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Energy Storage EDITORIAL

CO_2 thermodynamic battery: Technological advancements and system support from power generation to integrated energy platforms

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INTRODUCTION

The construction of a new-type power system in China dominated by renewable energy constitutes the major pathway to achieve the Dual Carbon Goals.[1] With the continuously increasing installed capacity share of renewable energy, such as wind and solar power, the power system faces severe peak-shaving pressure, serious curtailment risks, and increasingly complex challenges in coordinating multiple energy flows.[2] The development of large-scale, long-duration, high-efficiency, flexible, and economically viable thermodynamic battery has become an urgent demand for ensuring energy security and achieving the green transition. Thermodynamic battery, as an advanced energy storage technology that utilizes thermodynamic cycles to convert and store energy, have attracted considerable attention due to its advantages of large capacity, long lifespan, operational flexibility, and siting freedom. As Figure 1, the thermodynamic battery with carbon dioxide as the working fluid not only offer moderate critical temperature, compact equipment, and high cycle efficiency, yet more importantly, it demonstrates superior multi-scenario adaptability. These advantages position it as a promising candidate for integrated energy platform to facilitate large-scale renewable energy accommodation, advanced grid peak regulation, and multi-energy supply in industrial parks.

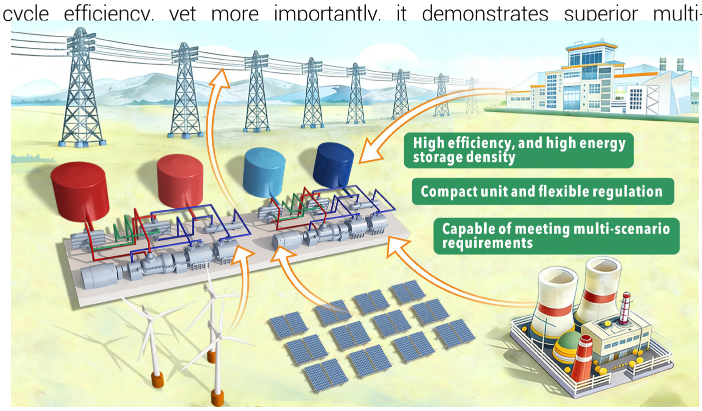

Figure 1. The Application and advantages of CO_2 thermodynamic battery.

Currently, CO_2 thermodynamic battery still face challenges in system integration, including the yet-to-be-matured design methodologies for key equipment such as high-efficiency heat exchangers and high-performance turbomachinery, as well as the complexities in operation control of integrated energy platforms that provide combined cooling, heating, and power services under fluctuating user requirement. This paper aims to summarize the authors' prior research contributions in the field of CO_2 power generation, as well as the progress and potential of the technical evolution toward CO_2 thermodynamic battery, and to explore the prospective value in supporting the new-type power system.

RESEARCH AND PILOT UNITS FOR CO_2 POWER CYCLE POWER GENERATION

The core technology of CO_2 thermodynamic battery is rooted in years of research in the field of CO_2 power generation. The author's team has achieved significant technological breakthroughs in supercritical CO_2 (sCO_2) thermodynamic cycle. A landmark achievement is the successful development and commissioning of the world's first pilot 5MW Supercritical CO_2 Modular Advanced Research and Test (SMART) fossil-fired power system, which fully verified the engineering feasibility of the sCO_2 power generation technology and provided foundational support for subsequent commercial demonstration of 50MW and above.

In terms of system integration and innovation, the generalized sCO_2 Carnot cycle for various heat sources is proposed, along with its system design principle and methodology. This addresses the system design challenges of the novel closed cycle. Regarding key equipment, the sCO_2 boiler has been successfully developed, a series of high-efficiency, low-resistance printed circuit heat exchangers (PCHEs) have been engineered, and the integrated design methodology of high energy & density sCO_2 turbines and near-critical aerodynamic design methods for sCO_2 compressors have been proposed. The dynamic simulation model for real-gas closed cycle is established, and a flexible and high-efficiency operation control strategy based on volume-mass control is proposed.

