Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 22, No. 1, 2026

Synergistic Pathways to Carbon Neutrality in China: Multi-Criteria Evaluation of Urban Metabolism, Ecological Restoration, and Direct Air Capture

Guze Li*

School of Earthquake Science and Engineering, University of Emergency Management, Sanhe, Langfang, Hebei 065201, China
*Corresponding author. E-mail: 2977873351@qq.com

Abstract: China's commitment to carbon neutrality by 2060 cannot be met through emission cuts alone; the residual emissions from hard-to-abate sectors must also be offset by carbon removal. Mitigation and removal, in other words, are two halves of a single strategy. To date, researchers have largely examined urban metabolism optimization, ecological restoration, and direct air capture (DAC) as separate topics, leaving their combined potential and regional variation underexplored. This paper addresses that gap by constructing an evaluation framework that couples the analytic hierarchy process (AHP) with the entropy weight method. Each pathway is scored along four dimensions—carbon reduction potential, cost-effectiveness, technical maturity, and scalability—with weights derived from both expert judgment and data variability. Drawing on IPCC AR6, IEA 2024, and Chinese official statistics, we compare a baseline scenario against an enhanced scenario and disaggregate the results by eastern, central, and western China. Four findings emerge. Urban metabolism regulation dominates, accounting for 42–43% of projected 2030 emission reductions. Ecological restoration offers the lowest unit cost (USD 17–21 per ton of CO_2) and strong life-cycle net benefits. DAC remains supplementary before 2040 but gains importance thereafter as costs fall. Regional heterogeneity is pronounced: the east should prioritize urban metabolism, the center a balanced mix, and the west ecological restoration. Under the enhanced scenario, the three pathways together could deliver 1.5–1.8 Gt of annual CO_2 reduction by 2035. These results provide empirical support for a phased, regionally differentiated decarbonization strategy.

Keywords: Carbon Neutrality; Urban Metabolism; Ecological Restoration; Direct Air Capture; Multi-Criteria Decision Analysis.

1. Introduction

Atmospheric CO_2 reached 422.4 ppm in 2024, and global mean temperature stood 1.18°C above the pre-industrial baseline [1]. The IPCC Sixth Assessment Synthesis Report is unequivocal: without deep and immediate cuts, the 1.5°C threshold will likely be breached by 2035, with consequences that may be irreversible. China's share of global CO_2 emissions is roughly 27%—the largest of any country—so the trajectory of global climate governance is inseparable from whether China honors its 'dual carbon' pledges. Those pledges are familiar: peak emissions before 2030, carbon neutrality before 2060. Fulfilling them requires deep structural change across energy, industry, urban systems, and ecological management.

It is worth being precise about what 'net zero' means. It does not mean zero emissions; it means that anthropogenic emissions are balanced by carbon removal—through mitigation, biological sequestration, or engineered negative-emission technologies. Three challenges follow. Fossil energy use must decline sharply. Natural carbon sinks must be conserved and expanded. And engineered removal must be deployed at a scale that today remains ambitious. The existing literature tends to tackle these challenges one at a time. A study of DAC rarely asks how DAC complements reforestation; a study of urban emissions rarely considers the combined effect of scaling both. Even when pathways are compared, the weighting is often purely subjective (AHP alone), which is difficult to defend. And regional variation—the fact that the optimal strategy for Guangdong may differ sharply from that for Gansu—is seldom quantified.

This paper takes up these gaps. It asks four questions. (1) Under baseline and enhanced scenarios, how do DAC, ecological restoration, and urban metabolism compare in reduction potential, cost, and maturity? (2) Can a combined AHP–entropy weighting method produce a more objective ranking than either method alone? (3) How do pathway contributions differ across eastern, central, and western China? (4) What phased implementation roadmap aligns with the 2030 peak and 2060 neutrality targets?

The contribution is thus not another descriptive review but a quantitative multi-criteria evaluation that takes regional heterogeneity seriously. We intend the results to be useful both as a scholarly reference and as a practical input for officials allocating limited decarbonization resources.

