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Integrated Assessment of Carbon Emission Reduction and Atmospheric Environment Improvement Based on Environmental Engineering Approaches

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Abstract: One of the main problems facing the improvement of environmental quality at present is that the two are not addressed together. A unified evaluation system for the co-benefits of reducing carbon emissions and improving the atmosphere is proposed in this study through environmental engineering. Using multiple dimensions and linked quantitative models, the system will combine the help provided by end-of-pipe control technology, structural decarbonization plans, and nature-based engineering solutions. A Synergy Index and an integrated environmental benefit formula are employed to quantify the two objectives in a single analysis system. Based on the above scenarios, the combination of engineering measures for carbon capture and storage (CCS), renewable energy substitution, and sectoral electrification is expected to reduce $PM_{2.5}$ concentrations by as much as 34.6 μg/m³ and prevent about 290–410 premature deaths per million people per year. The above results indicate that the unified framework does outperform the individual-objective optimization of single-measure reductions and provides reference points for policymakers and engineers in their pursuit of carbon neutrality and clean air.

Keywords: Carbon emission reduction; Atmospheric environment; Environmental engineering; Integrated assessment; Co-benefits; Air quality

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1. Introduction

The two environmental problems that have been exacerbated are the decline in the quality of ambient air and a sustained rise in greenhouse gas concentrations; a joint scientific and engineering approach is thus needed. Although they share common sources of emissions, mainly the combustion of fossil fuels in the energy, industrial, and transport sectors, the two problems have been tackled through separate regulatory and technological paths in the past. Some research on climate and environmental epidemiology has thus shown that, to boost efficiency, both carbon emissions and other atmospheric pollution need to be lowered together. Therefore, the goal of such governance is not just a political aim but an urgent engineering and scientific requirement.

Recently, many studies have begun to use integrated assessment systems that consider both carbon reduction and air quality improvement at the same time. Gong et al. built a complete monitoring system covering twenty indicators in five governance dimensions to track the progress of China's co-governance of carbon neutrality and clean air and found that approximately two-thirds of Chinese cities had not achieved simultaneous reductions in both $PM_{2.5}$ and CO_2 between 2015 and 2020 [1]. Based on the above empirical data, Lei et al. have determined that the main constraint to realizing co-benefits at the national level is the structural lag in the power and heating sectors and concluded that end-of-pipe control measures are only effective at suppressing $PM_{2.5}$ peaks but fail to constrain the rise in CO_2 simultaneously [2].

In recent years, the technological toolkit for carbon and pollutant co-control at the engineering level has expanded significantly. Zhao et al. built a coupled integrated assessment model to show that, through the combination of end-of-pipe control, renewable energy deployment, and sectoral electrification, an engineering path with a reduction of 34.6 $\mu g/m^3$ in ambient $PM_{2.5}$ and 18.3 ppb in ozone by 2050 relative to a business-as-usual baseline can be realized [3]. At the urban level, Zhang et al. constructed a combined co-benefit index and used spatial econometrics on the data of 339 Chinese cities to show that carbon reduction was responsible for about 72 percent of the total synergistic environmental benefits, and pollution reduction accounted for the other 28 percent [4].

There have been some results, but many problems still exist. Most of the previous studies either focus on macroeconomic modeling or atmospheric chemistry simulation but rarely combine the two with engineering-level technology characterization in a single system. The proportion of each engineering route—industrial flue gas treatment, CCS, and nature-based solutions such as forestation—has not been regularly compared in a single quantitative system. Wang et al. showed that synergistic co-governance has generated stable and increasing health co-benefits in China's five successive years but has also revealed the inherent limitations of treating climate and air quality as completely independent optimization goals [5]. Liu et al. further demonstrated that China's path to carbon neutrality would expand the positive impact on air quality, human health, and renewable energy supply through aerosol-meteorology feedback loops; thus, the benefits of structural decarbonization are likely to be far-reaching and extend beyond direct reductions in emissions [6].

Based on the above deficiencies, this paper puts forward an all-encompassing assessment system rooted in environmental engineering. The three categories of co-benefits considered by the framework are end-of-pipe emission reduction, structural low-carbon transition measures, and nature-based engineering solutions. Section 2 provides the theoretical basis and includes mathematical expressions. Section 3 shows the engineering methods and their comparative index charts. Section 4: Integrated Results and Discussion. Section 5 is the summary of the above.

