

# 建筑需求侧转型如何缓解中国深度脱碳中的能源、材料与土地约束

## 摘要

在全球气候变化背景下，以可再生能源扩张和终端电气化为核心的供给侧脱碳路径正逐渐受到关键矿产、土地空间及生态承载能力等资源约束的限制，使气候问题从“碳排放约束”转向“资源与系统规模约束”。在此背景下，需求侧转型被重新审视为实现深度脱碳的重要路径。尤其在中国，建筑部门正处于存量快速累积与集中更新并存的关键阶段，其规模与使用方式将长期锁定能源与材料需求。然而，现有研究多将需求侧简化为能效提升或减排潜力，缺乏对其如何通过跨部门传导重塑供给侧扩张路径及资源约束的系统性分析。本文构建建筑存量物质流模型（MFA）与能源系统优化模型（China-More 3.0）的顺序耦合框架，从“需求—系统规模—资源约束”的链条出发，系统评估建筑需求侧转型的宏观影响。结果表明，建筑需求侧转型在 2022–2060 年间可累计减排约 37 Gt CO<sub>2</sub>-eq，其中相当部分来源于通过控制建筑存量规模与优化空间利用所带来的需求收缩效应。在温室气体中和约束下，需求侧协同路径通过压缩终端能源需求，从源头降低系统规模，使 2060 年电力装机需求减少约 23%（约 2.3 TW），并显著缓解钢铁、水泥等难减排行业的转型压力。同时，需求侧转型通过避免供给侧扩张，在关键矿产、土地占用及系统成本等方面产生系统性资源缓解效应。总体而言，建筑需求侧转型的核心作用在于通过改变服务提供方式，从源头决定能源与材料系统规模，从而避免供给侧扩张并释放资源约束压力。这一机制为资源约束趋紧背景下实现深度脱碳提供了新的系统性路径。

## 关键词

建筑部门；需求侧转型；深度脱碳；物质流；能源系统优化

## Abstract

In the context of global climate change, supply-side decarbonization pathways centered on renewable energy expansion and electrification are increasingly constrained by critical minerals, land availability, and ecological limits. As a result, the climate challenge is shifting from carbon mitigation alone to one shaped by resource availability and system scale. Demand-side transformation has therefore emerged as a critical but under-explored pathway for deep decarbonization. This is particularly important for China, where rapid building stock accumulation and large-scale renewal create a crucial window for shaping long-term energy and material demand. However, existing studies largely reduce demand-side interventions to efficiency improvements, overlooking their role in reshaping system-scale dynamics and resource constraints. Here, we develop a sequentially coupled framework integrating a building stock-based Material Flow Analysis (MFA) model with an energy system optimization model (China-More 3.0) to assess demand-side transformation along the chain of demand, system scale, and resource constraints. We find that building demand-side transformation can deliver approximately 37 Gt CO<sub>2</sub>-equivalent cumulative emission reductions over 2022–2060, with a substantial share arising from demand reduction effects rather than efficiency improvements alone. By reducing final energy demand at the source, demand-side transformation fundamentally reshapes decarbonization pathways, lowering power system capacity requirements by about 23% (2.3 TW) by 2060 and alleviating transition pressures in hard-to-abate sectors such as steel and cement. Importantly, demand-side transformation generates systemic benefits by avoiding supply-side expansion. It reduces critical mineral demand, mitigates land use pressures by avoiding 17,800–32,500 km<sup>2</sup> of renewable energy deployment, and yields cumulative net system savings of approximately 9 trillion RMB. Overall, the primary value of demand-side transformation lies not only in emissions reduction, but in its ability to determine system scale by altering service provision, thereby alleviating multiple resource constraints simultaneously. These findings highlight the importance of shifting from supply-driven decarbonization strategies toward system-level approaches in which demand plays a central role.

## **Keywords**

Building sector; Demand-side transformation; Deep decarbonization; Material flow analysis; Energy system optimization

**Author:** 吴, 紫琪 (清华大学)

**Presenter:** 吴, 紫琪 (清华大学)

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