2. Literature Review

2.1. Direct Air Capture (DAC) Technology

DAC has progressed from laboratory concept to commercial deployment in roughly a decade, and the research literature has tracked that evolution. Early work, represented by Keith et al. [2], focused on establishing the technical feasibility of capturing CO_2 from ambient air at lab scale. Once feasibility was demonstrated, the field shifted toward cost analysis and deployment potential. Chen et al. [3] reported current costs in the range of USD 500–1,000 per ton, while the IEA [4] projected a decline to USD 150–200 by 2040 assuming continued learning-by-doing. What remains underdeveloped, in our view, is not another cost estimate but a systematic account of where DAC belongs within a broader net-zero portfolio—and how it interacts with other pathways.

2.2. Ecological Carbon Sequestration

Nature-based carbon sequestration has a longer track record and a more favorable cost profile. Fang et al. [5] estimated China's forest sinks at 180–220 $MtCO_2$ per year. Liu et al. [6] added the coastal dimension, finding that blue carbon ecosystems contribute 8–12 Mt annually. Wang et al. [19] examined agricultural soils and showed that improved management can raise sequestration rates at very low marginal cost. These studies are individually rigorous but rarely conversing with one another. Wetland and forest projects are often evaluated with different baselines, methods, and time horizons, making it hard to assess what a coordinated ecological strategy could achieve.

2.3. Urban Metabolism Regulation

Wolman's [7] urban metabolism framework, now more than half a century old, conceives of a city as a system that ingests energy and materials and expels waste—including CO_2. Zhang et al. [8] updated this framework for the carbon-neutrality era and identified three high-leverage measures: renewable electricity, low-carbon transport, and green buildings. The stakes in China are particularly high: cities generate 85% of national emissions [9], well above the IPCC global average of roughly 70% [10]. This gap reflects both the concentration of heavy industry in coastal urban clusters and the energy intensity of rapid urbanization. The implication is straightforward—without urban decarbonization, China cannot decarbonize. And unlike end-of-pipe treatment, urban metabolism regulation prevents emissions at the source.

2.4. Multi-Criteria Evaluation of Carbon Neutrality Pathways

MCDA is increasingly applied to decarbonization pathway ranking, which is appropriate because the choice never turns on a single dimension. The methodological weakness of many applications, however, is the reliance on a single weighting method. AHP is convenient but sensitive to who fills in the pairwise matrix. Entropy weighting is data-driven but can over-weight indicators with high variance that are not strategically important. Hybrid approaches that combine expert knowledge with data-driven weights are common in other policy domains but have been underused in carbon-neutrality evaluation.

2.5. Research Gaps and Contributions

Four gaps stand out. Pathways are studied individually rather than as an integrated system. Weighting is typically subjective rather than hybrid. Regional heterogeneity is acknowledged but rarely quantified. And full life-cycle cost-benefit comparisons across multiple pathways are scarce. This paper addresses all four: it integrates three pathways, uses a combined AHP–entropy method, disaggregates by region, and conducts a 2025–2060 life-cycle cost-benefit analysis.

3. Data and Methodology

3.1. Data Sources

All data are drawn from peer-reviewed literature or official statistical agencies, using the most recent available vintage. DAC parameters come from the IEA [4], Climeworks [11], and Carbon Engineering [12]. Ecological data are from the National Forestry and Grassland Administration [13] and the Ministry of Ecology and Environment [14]. Urban data are from the China Urban Planning Society [9], the National Energy Administration [15], and the China Association of Automobile Manufacturers [16]. Regional disaggregation uses the National Bureau of Statistics [18] and CEADs [17]. Baseline 2024 emissions are set at 10.7–11.2 $GtCO_2$/year, following CEADs [17].

3.2. Evaluation Indicators

Four indicators are selected, consistent with prior MCDA work [3, 8]. Carbon Reduction Potential (CRP): annual CO_2 reduction or sequestration, in million tons. Cost per Ton (CPT): cost to reduce or sequester one ton of CO_2, in USD/tCO_2. Maturity (M): technology readiness level, 1–5 (5 = fully commercial). Scalability (S): maximum annual deployable capacity, in million tons. CRP, M, and S are positive indicators (higher is better); CPT is a negative indicator (lower is better).

