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Editorial

Editorial for the Special Issue on Low Carbon Transformation for Conventional Energies

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Conventional energy sources, including coal, oil, and natural gas, remain the primary energy supply for the great majority of countries around the world. While being used for power generation, heating, transportation, and other industries, they serve as the main source of global carbon dioxide (CO_2) emissions. Reducing carbon emissions from the utilization of conventional energies by achieving low-carbon transformation for conventional energies (LCT4CE) is crucial for carbon neutrality.

LCT4CE involves a wide scope and spans multiple industries, encompassing the efficiency upgrades, replacements, and modernization of existing energy-utilization systems, the research and development of various emerging technologies, and the formulation of relevant policies. To date, extensive academic and practical engineering research has been conducted globally. Some developed technologies have achieved widespread application, while others remain in experimental research and engineering demonstration phases.

This special issue introduces state-of-the-art research findings and engineering experiences in developing and applying novel technologies to resolve LCT4CE challenges in the power-generation, heating, and transportation industries. The main topics include the status and perspective of LCT4CE; the feasibility of global LCT4CE development and a roadmap toward this objective; the upgrading and replacement of existing power-generation technologies; hydrogen- and ammonia-fuel-related technologies; energy storage and its coupling in conventional energies; carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) for conventional energies; oxyfuel combustion technology; chemical looping combustion (CLC) technology; biomass energy; the flexibility of thermal power plants; and modeling for low-carbon energy utilization. This special issue contains 19 papers, including 3 Views & Comments papers and 16 Research papers (2 Perspectives, 6 Reviews, and 8 Articles).

Tsinghua University is well-known for carbon-reduction policy research in China. A research team led by Li et al. employs maximum likelihood estimation (MLE) combined with Monte Carlo simulation and random sampling to analyze the probabilities of China meeting its carbon peak target and other climate targets under different scenarios. It also provides policy recommendations to ensure these climate targets are met. Also, the work of Ma and Arras emphasizes the need for a comprehensive integration of energy and societal systems, as well as conventional and emerging energy systems, in the energy system transformation (EST) through technological advancements and policy adjustments. The scholars propose a system integration pathway for the EST toward carbon neutrality and offer system principles to guide immediate actions that can be undertaken by global society. The four-stage pathway includes smart grids, smart energy, ecological energy, and interstellar energy.

The power system serves as the critical enabler of LCT4CE by facilitating the large-scale integration of renewable generation, optimizing energy allocation across regions, and driving the

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electrification of end-use sectors to replace fossil fuel consumption. Zhao et al. first outline macro development trends of the power system, then constructs typical future grid scenarios for China, based on which technical challenges are derived. Finally, several recommendations for scientific and technological innovation priorities are made.

The steel industry is another major source of carbon emissions. To achieve carbon neutrality, transitional solutions are required before full-scale hydrogen-based reduction becomes viable. Kim et al. evaluate the combustion behavior and injection limits of four biocarbon samples that could be used to partially replace pulverized coal injection (PCI) in blast furnace (BF) operations. They report that, as biomass is carbonized, its combustion kinetics increasingly resemble those of PCI coal. Co-firing tests confirm improved performance at higher blending ratios, especially with highly treated samples, due to increased fragmentation and char reactivity. Injection limits have been determined based on combustion performance, heating value, and ash content. Overall, biocarbon exhibits strong potential as a PCI substitute, offering a feasible low-carbon pathway for existing BF systems.

Cement production accounts for 5%–8% of global CO_2 emissions. Yu et al.'s paper exposes three systematic failures in current climate accounting, revealing patterns that are invisible when research remains fragmented, while proven alternatives demonstrate superior performance. Consequently, although carbonation remains chemically viable, its slow kinetics, performance uncertainty, and temporal misalignment with climate targets necessitate a policy recalibration prioritizing transparent temporal accounting and proven alternatives over uncertain future absorption processes.

Retrofitting and upgrading coal-fired power plants (CFPPs) are crucial approaches to improve energy-utilization efficiency and naturally reduce carbon emissions. Magalhaes et al. have extended pressurized oxy-combustion technology from coal-firing to biomass-firing to yield carbon-negative power. They propose a staged, pressurized oxy-combustion (SPOC) process for a modular boiler to improve the plant's flexible operation, meeting the demands of a modern grid with intermittent wind and solar power sources. Two boiler-retrofit applications are modeled with Aspen Plus: power generation and cogeneration (i.e., heat and power). The results from pilot-scale experiments clearly demonstrate the capability of the SPOC process to integrate additional heat into the steam cycle and to optimize efficiency when utilizing biomass feedstocks. The integrated system under 100% biomass firing exhibits excellent performance during startup, steady-state operation, and turndown.

