

空间解析建模评估碳中和目标下我国抽水蓄能与水电发展布局

摘要

中国承诺到 2060 年实现碳中和，这需要整合 5000 至 8000 吉瓦的可变可再生能源，可能对电网稳定性带来前所未有的挑战。本研究采用具有时空高分辨率的模型，对风-光-水混合系统的容量扩张和系统运行进行协同优化，量化了脱碳电网中抽水蓄能（PHS）和梯级水电的灵活性需求。结果表明，部署 205 吉瓦的开环抽水蓄能可使系统年成本降低 810 亿元人民币，同时将可变可再生能源弃电率降低 11%。通过对闭环抽水蓄能进行水库级别的精细化建模，我们发现，传统方法由于未能捕捉实际运行的灵活性，系统性地高估了 30% 的容量需求，并导致每年成本虚高 360 亿元人民币。关键在于，以可再生能源为主导的电力市场中的价格波动能产生足够的套利收益，使抽水蓄能无需补贴即可具备商业可行性——这一发现对全球能源转型的融资具有重要指导意义。此外，优化水电梯级运行每年可额外节省 1160 亿元人民币的成本。多年气候模拟进一步证实了该系统在多变气象条件下的强韧性。对抽水蓄能和水电灵活性进行高保真建模，对于设计大型电力系统深度脱碳的经济可行路径至关重要。

关键词

碳中和；抽水蓄能；梯级水电；电力系统扩展规划；可再生能源并网；系统灵活性

Abstract

China's commitment to carbon neutrality by 2060 requires 5000–8000 GW integration of variable renewable energy, which may pose unprecedented grid stability challenges. Using spatial-temporally resolved modeling to co-optimize capacity expansion and system operation for hybrid wind-solar-hydropower systems, we quantify the flexibility requirements of pumped hydro storage (PHS) and cascaded hydropower in a decarbonized grid. We demonstrate that deploying 205 GW of open-loop PHS reduces system costs by 81 billion yuan (about 11.6 billion USD) annually while decreasing VRE curtailment by 11%. Through reservoir-level modeling of closed-loop PHS, we reveal that conventional approaches systematically overestimate capacity requirements by 30% and inflate costs by 36 billion yuan (about 5.2 billion USD) annually by failing to capture operational flexibility. Crucially, price volatility in renewable-dominated markets generates arbitrage revenues sufficient to enable the commercial viability of PHS without subsidies—a finding with global implications for financing energy transitions. Optimizing hydropower cascade operations yields an additional 116 billion yuan (about 16.6 billion USD) in annual savings. Multi-year climate simulations confirm system resilience across diverse weather conditions. Sophisticated modeling of pumped storage and hydropower flexibility is essential for designing economically viable pathways to deep decarbonization in large-scale power systems.

Keywords

Carbon neutrality; Pumped hydro storage; Hydropower cascade; Power system expansion modeling; Renewable energy integration; System flexibility

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