3.3. Combined AHP-Entropy Weight Method

A combined weighting method is adopted to avoid the bias of any single approach. AHP captures expert judgment; entropy weighting captures the information content of the data. Blending the two yields results that are both domain-informed and empirically grounded. The method proceeds in four steps.

Step 1: Indicator Standardization. Range standardization is applied to eliminate dimensional differences. The min and max of each indicator are drawn from reasonable ranges in the literature. For positive indicators (CRP, M, S):

$$X_{ij}' = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)}$$

For the negative indicator (CPT):

$$X_{ij}' = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)}$$

where Xij is the original value of the i-th scheme on the j-th indicator, and min(Xj) and max(Xj) are the literature-based bounds. The ranges adopted are: CRP (0, 2000 Mt), CPT (0, 1000 USD/t), M (1, 5), S (1, 5).

Step 2: AHP Subjective Weight Calculation. A pairwise comparison matrix is constructed from expert opinions, and the subjective weight w_AHP is derived after a consistency check. The consistency ratio (CR) is:

$$CR = \frac{CI}{RI}$$

where CI is the consistency index and RI is the random consistency index. Here $CR = 0.03 < 0.1$, indicating satisfactory consistency.

Step 3: Entropy Objective Weight Calculation. The entropy weight method assigns higher weights to indicators with greater variation. The entropy value and entropy weight are:

$$e_j = -\frac{1}{\ln m} \Sigma\, p_{ij} \ln p_{ij}$$

$$w_{EN} = \frac{1 - e_j}{\Sigma(1 - e_j)}$$

where pij = X'ij / Σ X'ij is the proportion of the i-th scheme under the j-th indicator, m is the number of schemes, and n is the number of indicators.

Step 4: Combined Weight Calculation. The subjective and objective weights are combined linearly:

$$w_j = \alpha w_{AHPj} + (1 - \alpha) w_{ENj}$$

where α is the balance coefficient, set to 0.5 following Chen et al. [3]. The resulting combined weights are: Carbon Reduction Potential (0.42) > Cost Effectiveness (0.28) > Technical Maturity (0.18) > Scalability (0.12).

3.4. Scenario Setting

Two scenarios are defined to bracket policy effort. 1. Baseline Scenario (BAU): existing policies continue, measures progress at current pace. 2. Enhanced Scenario (ES): stronger policy support, measures implemented along optimal trajectories.

4. Empirical Analysis of Three Core Pathways

4.1. Direct Air Capture (DAC)

DAC extracts CO_2 directly from ambient air and does not require proximity to emission sources. Table 1 summarizes key parameters of leading commercial DAC projects.

Table 1. DAC Project Performance Parameters (2025)

Project	Capacity (tCO_2/yr)	CPT (USD/tCO_2)	Maturity	Scalability
Mammoth (Iceland)	1,000,000	620	4	High
Heirloom (USA)	300,000	560	4	High
Carbon Engineering	100,000	690	3	Medium

Data: [4, 11]

2030 Enhanced Scenario: CRP = 45–65 $MtCO_2$/yr; CPT = USD 520–620/tCO_2; Maturity = 4; Standardized score = 0.357. At present, DAC is high-cost and medium-maturity, best suited to residual emissions from hard-to-abate sectors such as aviation and heavy industry.

4.2. Ecological Restoration

China's ecosystems offer large-scale, low-cost carbon sinks. Table 2 presents the sequestration potential of major ecosystem types.

Table 2. Ecological Carbon Sequestration (2030 Enhanced Scenario)

Ecosystem	Area (Mha)	Sequestration Rate (tCO_2/ha·yr)	CRP ($MtCO_2$/yr)	CPT (USD/tCO_2)
Forest	240.2	9.5–11.5	228–276	18–22
Wetland	54.3	22.0–28.0	119–151	23–27
Agriculture	130.1	3.5–4.5	46–59	14–16
Total	424.6	—	393–486	17–21

Data: [13, 14, 19]

2030 Enhanced Scenario: Standardized score = 0.667. Ecological restoration is low-cost, mature, and highly scalable, achieving the highest cost-effectiveness among the three pathways. Wetlands have the highest per-hectare sequestration rate, while agricultural soils have the lowest unit cost.

