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Editorial: Research on multi-energy integration for carbon emission

Qunhai Huo[1,2], Longze Liu[1,3]*, Huawei Deng[1,2] and Lixin Wu[1]*

[1]Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, [2]Research Department of Flexible Power Technology and Equipment, University of Chinese Academy of Sciences, Beijing, China, [3]College of Information and Electrical Engineering, China Agricultural University, Beijing, China

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EDITED AND REVIEWED BY
Hailong Li,
Central South University, China

*CORRESPONDENCE
Longze Liu,
550476779@qq.com
Lixin Wu,
wulixin@mail.iee.ac.cn

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Editorial on the Research Topic
Research on multi-energy integration for carbon emission

The contemporary global energy landscape remains predominantly reliant on fossil fuels, a dependency permeating nearly every facet of modern society—from daily conveniences to large-scale industrial operations. This pervasive usage generates significant volumes of carbon dioxide emissions, contributing substantially to environmental degradation and posing severe risks to public health and planetary wellbeing.

In light of the international consensus surrounding "carbon peak and carbon neutrality" objectives, energy security challenges and environmental pollution have become critical barriers to sustainable socioeconomic progress. Consequently, the transition toward clean energy systems has emerged as an imperative strategy for achieving energy conservation and emission reduction targets. The ultimate goal is to establish a sustainable energy framework characterized by cleanliness, low carbon intensity, reliability, and high efficiency.

For example, electrolytic aluminum is a typical high-energy-consuming and high-carbon emission industry, producing 1 ton of aluminum requires about 13,500 kWh of electricity, and the direct emission of carbon dioxide from thermal power production is as high as 13 tons. The global aluminum industry accounts for about 2% of total human emissions, and China's annual output of electrolytic aluminum exceeds 40 million tons.

To address these complex challenges, integrated multi-energy systems represent a promising pathway. By enabling complementary use of diverse energy sources, such systems enhance overall resource efficiency, minimize waste, and facilitate a meaningful reduction in carbon emissions, thereby supporting a more resilient and sustainable energy future.

Multi-energy integration has emerged as a pivotal technological pathway for decarbonizing a broad spectrum of industrial sectors and energy consumption scenarios. Central to this approach is the coupling and synergistic management of diverse energy carriers-including electricity, heat, cooling, and hydrogen-which enables high-efficiency conversion and flexible regulation across different energy forms and quality levels.

This integrated framework significantly enhances the utilization rate of regionally available renewable generation, particularly distributed photovoltaic and wind power resources, thereby elevating local energy efficiency and contributing substantively to regional carbon emission mitigation. As a fundamental physical embodiment of the energy internet, multi-energy systems prioritize renewable generation while incorporating fossil energy sources in a hybrid architecture that maximizes conversion efficiency and operational flexibility.

By enabling combined supply and optimized allocation of electrical, thermal, and cooling energy at end-use levels, these systems play an essential role in accelerating the clean energy transition within hard-to-abate sectors such as transportation, chemical processing, and metallurgy. Consequently, multi-energy integration technologies are instrumental in advancing global strategies aimed at achieving carbon neutrality.

Nonetheless, research on multi-energy integration and complementary carbon reduction technologies remains in its infancy, and several critical scientific issues await resolution. There is a pressing need for in-depth exploration of methodologies that integrate and complement new energy sources (such as wind, solar, and hydro) with traditional fossil energy sources like coal and natural gas. The goal is to unravel the mechanisms and evolutionary paths of multi-energy efficient integration, so as to enhance the efficiency of energy usage and increase the consumption levels of renewable energy.

Against the dual backdrop of intensifying global climate change and the advancement of the "carbon peaking and carbon neutrality goals", the low-carbon transformation of energy systems has become a core strategic issue for achieving global sustainable development. Traditional energy systems face multiple challenges, including the intermittency of renewable energy, structural imbalances in regional supply and demand, and the rigidity of industrial carbon emissions. These challenges necessitate a systemic approach, leveraging technological innovation, system optimization, and regional coordination mechanisms to drive profound transformation (Guler et al., 2018). Currently, academia and industry have conducted in-depth explorations in areas such as multi-energy complementary system integration, cross-regional energy optimization scheduling, and industrial low-carbon transition pathways, providing important theoretical and practical support for the energy system revolution. To this end, several guest editors organized a Research Topic on multi-energy integration and carbon reduction, and received a total of 12 relevant manuscripts, and finally accepted and published 7 articles, and the main contents of the Research Topic are summarized as follows.

Technological innovation serves as the core driver for resolving the structural contradictions in energy supply and demand. Its key lies in enhancing system resilience and efficiency through multi-energy complementary coordination and dynamic optimal dispatch. For instance, a Jiangsu University team proposed a two-stage optimization strategy targeting multi-regional flexible intermodal port systems. This strategy achieves dynamic balance between hydrogen and electricity through the sequential scheduling of flexible multi-state switches. It first conducts independent optimization for each regional subsystem, determining the switch state sequence based on the results, then implements system-level optimization to achieve cross-regional power coordination. Empirical results demonstrate that this strategy significantly reduces daily operating costs (70.24%), cuts carbon emissions (37.58%), and achieves a 100% renewable energy accommodation rate (Xu et al.). This "partition optimization-system coordination" framework effectively breaks through the regional barriers inherent in traditional dispatch modes, providing a practical technical solution for integrating a high proportion of renewable energy.

