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Article

IMED|HEL model: Evaluating co-benefits of air pollution control and climate policies for health and economic outcomes

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ABSTRACT

IMED|HEL is a health and economy assessment module within the Integrated Model of Energy, Environment, and Economy for Sustainable Development (IMED). It is designed to evaluate the health and economic implications of environmental and climate policy choices. The module follows a single chain from scenario assumptions to emissions, pollutant concentrations, population exposure, health outcomes, and economic metrics. It represents both ambient exposure and indoor exposure related to household fuel use. Across China-focused applications at national, regional, city, and sector scales, the framework has expanded from $PM_{2.5}$-focused burden accounting to ozone-inclusive and joint $PM_{2.5}$-O_3 assessments. It has also moved from damage estimation to evaluating end-of-pipe controls, structural transitions, and climate and air quality synergies. The model provides strong support for incorporating health damages as a core policy outcome when comparing and prioritizing pollution control and mitigation options.

KEYWORDS

HEL model, air pollution, health impact assessment, economic assessment, co-benefits, climate policy.

1 Introduction

As climate change accelerates, its deep impacts on human health are receiving increasing global attention. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) clearly emphasized that climate change is not only an environmental or economic challenge, but also a major public health concern[1]. Rising global temperatures, worsening air pollution, the increased frequency of extreme weather events, and the changing prevalence of infectious diseases are creating new and complex health burdens across populations. Among these, air pollution, including fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), has been repeatedly linked to elevated risks of premature mortality[2-7], respiratory[8-12] and cardiovascular diseases[13-17], as well as cognitive[18,19] and labor productivity[20,21] impacts. The World Health Organization (WHO) estimated that ambient and household air pollution together contribute to an estimated 6.7 million premature deaths annually[22].

In recent years, the health co-benefits of climate mitigation policies have earned increasing attention as governments strive to balance environmental objectives with public health improvements. The co-benefits include improvements in air quality, health, and economic productivity, as better air quality leads to fewer diseases, which in turn enhances labor productivity and overall economic performance. Research consistently shows that climate policies bring substantial health co-benefits across scales[23-25]. Measures such as national emissions trading systems[26], fossil fuel reduction[27], and trade interventions like tariffs[28] have been linked to improved air quality, reduced $PM_{2.5}$ exposure, and lower morbidity and mortality.

To address the need for more integrated assessments, many integrated assessment models (IAMs) have evolved to incorporate modules that estimate the health impacts of environmental change. However, health effects are still frequently treated in a relatively simplistic or exogenous fashion, limiting the accuracy and policy relevance of the results. In response to this limitation, we developed the IMED|HEL model as a dedicated component of the broader Integrated Model of Energy, Environment, and Economy for Sustainable Development (IMED). The IMED|HEL model is designed to quantitatively evaluate both the health and economic consequences of air pollution exposure under alternative development trajectories, with a particular emphasis on capturing the co-benefits of climate mitigation strategies. By embedding health outcomes directly into environmental and energy policy analysis, the model helps bridge disciplinary gaps and enhances the capacity for informed, equitable, and synergistic decision making.

2 Overview of the IMED|HEL framework

2.1 Conceptual structure of the IMED|HEL framework

The IMED|HEL module forms a core analytical component of the IMED, designed to evaluate the economic consequences of health outcomes arising from environmental exposures. It quantifies the pathways from policy driven emissions changes to pollutant concentrations, human exposure, health burdens, and resulting economic impacts. The model's flexible architecture allows it to address multiple types of pollution across varied spatial and socioeconomic contexts.

Figure 1 illustrates the architecture of the IMED|HEL framework. External control policies and energy structure assumptions are first translated into emissions using an energy system model together with GAINS. The resulting emissions include SO_2, NO_x, VOCs, CO, and particulate matter. These emissions then drive an atmospheric model such as GEOS-Chem