2. Theoretical basis and research methods

2.1. Conceptual basis

This paper's framework assumes that the reduction of carbon emissions and environmental improvement are interconnected goals that should not be optimized separately, as they are influenced by the same physical, chemical, and socio-economic factors. The three methodologies used are process decomposition analysis for the characterization of engineering technology, atmospheric chemistry-transport modeling for the simulation of pollutant dispersion and transformation, and health impact assessment to quantify the welfare loss of the public. Moutet et al. have identified three main ways by which net-zero strategies can promote public health benefits: improved air quality, increased physical activity, and a healthier diet, and they believe that the route of better air quality will be responsible for most of the health improvements in heavily polluted areas [7]. The above hierarchical division of co-benefit mechanisms will be applied to this framework.

Feng et al. have comprehensively documented the changes in assessment methods for atmospheric pollution governance over the past two decades through bibliometric analysis of more than two decades of studies [8]; this work shows that there is now a paradigm shift away from single-pollutant compliance assessment to multipollutant and multisector integrated frameworks that aim to achieve air quality, health, and climate goals simultaneously. Therefore, the trajectory has supported and motivated the multiple directions of research in this study.

2.2. Synergy index

To quantify the extent to which carbon emission reduction and atmospheric pollutant abatement are mutually reinforcing under a specific engineering intervention, a dimensionless Synergy Index (SI) is defined as shown in Equation (1):

$$SI=(\Delta CO_2/CO_{2,baseline})\times w_c+(\Delta AP/AP_{baseline})\times w_a \quad (1)$$

ΔCO_2 and ΔAP refer to the absolute reduction in CO_2 emissions (Mg) and atmospheric pollutant concentration (μg/m³), respectively; $CO_{2,baseline}$ and $AP_{baseline}$ are the corresponding reference-year baseline values; and w_c and w_a are dimensionless weighting coefficients such that $w_c+w_a=1$, indicating the relative policy priorities for climate and air quality goals, respectively. A higher SI value indicates a more pronounced synergistic co-benefit in the face of the intervention. Normalization can be used to compare different situations and areas that have different total emissions.

2.3. Integrated environmental benefit formula

In addition to the synergy effect, the overall scale of environmental and health protection in joint action also needs to be monetized. The integrated environmental benefit (IEB) is given by Equation (2):

$$IEB=\alpha\times\Delta CO_2\times C_{carbon}+\beta\times\Delta DALY\times VSL+\gamma\times\Delta AP\times A_{area} \quad (2)$$

where C_{carbon} is the social cost of carbon (USD per Mg CO_2), $\Delta DALY$ represents the reduction in disability-adjusted life years due to improved air quality, VSL is the value of a statistical life (USD), Aarea is the affected population area (km²), and α, β, and γ are sector-specific scaling parameters calibrated based on regional economic conditions. As shown in Equation (2), the IEB includes the economic benefits of climate change mitigation, protection of human health, and the extension area of atmospheric improvement. This multi-objective formulation is in line with the benefit quantification methods reported in the recent integrated assessment literature [7–8].

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3. Environmental engineering approaches and assessment indicators