Wang et al. improve the flexibility of CFPPs through a pre-gasification burner with ultra-enhanced flame stability. Flame stability and responsiveness on the combustion side under extreme conditions of ultra-low loads and rapid load-change processes are the key to flexibility in thermal power plants. A burner based on a pre-gasification combustion technology has been developed, and its flexibility has been investigated through simulation and verified by 5 MW pilot-scale experiments. The results indicate that the pre-gasification burner holds the potential to improve the flexibility of industrial- to full-scale coal-fired boilers.

Yang et al. present a novel coal purification–combustion technology, focusing on purification characteristics and ultra-low nitrogen combustion at low loads. Verification results are provided for three coal types under a 50%–100% load on a 200-kW system. During high-temperature purification, 62%–85% of inorganic components are separated, achieving the separation of carbon and inorganic components. The process mainly involves the release and reduction of coke nitrogen to nitrogen gas (N_2), with a nitrogen conversion rate of 93.6%–96.6%. The results indicate that the proposed technology is feasible for clean and efficient coal combustion under low loads.

The development and application potential of intelligent technologies to increase the flexibility, efficiency, and autonomy of CFPPs are playing an increasingly important role in LCT4CE. Liu et al. deliver a critical review on intelligent coal-fired power technologies and applications. The paper comprehensively reviews the latest developments in intelligent coal-fired power technologies, focusing on three critical pillars: intelligent perception, intelligent control, and intelligent operation. Key enabling technologies such as ubiquitous sensing systems, advanced control algorithms, and automated operation platforms are examined in detail. Additionally, two representative engineering cases—namely, the intelligent control of coal-fired units coupled with novel energy-storage systems and the implementation of unmanned operation in smart power plants—are introduced to demonstrate practical applications and benefits. The findings of this study offer valuable insights into the pathway toward clean, flexible, and intelligent coal power generation under the evolving energy landscape.

Data-driven digital twins have emerged as powerful tools for optimizing performance and minimizing emissions in industrial combustion systems. Wang et al. address the limitations of existing approaches that typically treat reconstruction and optimization as separate tasks, limiting efficiency and scalability, and the impracticality of obtaining extensive high-fidelity data for real-world industrial digital twins. They propose the multi-field reconstruction net (MFRNet) framework, which integrates dimension expansion, variable extension, and feature fusion techniques to enhance data efficiency and predictive accuracy. A comprehensive dataset has been constructed for an industrial-scale biomass grate furnace as a case study. The MFRNet achieves high-precision multi-field reconstruction under complex conditions, while significantly reducing reliance on costly three-dimensional (3D) simulations. The application demonstrates robust predictive accuracy and reliable optimization guidance. This scalable and data-efficient digital twin framework could be easily adapted for other combustion systems, offering an intelligent paradigm for active control, real-time optimization, and enhanced operational efficiency in modern combustion facilities.

High-carbon fuel substitution is a key measure for carbon reduction. As a carbon-free carrier for renewable energies, hydrogen has the potential to contribute to the success of the energy transition. To address the combustion challenges the combustion challenges caused by hydrogen's special thermophysical and reaction kinetic properties, Li et al. summarize recent experiments to quantitatively describe the interaction between thermodiffusive instabilities and turbulence. Shrimpton and Balta-Ozkan emphasize that, although hydrogen holds the potential to support LCT4CE, hydrogen insurance remains in its infancy, compounded by data and knowledge gaps. The researchers identify opportunities for productive early engagement between engineering, science, and technology and the insurance sector, with the aim of stimulating multidisciplinary understanding and dialogue between EST and the insurance sector to manage risk.