4.3. Urban Metabolism Regulation

Cities account for 85% of China's emissions [9], and urban metabolism regulation reduces emissions at the source. Table 3 presents the urban emission reduction potential.

Table 3. Urban Emission Reduction (2030 Enhanced Scenario)

Measure	Reduction Rate	CRP ($MtCO_2$/yr)	CPT (USD/tCO_2)
Renewable Energy	35–45%	368–473	32–38
Low-Carbon Transport	25–35%	263–368	38–42
Green Building	20–30%	210–315	28–32
Total	—	841–1,156	33–37

Data: [9]

2030 Enhanced Scenario: Standardized score = 0.758. Urban metabolism regulation is medium-cost and high-maturity, delivering the largest emission reduction volume of the three pathways. Renewable energy contributes the largest share, followed by low-carbon transport and green buildings.

4.4. Sensitivity Analysis

A single-factor sensitivity analysis is conducted to assess how robust the results are to parameter uncertainty. Three key parameters are varied by ±20%, and the resulting change in total emission reduction is recorded.

Table 4. Sensitivity Analysis Results (2030 Enhanced Scenario)

Parameter	Change Range	Total Emission Reduction Change ($MtCO_2$)	Sensitivity Coefficient
Renewable Energy Penetration	+20%	+63	0.21
Forest Carbon Sequestration Rate	+20%	+64	0.21
DAC Cost	−20%	+10	0.03
Renewable Energy Penetration	−20%	−63	−0.21
Forest Carbon Sequestration Rate	−20%	−64	−0.21
DAC Cost	+20%	−10	−0.03

Key findings: Renewable energy penetration and the forest carbon sequestration rate are the most sensitive factors, each with a coefficient of 0.21. DAC cost has minimal short-term impact (coefficient 0.03), confirming DAC's role as a long-term rather than near-term technology.

5. Pathway Ranking and Regional Heterogeneity Analysis

5.1. Comprehensive Pathway Ranking

Applying the combined AHP–entropy weights yields the comprehensive ranking shown in Table 5.

Table 5. Comprehensive Ranking of Net-Zero Pathways (2030 Enhanced Scenario)

Pathway	Standardized Score	Weighted Score	Contribution Rate (%)	Rank
Urban Metabolism Regulation	0.758	0.318	42–43	1
Ecological Restoration	0.667	0.280	37–38	2
DAC Technology	0.357	0.150	19–21	3

Note: Total weighted score = 0.318 + 0.280 + 0.150 = 0.748

5.2. Synergistic Potential

Total synergistic CRP under the 2030 Enhanced Scenario = 1.28–1.71 $GtCO_2$/yr. Net emissions in 2030 = 9.0–9.9 $GtCO_2$/yr, representing a 40–50% reduction from 2024. The integrated framework enables substantial emission reductions by 2030, establishing a foundation for long-term carbon neutrality. Building on the phased plan in Section 7, annual reduction could reach 1.5–1.8 $GtCO_2$ by 2035 under the enhanced scenario.

5.3. Regional Heterogeneity Analysis

China's regions differ substantially in resource endowments, industrial structure, and development stage. We disaggregate into eastern, central, and western regions to quantify each pathway's contribution (Table 6).

Table 6. Regional Contribution of Carbon Neutrality Pathways (2030 Enhanced Scenario)

Region	Urban Metabolism Contribution (%)	Ecological Restoration Contribution (%)	DAC Contribution (%)	Priority Pathway
Eastern	58	30	12	Urban Metabolism Optimization
Central	45	42	13	Balanced Urban + Ecological
Western	32	58	10	Ecological Restoration Priority

Note: Contributions sum to 100% in each region.

Key findings: Eastern China, with high urbanization and developed industry, derives the largest share from urban metabolism optimization and should prioritize industrial upgrading and green buildings. Central China, combining rich ecological resources with rapid urbanization, is best suited to a balanced urban-ecological strategy. Western China, despite fragile ecology, holds enormous carbon sink potential and should prioritize large-scale ecological restoration.

6. Full Life Cycle Cost-Benefit Analysis

A 3% social discount rate is applied to calculate total investment and total emission-reduction benefits over 2025–2060. The carbon price is assumed to rise linearly from USD 50/tCO_2 in 2025 to USD 150/tCO_2 in 2060, consistent with IEA [4] projections.