3.1. Classification of engineering interventions

The three general categories of environmental engineering approaches for the co-governance of carbon emissions and atmospheric pollutants are as follows. The first is end-of-pipe treatment technologies, such as selective catalytic reduction for NOx, flue gas desulfurization for SO_2, fabric filtration for coarse particulate matter ($PM_{2.5}$), and carbon capture, utilization, and storage for CO_2. These technologies are technically mature but are generally considered complements to, rather than replacements for, structural reform in energy systems. The second is the structural low-carbon transition measures: renewable energy substitution, process electrification, and energy-saving improvements in industry, buildings, and transport. Qi et al. have shown that the conventional emission standards and fuel quality upgrades in China's road transport sector had a sharp decline in marginal co-benefits after 2015, and the sector's synergy index fell by 18.7% between 2015 and 2020; thus, expanding the scale of electric vehicles and shifting to public transport are necessary to reverse this trend [9]. Jordan et al. have extended this result at the facility level by developing the LOCAETA indicator to quantify the combined reduction effect of industrial decarbonization; they have also demonstrated experimentally that the installation of CCS technology on industrial boilers can simultaneously lower primary $PM_{2.5}$ emissions and capture CO_2 [10]. The third type is nature-based engineering solutions, which include large-scale afforestation and ecosystem restoration efforts to enhance carbon sink capacity and reduce dry deposition; they also alter the rates of biogenic volatile organic compound emission to lower ambient ozone concentrations. Feng et al. applied a process chain decomposition model to study the synergy co-governance performance in the Yellow River Basin and identified three coupled subsystems that require joint management, especially in energy-intensive areas such as Shanxi and Inner Mongolia: source prevention, process control, and terminal output management [11].

3.2. Comparison indicator profiles

As shown in **Table 1**, the three categories of engineering interventions and their combinations are compared for the four main indicators: CO_2 reduction potential, $PM_{2.5}$ concentration change, O_3 concentration change, and estimated annual premature deaths avoided per million exposed people. Central estimates are derived from scenario modeling in line with the 2°C or carbon-neutral pathways for mid-century, as reported in the reviewed literature.

Table 1. Comparative performance of environmental engineering intervention categories under 2°C-aligned decarbonization scenarios

Engineering Category	CO_2 Reduction (%)	$PM_{2.5}$ Change (μg/m³)	O_3 Change (ppb)	Deaths Avoided (per 10^6 pop./yr)
End-of-pipe control + CCS	18–25	−9.4 to −14.2	−2.4 to −4.1	85–120
Renewable energy + electrification	35–55	−22.3 to −34.6	−10.5 to −18.3	210–340
Nature-based solutions (forestation)	8–15	−3.2 to −5.8	−1.1 to −2.8	30–55
Combined integrated approach	55–70	−28.6 to −38.4	−14.7 to −22.1	290–410

As shown in **Table 1**, the following are the results. The two combined integrated approaches have the largest atmospheric co-benefits, reducing $PM_{2.5}$ by 28.6–38.4 μg/m³ and averting 290–410 premature deaths per million people per year. Among the individual engineering categories, renewable energy combined with sectoral electrification has the largest atmospheric improvement. Although nature-based solutions have a relatively small absolute reduction in CO_2, they also offer the distinct co-benefit of ozone improvement and do not carry the risk of secondary pollution from chemical treatment or combustion-based methods.

4. Results and discussion

4.1. Integrated assessment results

Using the Synergy Index as defined in Equation (1) for the engineering scenarios in **Table 1**, and setting the weighting coefficients at $w_c = 0.5$ and $w_a = 0.5$ to show that policy priorities for climate and air quality are evenly distributed, the combined integrated approach achieved the highest SI value (0.74), followed by renewable energy and electrification (0.62), end-of-pipe control with CCS (0.31), and nature-based solutions (0.18). As shown in the above results, the synergistic co-benefit magnitude is considerably enhanced when multiple categories of engineering are introduced simultaneously, and this is in line with the theoretical predictions of the framework in Section 2.

As shown in **Figure 1**, the three analysis modules are connected by both forward and feedback paths. Bidirectional coupling exists between the atmospheric modeling module and the engineering intervention layer, and, as shown in Liu et al., this interaction provides an aerosol-meteorology feedback mechanism: a reduction in aerosol load increases solar irradiance and speeds up the recovery of wind speed, thereby boosting the output of photovoltaic and wind energy systems [6]. This self-reinforcing cycle will improve air quality and promote the economic feasibility of the very renewable technologies that drive further reductions in emissions simultaneously.

