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# The Innovative Application and Development Trend of $CO_2$ Thermodynamic Cycle Technology in the New Energy Structure system

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**Dear Editor,**

Within the global climate governance framework, adhering to the provisions of the Paris Agreement has become a core international consensus. According to statistical data from the Intergovernmental Panel on Climate Change (IPCC), the industrial sector accounts for over 32% of global GHG emissions, and this share continues to trend upward.[1] Furthermore, within sectors such as industry and buildings, energy consumption and GHG emissions attributed to heating account for over 50%,[2] positioning them as one of the primary targets for global climate governance.

As a key technology for addressing the aforementioned heating challenges and achieving emission reduction targets, heat pump technology is regarded as the optimal substitute for conventional heating based on primary energy combustion. This technology facilitates the transfer of substantial heat from a low-temperature source to a high-temperature sink[2] with minimal electricity consumption. In emerging energy systems that emphasize combined cooling and heating and multi-energy synergy, heat pump technology is poised to play an increasingly vital role in future building, industrial, transportation, as well as commercial and residential sectors.

Among the numerous working fluids for heat pump systems, carbon dioxide ($CO_2$) stands out due to its negligible Global Warming Potential and unique thermodynamic properties that enable efficient operation from -40°C to 600°C. However, technical hurdles persist, where -40°C refrigeration requires complex cycle modifications to counter efficiency loss, while heating above 120°C faces constraints in compressor lubrication and sealing durability. Nevertheless, its application potential is demonstrated by diverse applications, ranging from -20°C to 120°C residential/industrial systems,[3] to emerging 180°C–220°C steam heat pumps[1] and 600°C ultra-high-temperature heating technologies,[4] which in turn enables it to flexibly meet the diversified demands of the complex source-grid-load-storage scenarios illustrated in Figure 1.

Despite this broad potential adaptability, the industrial application of $CO_2$ heat pumps is presently limited to temperatures below 120°C, though their potential extends far beyond this range. To bridge this technological gap and promote the development of industrial heat pumps towards higher temperatures and more environmentally friendly solutions, this paper systematically reviews the application of $CO_2$ heat pump technology in two frontier areas: first, $CO_2$ super-high temperature heat pump technology targeting 300°C-level industrial steam production; and second, $CO_2$ ultra-high temperature heat pump technology integrated as a core component in 600°C-level "Thermal Battery" thermal energy storage systems.

## STATE-OF-THE-ART OF $CO_2$

### Super-high Temperature Heat Pump Targeting 300°C

Fundamentally, the $CO_2$ heat pump shows great promise for 300°C heating applications. As the high-pressure heat rejection process occurs in the supercritical region, the discharge state point temperature can be significantly elevated merely by increasing the $CO_2$ cycle's suction temperature, without a corresponding increase in discharge pressure. This shifts the cycle to the right on the *p-h* diagram, enabling the discharge temperature to exceed 300°C[5]. Notably, the heat pump's maximum temperature increase is achieved solely through internal heat recuperation, without additional heat sources. As the working fluid exiting heat rejection is above 100°C, an internal heat exchanger can be used to raise the compressor suction temperature to the 100°C range, maintaining compressor discharge temperature in the 300°C range under an engineering-feasible pressure ratio.[5] Subsequently, the high-temperature, high-pressure $CO_2$ working fluid passes through different gas coolers to release heat to superheated steam and pressurized water, respectively, heating them to the required process temperature conditions. Meanwhile, the $CO_2$ working fluid, after being cooled in the internal heat exchanger, is throttled to a lower pressure. It then absorbs heat in the evaporator and finally returns to the compressor suction inlet via the low-pressure side of the internal heat exchanger, completing the cycle. Nevertheless, achieving such high discharge temperatures imposes strict requirements on cycle configuration. The system relies heavily on efficient internal heat recuperation to elevate suction temperatures, as standard compression alone cannot bridge the temperature gap without encountering excessive pressure ratios or discharge pressures that exceed component safety limits.

On the thermal energy application side, the system is configured with a high-temperature, high-pressure water flash device to ensure the heat transfer medium remains in a single-phase state. This configuration facilitates a continuous temperature rise that matches the continuous temperature glide of the supercritical $CO_2$ during heat rejection. Based on this principle, two distinct technical routes are adopted to accommodate different transport

