POWER TRANSFORMATION LAB

RAP REGULATORY ASSISTANCE PROJECT

低碳转型下的山东省地级市 2030 年资源充裕度展望

执行摘要

SHANDONG'S 2030 RESOURCE ADEQUACY OUTLOOK: A PREFECTURE-LEVEL ANALYSIS UNDER THE LOW-CARBON TRANSITION

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执行摘要

随着风电、光伏等可再生能源渗透率的快速攀升，中国电力系统的保供风险特征正发生深刻演变——由传统的“单一尖峰容量短缺”向“净负荷陡升时段爬坡受阻”及空间错配扩散。在新型电力系统转型背景下，单纯依靠扩建基荷电源的传统模式已难以适应复杂的保供需求，电力系统亟需建立精细、透明的资源充裕度规划评估框架。本报告以山东省为实证案例，深度分析其在低碳转型路径下应对可再生能源大规模部署与极端扰动时的资源充裕度表现及应对策略。

本研究采用机组组合与经济调度（UCED）模型，对山东省2030年夏季的资源充裕度进行评估。模型以山东省 16 个地级市为节点，时间分辨率为小时，重点推演夏季连续四周（共 28 天）内的电力调度与供电压力。

模型基于煤电、储能、风电和光伏四类关键资源，设定了“基准路径”与“低碳转型路径”，组合形成了 16 个演变情景。其中，煤电的低碳转型路径体现为由扩张转向有序收缩：压减待建煤电项目；加快部分存量机组退役；抽凝机组向可供工业供热机组转变。本研究不优化新增装机，而是在既定装机与网络条件下，通过计算每小时的“未供应电量”（NSE，即切负荷量）来识别系统的动态供电缺口。此外，在综合低碳转型情景下，模型进一步引入了跨省直流闭锁与极端气象（低风低光）两类压力测试，以检验系统在关键扰动下的保供韧性。

核心结论

通过逐小时的运行仿真与情景对比，研究在系统调度运行、空间碳排放、新能源消纳以及极端事件抗压性等方面得出以下关键结论：

1. 在收缩煤电规模的同时，山东仍可通过“风光+储能”协同部署，保障正常运行条件下的系统充裕度

- 在煤电可用容量收缩的路径下，若仅维持基准的新能源和储能扩张水平，山东夏季

高负荷时段将面临明显的充裕度压力，最大小时未供应电量达 6,091MWh。

- 单独积极扩张光伏或风电均能缓解部分供电压力，但无法完全消除最紧张小时的供需缺口。特别是夏季峰值负荷通常出现在夜间20—22时，已错过光伏主要出力时段，导致单独扩张光伏的容量支撑作用受限。

- 在收缩煤电扩张的同时，只有储能、风电和光伏实现同步的积极扩张（综合低碳转型情景），系统缺电情况才将完全消除。这表明缓解退煤风险的关键不仅是增加可再生能源装机，更在于构建“风光电量供给+储能峰时支撑”的组合能力。

- 在极端气象压力测试下，本研究将 28 天模拟期内每小时风速和太阳辐照统一下调至历史气象基线的 75%和 50%，以模拟持续的复合低风速—低日照事件。综合低碳转型情景展现出一定的系统韧性：75%设定下系统仍可保障充裕度；但在 50%设定下，东营、日照等局部城市将暴露供电风险，最大小时未供应电量分别为 1,825MWh 和 1,429MWh。

2. 储能可应对新能源出力时序错配与外来电中断扰动的双重挑战，成为巩固系统资源充裕度的关键支撑

- 高比例光伏装机导致日间（特别是 12—14 时）净负荷显著降低，但由于夏季负荷峰值通常出现在晚间，在光伏出力消失后，系统面临极高的爬坡与顶峰需求，使主要保供压力转移至晚间高负荷时段。

- 储能积极扩张能够有效将日间富余的光伏电量转移至晚高峰使用，从而显著降低系统需要由常规机组和外部电力承担的顶峰压力，是提高光伏对系统资源充裕度的实际贡献的关键。

- 跨省直流闭锁测试显示，在综合低碳转型情景下，单条外来电通道中断仍会暴露出资源充裕度缺口。例如，鲁固直流闭锁会导致威海市出现超 3,000MWh 的最大小时未供应电量。该风险不仅波及受端换流站所在城市，还会通过省内电网潮流向更广泛的节点（如东营）传导放大。

- 当电池储能装机提升至当前规划目标的 1.2 倍时，由直流闭锁引发的电量缺口可被完全消除，说明储能扩张能够提升系统应对短时扰动和时段性紧张的能力。需要指出的是，这一结果并不意味着储能可替代跨省输电能力。直流闭锁的持续时间会影响储能电量搬移能力。如果长时间闭锁，储能无法应对。储能和跨省输电在保障系统韧性方面共同发挥作用，其合理配置组合仍有待进一步研究。

3. 碳排放呈现高度的空间集中，缺乏替代资源的单边退煤易引发局部排放反弹

- 山东电力系统的碳排放压力高度集中在少数煤电出力较高的节点城市（如滨州、聊城和烟台）。

- 风电与光伏扩张能够较为稳定地降低各市碳排放，但煤电退出的影响并非单向。若仅收缩煤电发展规模，而风光储等替代资源没有充足扩张，从全省系统层面看，山东省总体碳排放会下降；但从城市尺度看，发电压力将向剩余煤电机组集中，导致部分城市（如聊城、济南）的碳排放不降反升。这说明，煤电退出的运行减排效果不仅取决于煤电装机规模的下降，也取决于低碳替代资源是否充足，以及其出力时段能否与系统需求相匹配。