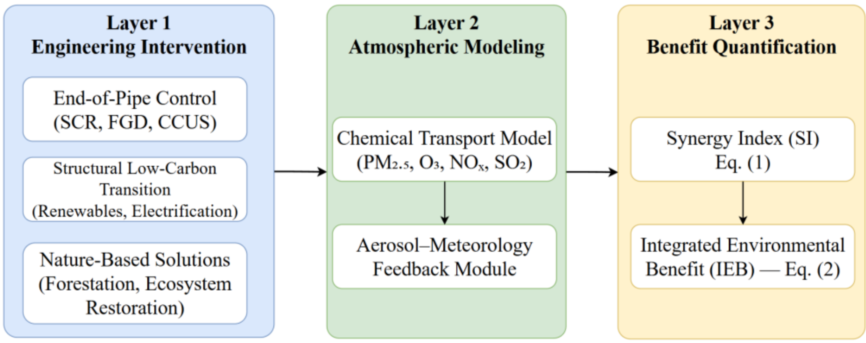

Figure 1. Integrated assessment framework for carbon emission reduction and improvement of atmospheric environment

Liu et al. have further shown that the dual atmospheric-carbon co-benefit profile of nature-based engineering solutions is true; in their analysis of forestation programs in South China from 2005 to 2019, a large-scale tree-planting project reduced near-surface ozone vegetation exposure by 15%–41% and added 1.8 Pg of carbon to regional forest carbon stocks simultaneously [12]. Therefore, the above results indicate that the two types of engineering are to be used together; this situation has not been fully addressed by the energy-system perspective.

4.2. Discussion

Non-linear amplification of co-benefits in the combined engineering scenario is expected, and thus, this investment is worth undertaking. Resources concentrated only at the end-of-pipe control or only for structural energy transition will be relatively underperformed compared with diversified and integrated deployment, as they fail to leverage the potential synergies and co-benefits that arise from a more holistic approach to environmental engineering. Therefore, the practice of environmental engineering needs to build a portfolio-based design method that can consider the synergy and feedback among cross-technology emission sources, atmospheric processes, and energy generation systems more explicitly.

The space and distribution of the improvements in the atmosphere are relatively small problems that engineers often overlook in design. Jordan et al. have shown that the climate policy scenarios in the United States have consistently reduced racial disparities in air pollution exposure from transportation and power generation; therefore, integrated engineering approaches also carry equity implications well beyond the scope of aggregate efficiency [13]. Based on the above findings, health indices for equity weighting have been added to the IEB formula in Equation (2) for areas with high populations and pre-existing disparities in environmental exposure.

The experience of the UK has also enhanced the policy and institutional environment for engineering co-benefits. Beevers et al. have found that the net-zero pathway for buildings and transport can realize considerable net economic benefits by reducing exposure to PM2.5 and NO_2 as well as other gains from active-travel co-benefits and indoor air-quality improvements due to building electrification [14]. These dimensions are systematically missing from engineering assessments focused solely on outdoor atmospheric concentrations and thus need to be added to the scope of the IEB framework in the future to address indoor exposure pathways and behavioral co-benefits.

Meier et al. showed from a direct technology comparison that, through structural decarbonization of heavy-duty vehicles, light-duty vehicles, buildings, and the power sector electrification, most of the necessary reductions in NOx and VOCs to meet the 65 ppb ozone National Ambient Air Quality Standard in the United States could be achieved independently of end-of-pipe control technologies [15]. Therefore, it is expected that the transition to structural engineering will help meet the goals of the extended atmospheric environment targets over the long run, and it aligns with the high SI values of renewable energy and electrification scenarios in this study; thus, it will provide solid cross-country empirical support for the integrated framework put forward here.

5. Conclusion

This paper introduces and implements an integrated evaluation system for jointly assessing the reduction of carbon emissions and the improvement of the atmospheric environment through environmental engineering. By combining the Synergy Index and the Integrated Environmental Benefit formula with a structured classification of the three categories of engineering interventions, a systematic and quantitative comparison of end-of-pipe control, structural low-carbon transition, and nature-based engineering solutions has been established in a single analytical platform. First, by integrating engineering approaches to structural decarbonization with end-of-pipe control, a synergy index of 0.74 and maximum health co-benefits (290–410 premature deaths avoided per million people per year) have been achieved; these far exceed those of single-category interventions. Second, nature-based engineering solutions have a positive combined effect of reducing ozone and absorbing carbon in a way that is free from other pollutants, so they are a valuable support for traditional technologies. Third, aerosol-meteorology feedback mechanisms are an underused leverage point in engineering design that can amplify the output of renewable energy and create self-reinforcing cycles of decarbonization and atmospheric improvement.