Ammonia has been identified as a promising hydrogen energy carrier, with the potential to be utilized directly as a fuel. Fujimori introduces the status of the development of new ammonia combustion technologies used in power generation, including demonstration tests in a boiler, internal combustion engine, and gas turbine in Japan, aiming to substitute 10% of its primary energy with hydrogen ammonia by 2050. Wu et al. presents a review on liquid ammonia injection and combustion for engine applications. The review examines the application of liquid ammonia injection and combustion in engine systems, highlighting ammonia's potential as a carbon-neutral fuel alternative. The study synthesizes recent advancements in liquid ammonia injection and combustion technologies, addressing critical domains such as fundamental fuel properties, injection and spray dynamics, combustion behavior, and engine performance. It also identifies key challenges and topics for future research.

Biofuels are promising alternatives to fossil fuels, and the combustion application of biofuel could reduce the consumption of a large amount of fossil fuels, playing a crucial role in LCT4CE. Liu et al. provide a review that focuses on recent progress in understanding the combustion kinetics of oxygenated biofuels derived from biomass. It begins with fundamental concepts and research methodologies in reaction kinetics, intended as a primer for engineering researchers. Subsequently, kinetic studies from the past decade on typical oxygenated biofuels are summarized. Emphasis is placed on the influence of different oxygenated functionalities and their positions within the molecule on combustion characteristics and reaction pathways. Distinct reaction patterns for each class are highlighted. To advance predictive kinetic models for biomass-derived oxygenated fuels, several targeted research directions are proposed.

CO_2 capture will be mandatory for carbon neutrality if remarkable amounts of fossil fuels are still needed for power generation. This review from Massa et al. summarizes both early and recent developments in the sorption-enhanced catalytic hydrogenation of carbon oxides into products. It covers experimental and modeling studies, and highlights key challenges and research directions for scaling up this promising technology to commercial levels. Moreover, the article proposes a chemical looping process based on the technology of coupled fluidized-bed reactors rather than conventionally used fixed-bed reactors for sorption-enhanced hydrogenation. The proposed process enables continuous sorbent transfer and regeneration, as well as easier heat management.

CLC is an innovative combustion technology involving the use of a solid oxygen carrier as an intermediate medium to transfer oxygen from the air to the fuel, thereby avoiding direct contact between the fuel and the air. In the fuel reactor, high concentrations of CO_2 and H_2O are produced, along with reduced metal particles. After the condensation of water vapor, almost-pure CO_2 can be obtained, which can then be easily captured and stored. Li et al. led the worlds' largest CLC demonstration project with a capacity of 5 megawatt thermal (MW_{th}), funded by China's Ministry of Science and Technology and the EU's Horizon 2020 program. The facility was installed and put into operation in 2023. The latest progress of this project is reported by the international team, which includes members from China, France, and Norway. During operation, the temperatures of the air reactor and fuel reactor were 1000–1040 and 940–980 °C, respectively. The maximum CO_2 capture efficiency of the lignite-fed CLC unit was over 96%, and the minimum oxygen demand for unburnt gases from the fuel reactor was 2.45%. This work bridges the gap between lab-scale research and industrial applications in the field of CLC.

The large-scale utilization of renewable energy challenges the stability and safety of the grid; thus, the flexibility of CFPPs should be increased to balance unstable renewable energies. To achieve this goal, a heat-storage system (HSS) can be integrated into power plants. Xu et al. propose for the first time the utilization of furnace flue gas to drive a molten-salt heat exchanger (MSHE). Furthermore, they demonstrate the concept, design, fabrication, and experiments of this MSHE. The advantages and novelties of the MSHE are examined. Based on the 300 kW MSHE results, a 10-MW MSHE has been designed, fabricated, and integrated into a 350-megawatt electric (MWe) coal-fired plant to achieve a higher load variation rate of 6% $Pe \cdot min^{-1}$ for a CFPP.

Heat exchangers are critical devices in molten-salt energy-storage systems. Gui et al. have numerically studied the heat-transfer performance of molten-salt-based nanofluid in a novel twisted cloverleaf U-tube. To avoid the non-uniform flow distribution caused by the high viscosity and density of molten salt in conventionally used exchangers with U-tube configurations, they propose a heat transfer enhancement strategy that applies a twisted cloverleaf U-tube in combination with molten-salt-based nanofluids. Numerical simulations show that the twisted structure and nanoparticles significantly increase heat transfer and improve temperature uniformity, although they increase the pressure drop. Operational optimization is performed.

This issue contains valuable knowledge and perspectives and provides a useful reference for researchers, engineers, and even policymakers working in the field of LCT4CE.