RESEARCH ON KEY TECHNOLOGIES AND ENGINEERING DEMONSTRATION FOR CO_2 THERMODYNAMIC BATTERY

Currently, CO_2 thermodynamic battery is advancing to overcome challenges in its engineering-scale deployment. The authors' team has established the system integration framework for the deep combination of heat pump and heat engine, grounded in the principles of CO_2 thermodynamic cycle developed from closed Brayton cycle. In the early stages, the key equipment design and manufacturing challenges have been successfully overcome, providing valuable experiences for the system key components. Furthermore, the developed dynamic simulation model and operational control strategy have laid the technical foundation for the variable-load operation of the system.[3]

50 MW sCO_2 power cycle demonstration unit

Since 2023, the 50MW/600°C sCO_2 coal-fired power generation demonstration unit has been supported by a National Key Research and Development Program project. Focusing on this demonstration unit, the author's team has carried out original research, spanning fundamental theory, key equipment, system integration, and operational control. Three core challenges have been addressed:

1) A novel collaborative optimization design process for systems and equipment, incorporating dynamic variable-load objectives, was developed based on the generalized Carnot cycle construction method for different heat sources.

2) Achieved breakthroughs in core technologies, including the integrated aerodynamic-sealing-cooling design of high-temperature, high-pressure compact sCO_2 turbines and compressors, as well as near-zero-leakage dry gas seals.

3) The mass flow distribution issue of large-scale PCHEs has been resolved, enabling the development of a series of high-efficiency, low-pressure-drop PCHEs.

As a key project in the Fifth Batch of First Units (Sets) of Major Technical Equipment by the National Energy Administration, this demonstration unit represents the world's first large-capacity commercial sCO_2 power generation unit. It can sufficiently validate the performance of the heat engine, providing technical support for high-efficiency flexible coal-fired power, advanced nuclear energy, and concentrated solar power, and other fields in China. Furthermore, it has comprehensively promoted technological progress and self-reliance in the domestic advanced power equipment industry chain.

50 MW CO_2 thermodynamic battery demonstration unit

In response to the urgent demand for large-scale and long-duration energy storage, author's team has pioneeringly achieved the in-depth integration of the CO_2 heat engine cycle and the CO_2 heat pump cycle through the CO_2 thermodynamic battery demonstration unit to meet the needs of diverse scenarios. In coal-fired power generation applications, it enables rapid peak shaving to ensure grid security and stability. Furthermore, for renewable energy applications, it enhances the utilization rate of wind and solar power while reducing curtailment rates.[4] Additionally, in industrial park applications, it achieves both high efficiency and low costs through integrated multi-energy supply. Following the scientific approach of "system construction-equipment development-intelligent control-engineering demonstration", and significant breakthroughs have been achieved in key technologies:

1) An active learning multi-scale model integrating physical modeling and data-driven methods is constructed, and a systematic configuration optimization design method has been proposed to adapt to multiple scenarios such as grid peak shaving, renewable energy accommodation, and integrated multi-energy supply.

2) An intelligent design method for CO_2/Molten salt heat exchanger capable of handling rapid load change and operating over a wide temperature range, along with a thermal shock-resistant storage tank, has been developed.

3) The design and manufacturing challenges of core equipment is overcome, including high-temperature compressors and high-efficiency turbines in the CO_2 heat pump system.

4) A multi-tiered online monitoring and intelligent collaborative control strategy encompassing "equipment-process-system" is established to facilitate the transformation of the operation and maintenance mode from passive response to active early warning.

