energy infrastructures. IMCMGs provide a flexible framework for jointly managing electricity, natural gas, heat, and cooling by coupling renewable generation, conversion technologies, storage systems, and local energy demands (Liu et al., 2025; Nwagu et al., 2025; Valipour, Nourollahi, Zare and Ghassem Zadeh; Huang et al., 2025; Martsinchyk et al., 2025). Compared with independently operated energy networks, IMCMGs can exploit the complementary characteristics of different energy carriers, improve renewable-energy utilization, and increase operational flexibility. Alongside system-level coordination, progress in sustainable energy systems also depends on material-level innovations that improve clean-energy conversion, storage, and environmental compatibility. Green synthesis routes for nanostructured materials and advanced composites have been investigated for applications including the photocatalytic removal of organic contaminants and electrochemical hydrogen storage. Recent studies on morphology-controlled nanostructured ZrO_2 synthesized through sonochemical methods have demonstrated the potential of advanced oxide materials for the photocatalytic degradation of organic pollutants (Zinatloo-Ajabshir and Salavati-Niasari, 2016). Similarly, green ultrasound-assisted synthesis of Pr_2Ce_2O7 -based mixed-oxide photocatalysts has shown effective visible-light degradation of organic contaminants (Zinatloo-Ajabshir et al., 2026). In the context of circular economy and low-carbon infrastructure, the upcycling of post-demolition autoclaved aerated concrete into high-performance geopolymers has also achieved substantial reductions in lifecycle climate-change impacts (Hanafi et al., 2026). Furthermore, magnetically recoverable nanocomposites have enabled efficient photocatalytic wastewater treatment (Zinatloo-Ajabshir and

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https://doi.org/10.1016/j.egyr.2026.109905
Received 9 May 2026; Received in revised form 29 August 2026; Accepted 30 October 2026
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