

未来气候条件下基于数据驱动预测的净零电力系统充裕性评估

摘要

随着全球能源系统向碳中和转型，可再生能源发电波动性的不断增强以及负荷对气候变化的敏感性上升，正对净零电力系统的充裕性带来重大挑战。然而，现有评估通常缺乏一种能够在未来气候条件下，同时刻画高时空分辨率长期负荷变化以及输电与储能约束的分析框架。为此，本研究构建了一个综合评估框架，通过耦合高分辨率负荷预测与电力系统模拟，对净零电力系统的充裕性进行评估。首先，我们为中国开发了一个基于神经网络的小时电力负荷模型（HELM），用于预测不同社会经济与气候情景下的省级电力负荷。随后，将预测结果嵌入一个覆盖 30 个省份、8760 小时的模拟模型中，在每种碳中和转型情景下，通过超过 300 组跨省输电与储能配置方案评估系统运行表现。结果表明，到 2060 年，全国电力需求将达到 23262.59 TWh，夏季峰值负荷将达到 3234 GW，显示出未来电力系统在负荷波动加剧和峰值负荷攀升方面面临的挑战。在以风电和光伏为主导的电力系统中，显著的时空错配将导致最高达 59.54% 的潜在电力短缺。针对性扩张输电和储能可有效缓解这些缺口，使全国系统充裕性提高 16.25%，并在浙江等受电省份实现超过 50% 的提升。这些发现通过强调跨省基础设施、灵活性资源和市场化支持机制的协同发展，为中国能源转型提供了战略性路线图。

关键词

净零电力系统，电力负荷预测，机器学习，系统充裕性，跨省电力传输，储能

Abstract

As global energy systems transition toward carbon neutrality, the increasing variability of renewable generation and climate-sensitive load poses significant challenges to net-zero power system adequacy. However, current assessments often lack a framework that captures high-resolution, long-term load dynamics alongside transmission and storage constraints under future climate conditions. This study constructs an integrated assessment framework to evaluate the adequacy of a net-zero power system by coupling high-resolution load forecasting with power system simulations. We first developed a neural network-based Hourly Electricity Load Model (HELM) for China to forecast provincial load under diverse socioeconomic and climate scenarios. These forecasts were then integrated into an 8760-hour simulation model encompassing 30 provinces to assess system performance under more than 300 configurations of interprovincial transmission and energy storage for each carbon-neutral transition scenario. Results show that national electricity demand will reach 23262.59 TWh in 2060, with a summer peak of 3234 GW, revealing the challenges ahead in demand volatility and rising peak loads. In a power system dominated by wind and solar power, substantial spatiotemporal mismatches lead to potential electricity deficits of up to 59.54%. Targeted expansion of transmission and storage can mitigate these gaps, enhancing national system adequacy by 16.25% and exceeding 50% in power-importing provinces such as Zhejiang. These findings provide a strategic roadmap for China's energy transition by emphasizing the coordinated development of interprovincial infrastructure, flexible resources, and market-based support mechanisms.

Keywords

Net-zero power system, Electricity load forecasting, Machine learning, System adequacy, Interprovincial transmission, Energy storage

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