Furthermore, it is expected that by 2030, the world's first 50MW CO_2 thermodynamic battery demonstration unit will be built at the Shandong Bajiao Power Plant operated by China Huaneng Group. The unit can achieve an energy storage duration of 6 hours under the condition that the low temperature heat source does not exceed 100°C and the heat storage temperature remains no lower than 560°C, and the round-trip efficiency is more than 63% and maintain a charging and discharging load variation rate of no less than 10% Pe/min. The commercial operation of the demonstration unit not only verifies the engineering feasibility of CO_2 thermodynamic battery as a large-scale and long-duration energy storage technology, but also establishes a replicable and scalable technical framework.

ARTIFICIAL INTELLIGENCE SUPPORT FOR CO_2 THERMODYNAMIC BATTERY TECHNOLOGY

For integrated energy systems involving combined cooling, heating, and power supply, the deep integration of CO_2 thermodynamic battery with artificial intelligence (AI) and digital twin techniques constitutes the most promising pathway toward intelligent, smart, and autonomous system operation.[5]

Digital twin technology enables high-fidelity virtual representations, thereby supporting transparent lifecycle management. By integrating Internet of Things (IoT) sensors with a hybrid physics-data-driven model established using Physics-Informed Neural Networks (PINN), a digital twin achieves real-time perception and synchronization of state parameters of key equipment, establishing a real-time synchronized mapping with the physical entity in virtual space. This virtual counterpart facilitates comprehensive monitoring, performance evaluation, and operational optimization throughout the entire system lifecycle.

AI algorithms can perform multi-objective collaborative optimization and-support autonomous decision making and adaptive operation. Against the background of increasing demand for deep peak shaving caused by the large-scale integration of renewable energy, traditional Proportional-Integral-Derivative (PID) control relies solely on feedback adjustment and exhibits lag issues when handling the strong nonlinearity and large delay characteristics of the CO_2 thermodynamic battery, making it difficult to meet real-time requirements under rapid load changes. Therefore, we propose a control method that combines the established digital twin model with intelligent optimization algorithms to achieve feed-forward control. By utilizing the high-fidelity simulation capabilities of the digital twin, the system predicts dynamic responses under different operating conditions and dynamically optimizes control parameters in advance, upgrading "post-feedback" to "pre-prediction". As a result, controllers can coordinate, on a millisecond timescale, the charging and discharging processes of the CO_2 thermodynamic battery, the output allocation between heat pump and heat engine subsystems, as well as the collaborative operation with other renewable energy resources and energy storage units. While satisfying the demands for cooling, heating, and power, such controllers can simultaneously optimize multi-objective at the system level, including energy efficiency, economic performance, carbon emissions, and equipment lifetime.

The closed loop integration of AI and digital twin technology empowers predictive maintenance and unmanned operation and maintenance. Through continuous learning from equipment operating data using time-series neural networks, Transformer-based models, and related algorithms, the system can provide early warning of potential faults and automatically generate diagnostic reports and maintenance recommendations. This closed-loop framework of "perception-prediction-decision-execution" enables full-process automation of the CO_2 thermodynamic battery, ranging from condition monitoring and fault self-diagnosis to strategy self-adjustment. As a result, human intervention can be significantly reduced, promoting the transition of operation and maintenance practices toward predictive maintenance and unattended operation.

By establishing a complete technical chain featuring precise perception, intelligent decision-making, and autonomous execution through AI and digital twin technologies, robust support can be provided for achieving efficient, reliable, and cost-effective energy management of CO_2 thermodynamic battery.

OUTLOOK

Moving forward, we will leverage the 50MW CO_2 thermodynamic battery demonstration unit to accelerate the development of an industrial ecosystem, promote full-chain autonomous control and standardization of system integration, and establish a replicable and scalable technical framework. Further, beyond the conventional single-function energy storage paradigm, the system will evolve toward an integrated energy platform driven by digital and intelligent technologies, enabling multi-energy flow collaboration and unmanned operation and maintenance. Refining market rules and carbon finance instruments will provide economic incentives and risk management support for the large-scale deployment of this technology. Ultimately, those will provide robust support for ensuring energy security and achieving the Dual Carbon Goals.

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DECLARATION OF INTERESTS

The authors declare no competing interests.