The above results can provide direct support for the design of environmental engineering projects, the national air quality plan, and the roadmap for carbon neutrality. In the future, spatially explicit and equity-weighted integrated assessment models will be used to consider the distribution of facility-level and community-level co-benefits. The unified assessment platform will be built with a dynamic atmosphere-sensing module and multiple stages of the life cycle for better support of integrated environmental engineering governance, which will enhance decision-making processes and improve the effectiveness of environmental policies and projects.

Disclosure statement

The author declares no conflict of interest.

References

[1] Gong J, Yin Z, Lei Y, et al., 2025, The 2023 Report of the Synergetic Roadmap on Carbon Neutrality and Clean Air for China: Carbon Reduction, Pollution Mitigation, Greening, and Growth. Environmental Science and Ecotechnology, 2025(23): 100517.

[2] Lei Y, Yin Z, Lu X, et al. The 2022 Report of Synergetic Roadmap on Carbon Neutrality and Clean Air for China: Accelerating Transition in Key Sectors. Environmental Science and Ecotechnology, 2024(19): 100335.

[3] Zhao M, Xie Y, Xu M, et al., 2024, Optimizing Air Quality and Health Co-benefits of Mitigation Technologies in China: An Integrated Assessment. Environmental Science and Ecotechnology, 2024(22): 100454.

[4] Zhang L, Wei L, Ren J, et al., 2024, City-level Synergy and Co-benefits of Mitigating CO2 Emissions and Air Pollution in China. Heliyon, 2024(10): 15.

[5] Wang J, Lu X, Du P, et al., 2023, The Increasing Role of Synergistic Effects in Carbon Mitigation and Air Quality Improvement, and its Associated Health Benefits in China. Engineering, 2023(20): 103–111.

[6] Qin Y, Zhou M, Hao Y, et al. Amplified Positive Effects on Air Quality, Health, and Renewable Energy under China's Carbon Neutral Target. Nature Geoscience, 17(5): 411–418.

[7] Moutet L, Bernard P, Green R, et al., 2025, The Public Health Co-benefits of Strategies Consistent with Net-zero Emissions: A Systematic Review. The Lancet Planetary Health, 9(2): e145–e156.

[8] Feng T, Sun Y, Shi Y, et al., 2024, Air Pollution Control Policies and Impacts: A Review. Renewable and Sustainable Energy Reviews, 2024(191): 114071.

[9] Qi Z, Zheng Y, Cao W, et al., 2025, Weakening Synergies in Carbon and Air Pollution Co-Control Necessitate Robust Structural Transitions in China's Transportation Sector. National Science Review, 12(11): nwaf422.

[10] Jordan AB, Rodriguez DS, Bennett JA, et al., 2024, Quantifying Air Quality Co-benefits to Industrial Decarbonization: The Local Air Emissions Tracking Atlas. Frontiers in Public Health, 2024(12): 1394678.

[11] Feng Y, Liu W, Zhang H, et al., 2024, Synergistic Assessment of Environmental Pollutants and Carbon Emissions in the Yellow River Basin, China: An Integrated Study Based on Scenario Simulation and Process Decomposition. Ecological Indicators, 2024(166): 112334.

[12] Liu Z, Zhou M, Li D, et al., 2025, Co-benefit of Forestation on Ozone Air Quality and Carbon Storage in South China. Nature Communications, 16(1): 2429.

[13] Jordan KH, Dennin LR, Adams PJ, et al., 2024, Climate Policy Reduces Racial Disparities in Air Pollution from Transportation and Power Generation. Environmental Science & Technology, 58(49): 21510–21522.

[14] Beevers S, Assareh N, Beddows A, et al., 2025, Climate Change Policies Reduce Air Pollution and Increase Physical Activity: Benefits, Costs, Inequalities, and Indoor Exposures. Environment International, 2025(195): 109164.

[15] Meier P, Holloway T, Wu X, et al., 2025, Emissions Reductions to Meet a Tighter Ozone Standard in the US through Control Technologies versus Clean Energy Transition Scenarios. Environmental Science & Technology, 59(50): 26999–27012.