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## **Large-scale underground energy storage: A key technology for carbon neutrality in China and Germany**

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Since its carbon peak in 1990, Germany's energy productivity related to GDP has increased by 60 %, and the share of renewable energy generation is nearly 12 times greater. Numerous energy spatial-temporal complementarities, such as energy efficiency, green buildings, renewable energy power systems, hydrogenation, electrification, increasing usage of smart technology, and electricity future marketization have contributed to achieving a power grid input/output balance. Even underground energy storage sites are currently used for natural gas, Germany has set the goal to use green hydrogen as a medium to promote sector coupling by using energy multiple conversion and reconversion technologies. Germany has established an underground storage plan for 73 billion kWh of green hydrogen in 2045. Meanwhile, Germany's electricity storage demand is expected to reach 45 ~ 90 billion kWh in 2030.

In comparison, China's annual electricity consumption is about 11 times that of Germany's. China's electricity storage demand is 500 ~ 1,000 billion kWh in 2030 and 6,000 ~ 7,000 billion kWh in 2060. Therefore, we propose a clean large-scale energy system based on smart sector coupling (ENSYSO), which uses digital technologies such as artificial intelligence and big data to couple energy production, storage, transport and utilization intelligently. To achieve large-scale energy storage, which is the most essential part of ENSYSO, we develop four underground energy storage modes. By analyzing the characteristics, challenges, typical cases, and potentials of every mode in China, we illustrate that the pilot projects of regenerative enhanced geothermal system and pumped-storage hydropower in mines should be conducted in China to lay the technical and economic foundation for a wide-scale replication. Due to the strict requirements on site selection, especially for underground hydrogen storage in salt caverns and depleted hydrocarbon reservoirs, the authors suggest that extensive geological surveys should be conducted to promote project implementation.