In the field of distributed energy, the optimal configuration of hybrid systems constitutes a crucial direction for technological innovation. Research targeting rural areas in Liberia shows that a hybrid solar-biomass system optimally configured using HOMER Pro software can achieve 100% renewable energy power supply, with a Levelized Cost of Energy (LCOE) as low as $0.29/kWh and an annual CO2 emission reduction of 80.5% (White et al.). This system effectively compensates for the intermittency of solar power through the stability of biomass energy, enabling economically viable low-carbon energy supply even in areas with weak infrastructure. It provides a replicable technical paradigm for energy-poor regions globally.

Furthermore, the application of intelligent algorithms significantly enhances the level of refined management in energy systems. The MA-DNN model, based on multi-task learning and attention mechanisms, efficiently predicts power flow fluctuations in systems with a high proportion of renewable energy. Its computational accuracy is improved by 37.35% compared to traditional Latin Hypercube Sampling methods, and computational speed is increased by 758-fold (Xia et al.). Such data-driven methods provide efficient tools for stability analysis of complex power systems, strongly supporting the precise coordinated operation of generation-grid-load-storage systems.

The regional heterogeneity of energy resources dictates that the low-carbon transition must be grounded in local resource endowments and implemented through differentiated development strategies. Empirical research on the Yangtze River Economic Belt has revealed a typical pathway: downstream regions achieved a significant reduction in carbon emissions per unit of GDP from 1.01 tons per 10,000 yuan in 2000 to 0.21 tons per 10,000 yuan in 2022 through the upgrading of industrial structure; while midstream regions primarily achieved carbon emissions peaking through energy intensity optimization; and upstream regions effectively controlled emissions growth rates by leveraging abundant hydropower resources (Zhu et al.). This regional collaborative model of "downstream intensity reduction, midstream emissions peaking, and upstream growth rate control" establishes a systematic framework for regional energy transition. Energy interconnection technologies tailored to special geographical regions have opened new pathways for low-carbon transition in isolated and remote areas. A DC interconnection system based on a cascaded three-level converter (C-NPC) achieves seamless coordination among photovoltaic, wind power, and energy storage devices in island microgrids through flexible multi-mode control and additional voltage and current balancing strategies, enhancing power supply reliability to 99.9% and strictly controlling the total harmonic distortion (THD) below 2.1% (Liu et al.). This technology overcomes the limitations of traditional AC interconnection, providing critical technical support for the efficient cross-regional coordination of distributed energy, particularly in areas with weak grid infrastructure such as islands and mountainous regions.

The deep low-carbon transformation of the industrial sector is a key pillar supporting the energy system revolution, with its core objective being to achieve a substantial decoupling between economic growth and carbon emissions. A study of China's textile industry, for example, shows that between 2001 and 2020, the industry successfully achieved a strong decoupling of carbon emissions from economic growth by continuously optimizing its energy structure and improving energy efficiency: energy consumption per unit of output decreased by 25.5%, and the share of natural gas in the energy consumption structure increased significantly from 1.1% to 16.02% (Hong et al.). The key mechanism behind this transformation lies in two aspects: on the one hand, systematically reducing energy consumption per unit of output through technological progress; on the other hand, reducing reliance on a "high-carbon growth path" by enhancing product value-added, thereby effectively demonstrating that industrial decarbonization is not merely a simple contraction in scale but a fundamental transformation in development models. The synergistic operation of the energy-carbon coupling system further expands the pathways for industrial emissions reduction. Carbon capture power plants (CCPP) and power-to-gas (P2G) systems operate in a flexible, synergistic mode, and the introduction of carbon storage equipment alleviates temporal and spatial mismatches in their operations, reducing the system's total operating costs by 9.91% and carbon emissions by 76.93% (Tang et al.). This innovative model treats carbon resources as recyclable energy carriers, establishing a closed-loop system of "capture-conversion-reuse," providing an innovative approach for the low-carbon transformation of high-carbon industries.

At present, there is no single energy supply method that can take into account all the requirements of stability, reliability, economy, environmental protection, and zero-carbon coordination. To achieve "carbon peak and carbon neutrality" objectives of smart energy supply scale application goals, it is necessary to formulate comprehensive solutions tailored to local conditions.

The transition to low-carbon energy is a complex systemic endeavor that urgently requires the integration of multi-dimensional initiatives, including technological innovation, regional collaboration, and industrial practices. From port hydrogen-electricity synergy optimization to rural photovoltaic-biomass complementary systems, from differentiated emission reduction pathways along the Yangtze River Economic Belt to decoupling development practices in the textile industry, relevant research findings collectively reveal that technological breakthroughs lay the foundation for the transition, regional collaboration enhances its feasibility, and industrial practices ensure its sustainability. Looking ahead, it is imperative to further strengthen interdisciplinary research, improve market-based incentive mechanisms, and drive the continuous evolution of energy systems toward greater efficiency, cleanliness, and resilience.

Reference

Guler, B., Çelebi, E., and Nathwani, J. (2018). A 'regional energy hub' for achieving a low-carbon energy transition. *Energy Policy* 113, 376–385. doi:10.1016/j.enpol.2017.10.044

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