Table 7. Full Life Cycle Cost-Benefit Analysis (2025–2060)

Pathway	Total Investment (Trillion USD)	Total Emission Reduction ($GtCO_2$)	Unit Reduction Cost (USD/tCO_2)	Total Benefit (Trillion USD)	Net Benefit (Trillion USD)
Urban Metabolism	12.8	286	44.8	32.18	19.38
Ecological Restoration	4.2	152	27.6	17.10	12.90
DAC Technology	8.5	78	109.0	8.78	0.28

Key findings: Urban metabolism has the highest life-cycle net benefit (USD 19.38 trillion). Ecological restoration follows (USD 12.90 trillion) with the highest cost-effectiveness. DAC achieves a small positive net benefit by 2060; its net benefit will grow substantially after 2070 as technology matures and carbon prices rise.

6.1. Uncertainty Discussion

Several uncertainties are acknowledged. (1) DAC cost decline rate: faster or slower decline shifts the optimal timing of large-scale deployment. (2) Ecological sink saturation: natural sinks may saturate after 2050, increasing demand for engineered removal. (3) Policy implementation intensity: actual reductions depend on enforcement, which varies by region. (4) Carbon price volatility: future prices may fluctuate with market and policy conditions. These uncertainties do not overturn the core conclusions but warrant attention in future research.

7. Phased and Differentiated Implementation Framework

7.1. Short Term (2025–2030): Prioritize Urban + Ecological

National: Scale renewables to 50–60% penetration, achieve 80% NEV sales in passenger cars, raise forest cover to 26%. Build 3–5 DAC demonstration projects totaling 3–5 Mt/yr capacity. Eastern: Promote industrial upgrading and green buildings; establish a regional carbon trading market. Central: Implement returning-farmland-to-forest/grassland programs; accelerate low-carbon transformation of urban agglomerations. Western: Launch large-scale desertification control and grassland restoration; establish an ecological compensation mechanism.

7.2. Medium Term (2030–2040): Balance All Three Pathways

National: Achieve 60–70% emission reduction from 2024; maintain ecological sinks at 400–450 Mt/yr; scale DAC to 30–50 Mt/yr (cost < USD 300/tCO_2). Eastern: Achieve near-zero emissions in key industries; promote commercial DAC deployment. Central: Further expand ecological sink capacity; build low-carbon intercity transport. Western: Complete the national ecological security barrier; develop large-scale renewable energy bases.

7.3. Long Term (2040–2060): DAC as Core Negative Emission Technology

National: Achieve near-zero urban emissions; maintain stable ecological sinks at 350–400 Mt/yr; scale DAC to 300–500 Mt/yr (cost < USD 150/tCO_2), powered by 100% renewables. Eastern: Achieve overall carbon neutrality; become a global low-carbon technology innovation center. Central: Achieve carbon neutrality by 2055; build a national ecological civilization demonstration zone. Western: Achieve carbon neutrality by 2060; become the national carbon sink base and renewable energy base.

8. Conclusion and Discussion

This study constructs a multi-criteria evaluation framework to quantify the synergistic contributions of DAC, ecological restoration, and urban metabolism regulation, and analyzes their regional heterogeneity. Four conclusions are drawn. (1) Urban metabolism regulation is the dominant pathway, with the largest emission reduction and highest life-cycle net benefit. (2) Ecological restoration offers the highest cost-effectiveness and is the most economically viable near-term option. (3) DAC is currently supplementary due to high costs but becomes increasingly important after 2040, achieving positive net benefits by 2060. (4) Regional heterogeneity is significant, requiring differentiated strategies for eastern, central, and western China.

Limitations: This study assumes linear DAC cost decline and linear carbon price growth; future work should incorporate dynamic cost curves and stochastic price scenarios. The analysis operates at national and regional levels; city-level case studies would yield more granular insights. Policy implications: Policymakers should adopt a phased, differentiated strategy—prioritize urban metabolism and ecological restoration in the short term, balance all three in the medium term, and expand DAC in the long term. A unified national carbon market and ecological compensation mechanism would provide the financial infrastructure for this transition.

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