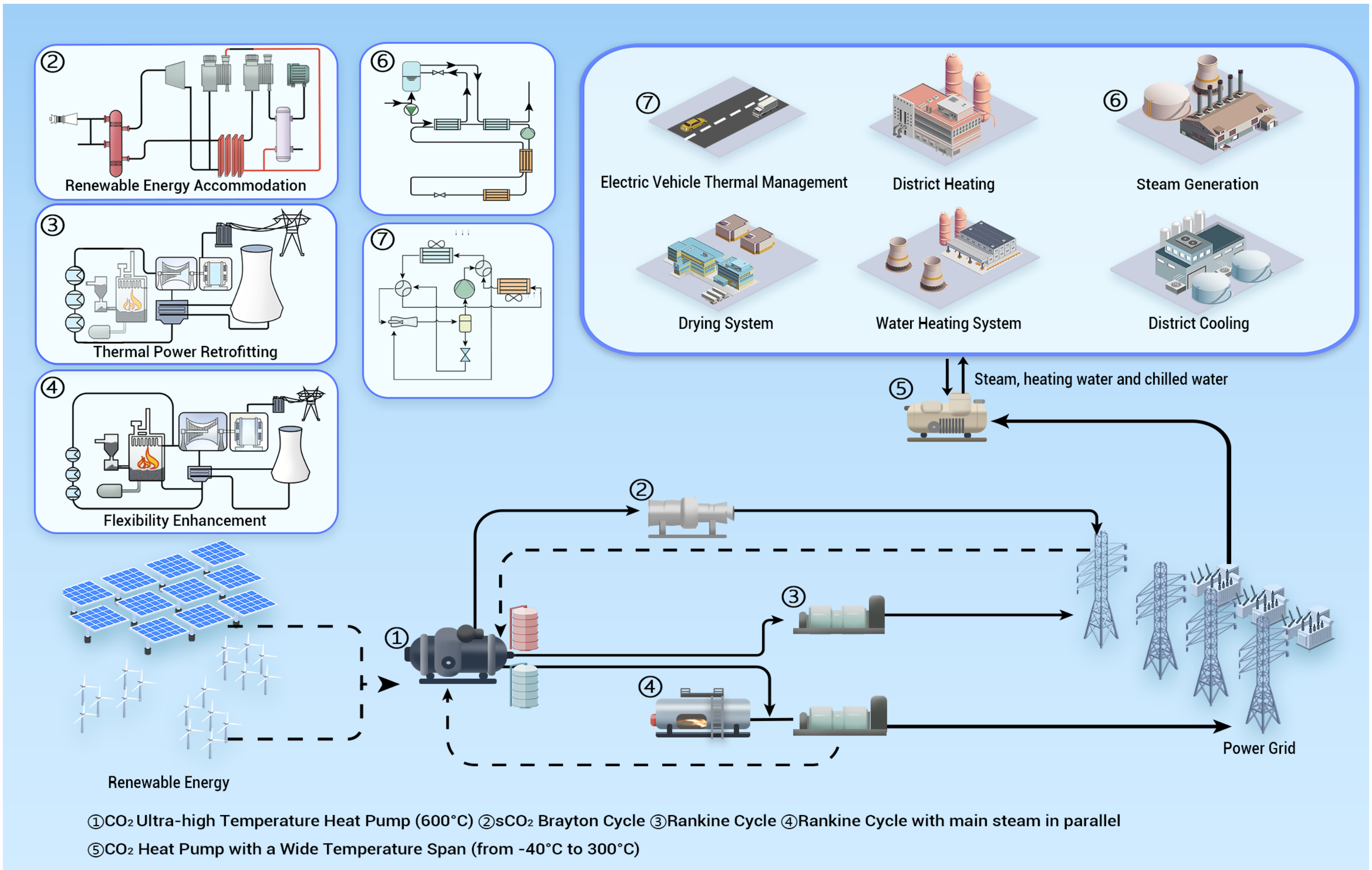


Figure 1. Diverse applications of $CO_2$ heat pumps in integrated source-grid-load-storage systems.

distances. For local applications, steam is generated via $CO_2$ superheating of flashed water; conversely, for long-distance transport, high-temperature water is pumped to remote sites for subsequent flashing.

Meanwhile, leveraging the $CO_2$ heat pump cycle's capability to span a wide temperature range, the high-temperature water/steam technical solution can stably supply 300°C-range steam while the heat pump cycle's evaporation temperature is maintained at an ambient state (0–10°C range).[5] This implies that the $CO_2$ super-high temperature heat pump system does not necessarily require an additional waste heat source. Therefore, the evaporator side can provide industrial chilled water. This capability makes the system ideal for combined cooling and heating in industrial parks, especially when coupled with thermal storage to leverage peak-valley electricity tariffs.

## Ultra-high Temperature Heat Pump Targeting 600°C

As previously discussed, for the transcritical $CO_2$ cycle, by continuously increasing the compressor suction temperature via high-temperature recuperation or waste heat supply, the upper heating limit can be significantly raised. Therefore, the heating temperature limit of the transcritical $CO_2$ cycle is by no means restricted to the 300°C range. Scholars worldwide have initiated research aiming to realize frontier transcritical $CO_2$ ultra-high temperature heat pump technology operating in the 500–600°C temperature range.[6] Notably, at such elevated temperatures, the transcritical CO2 cycle transitions into a phase-change-free reverse Brayton cycle. While stable operation above 600°C requires specialized high-temperature materials, reaching this temperature enables the replacement of conventional boilers, positioning the heat pump as pivotal for Pumped Thermal Electricity Storage (PTES). Validating this potential, the world's first 600°C 2MW ultra-high temperature heat pump recently successfully passed a 168-hour continuous full-load test, establishing a solid technical foundation for commercial deployment.[7] With this breakthrough, the system demonstrates significant potential across three scenarios illustrated in Figure 1: integrating renewable energy, retrofitting decommissioned thermal power plants, and enhancing the flexibility of active thermal power plants.