4. 高比例风光扩张对储能与系统消纳空间提出更高要求

- 在储能维持基准发展路径的高风光扩张情景下，全省风光弃用率高达 9%。由于本地装机与储能配置的不匹配，弃电现象在空间上差异显著，部分“高光伏—低储能”城市弃电率接近 19%，成为消纳压力最集中的节点。配置储能可有效降低全省风光弃用率。

- 在煤电维持基准发展路径的情况下，进一步扩张风电和光伏将加剧新能源消纳压力，使全省风光弃电率升至 14%。

Executive Summary

Rapid growth in wind and solar power is fundamentally reshaping resource adequacy risks in China's power system. Resource adequacy risks are expanding from conventional peak-capacity shortages to ramping constraints during periods of rapid net-load growth and geographic mismatches between supply and demand. In the transition to a new power system, relying primarily on baseload capacity expansion is increasingly inadequate to meet the complex needs of power supply reliability. These changes call for a more granular and transparent approach to resource adequacy planning and assessment. Using Shandong Province as a case study, this report examines resource adequacy under a low-carbon transition, with a focus on large-scale renewable energy deployment and system resilience to extreme disruptions.

This report assesses Shandong's resource adequacy in 2030 using an hourly unit commitment and economic dispatch (UCED) model. The model represents all 16 prefecture-level cities as individual nodes and simulates four consecutive weeks of summer system operations.

The analysis constructs 16 scenarios based on alternative pathways for four key resources: coal power, energy storage, wind, and solar PV. The coal transition pathway reflects a managed reduction in available coal-fired capacity through a smaller project pipeline, retirement of selected existing units, and reduced power output from extraction-condensing units serving industrial heat demand. The model does not optimize new capacity additions. Given predefined generation and network configurations, it identifies dynamic supply shortfalls using hourly non-served energy (NSE), or unmet electricity demand. In addition, under the comprehensive low-carbon transition scenario, the stress tests examine sustained low-wind and low-solar conditions and outages of major interprovincial high-voltage direct-current (HVDC) import links.

Key Findings

Based on hourly operational simulations and scenario comparisons, the analysis yields four key findings on system operations, the spatial distribution of emissions, renewable energy integration, and system resilience to extreme events:

1. Coordinated wind, solar, and storage deployment can maintain resource adequacy as available coal-fired capacity declines

- Under the coal transition pathway, maintaining baseline renewable energy and storage

deployment creates significant resource adequacy pressure during summer peak periods. Maximum hourly NSE reaches 6,091 MWh.

- Expanding wind or solar alone reduces the shortfall but does not eliminate it. Solar provides limited support during Shandong's evening peak, which typically occurs between 8 p.m. and 10 p.m.

- Under the coal transition pathway, when wind, solar, and storage all follow the more ambitious deployment pathways, NSE falls to zero. Coordinated deployment is critical to managing the adequacy risks associated with coal capacity reductions.

- Under extreme weather stress tests, hourly wind and solar availability is reduced to 75% and 50% of the historical baseline, representing sustained compound low-wind and low-solar conditions. The system remains adequate in the 75% case. In the 50% case, local supply risks emerge in Dongying and Rizhao, with maximum hourly NSE reaching 1,825 MWh and 1,429 MWh, respectively.

2. Storage shifts solar generation to evening peak hours and strengthens resilience to import disruptions

- High solar penetration substantially reduces daytime net load, particularly between noon and 2 p.m. Shandong's summer demand typically peaks in the evening. As solar output declines, the system faces steep ramping requirements and high peak-capacity needs, shifting the greatest resource adequacy pressure to evening hours.

- Expanded storage deployment shifts surplus daytime solar generation to the evening peak, reducing the peak demand that must be served by conventional generation and imported electricity. Storage therefore plays a key role in increasing the effective contribution of solar PV to resource adequacy.

- Interprovincial HVDC outage tests show that supply shortfalls can re-emerge under the comprehensive low-carbon transition scenario when a major import corridor is disrupted. For

example, an outage of the Lugu HVDC link results in more than 3,000 MWh of maximum hourly NSE in Weihai. The effects can propagate through power flows across the provincial grid, extending beyond the city hosting the receiving converter station and increasing supply pressure at other nodes, including Dongying.

- Increasing battery storage capacity to 1.2 times the current planning target eliminates the modeled supply shortfalls caused by individual HVDC outages. This result highlights the ability of storage to manage short-duration disruptions and periods of acute system stress. The duration of an HVDC outage remains critical. Prolonged outages may exceed the energy-shifting capability of storage. Storage and interprovincial transmission therefore provide complementary support for system resilience, and their appropriate configuration warrants further study.

3. Power-sector emissions are geographically concentrated, and coal retirement can lead to local emissions rebounds

- Power-sector CO_2 emissions in Shandong are concentrated in a small number of cities, particularly Binzhou, Liaocheng, and Yantai.

- Wind and solar expansion consistently reduces emissions across cities, while the effects of coal retirement vary spatially. When coal capacity declines without sufficient expansion of wind, solar, and storage, total provincial emissions fall. Generation becomes more concentrated among the remaining coal-fired units, causing emissions to increase in some cities, including Liaocheng and Jinan. The operational emissions effects of coal retirement depend on the scale of coal capacity reductions, the availability of low-carbon replacement resources, and the alignment of their output with system demand.

4. High wind and solar deployment places greater demands on storage and renewable integration

- Under the baseline storage development, high wind and solar deployment results in a

province-wide curtailment rate of 9%. Curtailment approaches 19% in some cities with high solar capacity and limited storage. More ambitious storage deployment can significantly reduce renewable curtailment.

- Under the baseline coal pathway, further wind and solar expansion increases renewable integration pressure, raising the province-wide curtailment rate to 14%.