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Editorial

Process Design and Modeling of Low-Carbon Energy Systems

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The need to transition toward low-carbon energy systems has never been more urgent [1]. Amid escalating climate crises, the global community faces a dual challenge: to decarbonize energy production while meeting growing demand for affordable and reliable energy [2]. Low-carbon energy systems are inherently complex, spanning combined heat and power generation [3], renewable generation [4], energy storage [5], telemeters [6], and electricity–gas–thermal coupling networks [7]. However, their deployment is hindered by multifaceted challenges. Technologically, the intermittent nature of solar and wind energy necessitates advanced forecasting [8] and storage solutions to ensure grid stability. Economically, the high capital costs of emerging technologies, such as hydrogen electrolyzers [9] and carbon capture systems [10], need innovative financing mechanisms. Politically, fragmented regulatory frameworks and misaligned incentives often slow the pace of adoption. Moreover, the socio-environmental dimensions (such as community engagement, land-use conflicts, and lifecycle environmental impacts) add layers of complexity to the energy transition.

This Special Issue of Processes (ISSN: 2227-9717), titled "Process Design and Modeling of Low-Carbon Energy Systems", responds to these challenges by curating cutting-edge research at the intersection of engineering, economics, and environmental science. Our goal is to bridge the gap between theoretical advancements and real-world implementation, offering actionable insights for policymakers, industry stakeholders, and university researchers. By focusing on process optimization, system integration, and policy coherence, this collection highlights how interdisciplinary approaches can accelerate decarbonization while addressing equity and scalability. This Special Issue, thus, serves as a platform to showcase innovations that not only enhance technical performance but also align with the United Nations Sustainable Development Goals.

The following sections synthesize the key contributions of the 14 papers published in this collection, spanning renewable energy prediction, carbon market mechanisms, energy storage optimization, and socio-technical analyses.

1. Renewable Energy Prediction and Optimization

Integrating renewable energy into power systems hinges on accurate prediction and intelligent optimization [11]. This Special Issue showcases groundbreaking methodologies that address the variability and uncertainty inherent in solar and wind while balancing economic and operational constraints.

The IAO-LSTM model [12] represents an advancement in solar prediction accuracy. By integrating the Improved Aquila Optimization (IAO) algorithm with Long Short-Term Memory networks, this framework dynamically adjusts hyperparameters to minimize prediction errors caused by cloud cover and seasonal irradiance fluctuations. A patch time series Transformer-based non-parametric model [13] combines the non-parametric

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Huberized composite quantile regression method to predict voltage fluctuations in low-voltage grids with distributed energy storage. Unlike conventional Gaussian assumption-based methods, this approach quantiles uncertainty bounds without prior distribution knowledge. In addition to directly improving the prediction method, [14] applies maximum power point tracking techniques to further reduce the uncertainty of photovoltaic power.

The VMD-AOA-GRU hybrid model [15] tackles the non-stationarity of wind signals through a two-stage decomposition–optimization approach. First, Variational Mode Decomposition separates raw wind speed data into intrinsic mode functions, reducing noise interference. Then, the arithmetic optimization algorithm (AOA) is employed to optimize the hyperparameters of the model of the gated recurrent unit (GRU), including the number of hidden neurons, training epochs, learning rate, learning rate decay period, and training data temporal length, thereby constructing a high-precision AOA-GRU forecasting model.

The bi-level inverse robust optimization model [16] bridges wind variability and grid demand through pumped storage hydropower. The upper layer minimizes total generation costs, while the lower layer enforces an Optimal Inverse Robustness Index to ensure stability against wind forecast errors. A robust power grid dispatching technology is proposed in [17,18] that integrates deep learning-based forecasting, reinforcement learning, and optimization techniques. This technology is capable of forecasting future electricity demand and solar power generation. References [19,20] make charging/discharging decisions for energy-storage devices based on current grid conditions. Moreover, this technology is effective in optimizing the configuration of circuit breakers and switches to improve the reliability of power systems [21].

2. Carbon Trading and Multi-Energy System

Carbon trading and multi-energy system are currently highly researched topics in the fields of environment and economy [22], especially against the backdrop of global climate change and the increasing significance of renewable energy. This research direction focuses on internalizing the cost of carbon emissions through market mechanisms and multi-energy complementary mode [23].

A thermoeconomic modeling approach is presented in [24] to incorporate carbon credits into the analysis of multiproduct systems. The study uses a gas turbine cogeneration system as a case study to demonstrate how carbon market dynamics can be integrated into thermoeconomic models. The authors develop a methodology to allocate carbon-related costs to final products, considering both revenue and expenses associated with carbon credits.

Reference [25] explores the resilience enhancement of electric and natural gas networks against extreme events such as windstorms and wildfires. The study proposes a novel integrated energy system planning strategy that combines deep learning-based forecasting, reinforcement learning, and optimization techniques. By integrating these approaches, the authors demonstrate a robust framework for improving the resilience of energy systems.

A centralized regional integrated market structure is developed in [26] involving industrial users, carbon capture, utilization, storage facilities, and carbon market operators. The authors formulate a generalized Nash equilibrium model to analyze the trading behaviors of different entities and their impacts on system operations. This research highlights the significance of market structures and equilibrium analysis in optimizing the performance of integrated energy systems with carbon trading.

3. Thermal Transmission and Nanomaterials

Heat transfer is an important subject in engineering, and it involves the process of heat transfer from one object or region to another [27]. Improving heat transfer efficiency

is a key factor in many practical applications, such as in compression equipment and air conditioning systems [28]. With the development of nanotechnology, nanomaterials have shown great potential in improving heat transfer properties.

The insufficient heat dissipation capacity of the gas head cover can lead to overheating, resulting in safety issues and increased operating costs. Ref. [29] investigates the heat dissipation issue of the gas head cover in a diaphragm compressor. The study analyzes the structure and heat transfer characteristics of the gas head cover, establishing a finite element simulation model for temperature distribution. Additionally, based on the temperature field distribution characteristics, two enhanced heat transfer gas head cover structures are proposed, and both simulation and experimental verifications are conducted.

Nanoporous alumina sheets have been widely applied in air conditioning heat exchangers. Ref. [30] focuses on the ability of nanoporous alumina sheets to inhibit frost layer growth in low-temperature environments. The researchers prepare nanoporous alumina sheets with various pore diameters using the anodic oxidation method and conduct an in-depth analysis of their anti-frosting properties. The results reveal that compared to conventional polished aluminum sheets, the nanoporous alumina sheets exhibited excellent anti-frosting performance. Notably, the porous alumina sheet with a 100 nm pore diameter demonstrated strong anti-frosting properties under low-temperature and high-humidity conditions.

4. Conclusions and Future Directions

The research presented in this Special Issue underscores the transformative potential of process design and modeling in advancing low-carbon energy systems. Key innovations, such as AI-driven prediction models, hybrid storage systems, nanomaterials, and carbon-internalized economic frameworks, demonstrate pathways to mitigate technical and economic barriers.

However, challenges remain. Future studies should prioritize the following:

(1) Cross-Sector Integration: Deeper coupling of electricity, hydrogen, and thermal networks to maximize resource synergy;
(2) Scalability: Translating laboratory-scale innovations (e.g., nanomaterials) into industrial applications;
(3) Policy Alignment: Developing adaptive regulatory frameworks to incentivize low-carbon investments and community participation.

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