## RENEWABLE ENERGY INTEGRATION

In large-scale renewable energy (RE) bases, wind and solar power can be electrically conditioned (via converters, inverters, etc.) to directly drive the stable operation of the $CO_2$ ultra-high temperature heat pump cycle. The $CO_2$ ultra-high temperature heat pump absorbs low-temperature heat from a cold storage tank, superheating it via an internal heat exchanger. Then, it is compressed to a high-temperature, high-pressure state, reaching the 600°C range.[6] Via a high-temperature heat exchanger, this heat raises the molten salt temperature in a hot storage tank, storing energy as sensible heat. After long-duration storage, the high-temperature molten salt is dispatched to a novel power cycle, such as a supercritical carbon dioxide Brayton cycle. It heats the power cycle's working fluid to a high-temperature, high-pressure state (e.g., 560°C) via a high-temperature heat exchanger, which drives rotating machinery to generate electricity.[8] However, renewable fluctuations lead to unavoidable off-design operation, risking turbomachinery stall and surge and heat exchanger thermal fatigue, thereby constraining system safety and durability.

## RETROFITTING OF DECOMMISSIONED THERMAL POWER PLANTS

Integrating novel PTES technology with conventional coal-fired power plants is a critical initiative for transforming the current power structure, particularly considering China's reliance on coal power. For the retrofitting model, similar to the RE integration scenario, a reverse Brayton $CO_2$ ultra-high temperature heat pump is utilized for high-efficiency power-to-heat conversion, producing 600°C-range heat stored in molten salt to drive the original steam turbines for power generation. In this process, key assets like turbines are fully repurposed, while the original boiler system is completely replaced. However, as steam turbine lifespan is not significantly longer than the boiler's, reusing old turbines may lack economic viability. Thus, many roadmaps suggest reusing only the plant's buildings and grid infrastructure while installing new power-to-heat and heat-to-power systems. Furthermore, conventional power plants are typically located near urban centers, often lacking large-scale local RE sources. Therefore, in the retrofitting scenario, the $CO_2$ ultra-high temperature heat pump's electricity input is unlikely to be sufficiently supported by renewable power. Consequently, scholars propose using the retrofitted plant for intra-grid energy storage. By drawing electricity during off-peak periods and feeding it back during peaks, this setup equips the grid with a "Thermal Battery" to address regulation challenges and act as a form of grid-level flexible load response.

## FLEXIBILITY ENHANCEMENT OF ACTIVE THERMAL POWER PLANTS

The integration of PTES with conventional coal power also includes enhancing the flexibility of active coal-fired power plants. In this application, the architecture (reverse Brayton $CO_2$ heat pump, molten salt storage, etc.) resembles retrofitting scenarios but operates concurrently with the conventional plant. When power load increases, the high-temperature steam generated from the stored molten salt is injected into the main steam line of the conventional plant, jointly driving the main turbine for power generation. In conventional systems, capacity and ramping rate are controlled at the boiler combustion stage, which involves significant time delays and hinders rapid, flexible load response. However, by adding the $CO_2$ ultra-high temperature heat pump and molten salt system as an auxiliary, the main steam volume can be rapidly increased by controlling the molten salt pumps. This is highly significant for flexibility modifications such as peak shaving and frequency regulation. Functioning as a plant-level load response mechanism, the heat pump draws electricity directly from the turbine output during low loads and dispatches it back when loads rise. However, current steady-state research fails to address the rapid load ramping for grid fluctuations. Therefore, it is critical to investigate the multi-scale dynamic characteristics of Carnot batteries to reveal the ordered energy potential mechanisms under bidirectional disturbances.

## CONCLUSION

Amid carbon neutrality goals, $CO_2$ heat pump technology is emerging as a key solution for industrial heating and large-scale energy storage. This paper systematically reviewed the application of the $CO_2$ heat pump in two major frontier temperature ranges. In the 300°C super-high temperature heating domain, the $CO_2$ super-high temperature heat pump can efficiently generate industrial steam, replacing fossil fuel boilers. In the 600°C ultra-high temperature domain, $CO_2$ heat pumps drive "Thermal Batteries" for large-scale storage, integrating renewables with thermal infrastructure, aligning with specific national conditions, particularly in China. Furthermore, its adaptability across the full -40°C to 600°C spectrum enables synergistic cooling and heating, offering a high-efficiency integrated energy solution for industrial parks. Looking ahead, the evolution of $CO_2$ heat pump technology is poised to follow two directions: large-scale capacity expansion and high-parameter operation. For the refrigeration and low-temperature heating sectors (-40°C to 120°C), the focus will shift to MW-class centralized systems. For high-temperature applications (300°C/600°C), the frontier lies in mastering 20–30MPa pressures to solidify the role of $CO_2$ "Thermal Batteries" in the future high-capacity energy infrastructure.

In summary, $CO_2$ thermodynamic cycle technology is a critical link connecting the new energy system's source-grid-load-storage elements. Spanning the full -40°C to 600°C temperature spectrum, it provides vital technical support for industrial decarbonization and power system transformation.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.