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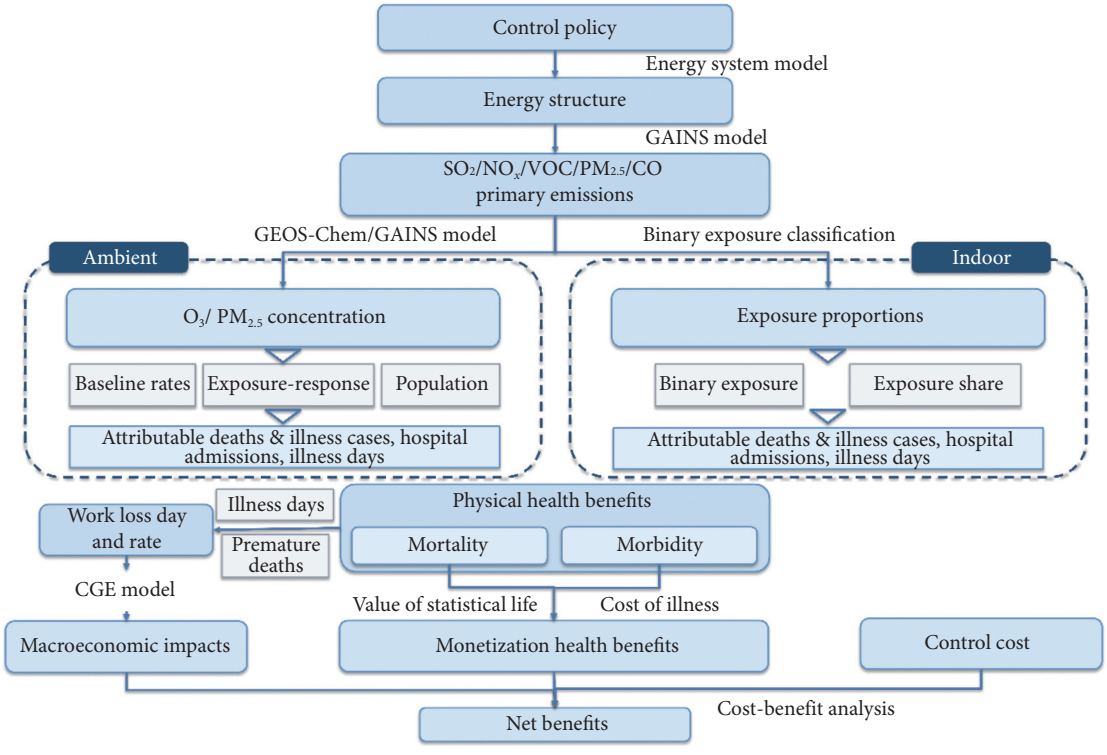


Fig. 1 General structure of the IMED|HEL model.

to produce spatially resolved concentrations of key pollutants, including $PM_{2.5}$ and ozone, for ambient and indoor exposure analysis.

To enhance the comprehensiveness of the model, an extension has been incorporated to account for indoor air quality in residential settings, with a particular focus on exposure to pollutants from household solid fuel use. This addition complements the existing ambient air pollution pathway by capturing a distinct yet significant source of health risk that is especially relevant in certain populations. To reflect these two key sources of exposure, the model now distinguishes between two parallel pathways, ambient air pollution and indoor air pollution. For ambient conditions, pollutant concentrations are spatially mapped to population distributions using geographic overlays. In contrast, indoor exposure is characterized using a binary classification approach, based on the proportion of the population using solid fuels and an associated ventilation coefficient. This dual-pathway structure enables more comprehensive and context-sensitive scenario analyses of air pollution-related health risks.

The resulting health effects are subsequently translated into economic terms. Monetization relies on two complementary approaches, the value of a statistical life is used to estimate the economic loss from premature deaths, while the cost of illness method captures direct healthcare expenditures and productivity losses. In parallel, the model computes labor loss metrics, such as per capita work loss rate, which can be further integrated with macroeconomic models such as computable general equilibrium (CGE) systems to estimate broader economic repercussions. All cost and benefit components are finally synthesized in a cost-benefit analysis framework, which allows for a direct comparison between monetized health benefits and control costs, supporting net benefit evaluations across scenarios and informing policy prioritization.

A key strength of the IMED|HEL framework lies in its modularity and compatibility with broader integrated assessment systems. The model can be applied in stand-alone mode to assess air pollution health impacts across regions and timeframes or coupled with CGE models to account for dynamic economic feedbacks. Its flexible design enables the incorporation of various pollutant types, geographical resolutions, and valuation methods, making it adaptable to both national-scale and sector-specific studies. By linking atmospheric science, health risk modeling, and economic valuation in a coherent structure, IMED|HEL provides an interdisciplinary tool for assessing the co-benefits of pollution control and climate mitigation policies.

2.2 Positioning IMED|HEL within existing integrated frameworks

A broad set of modelling tools has been developed to quantify the health and economic co-benefits of air-pollution and climate policies, with different tools emphasizing different segments of the policy-to-impact chain. Table 1 summarizes how IMED|HEL relates to several commonly used models/tools in China-related co-benefit assessments, including REACH (Regional Emissions Air-quality Climate Health assessment framework), GAINS, ABaCAS (Air Benefit and Cost and Attainment Assessment System), InMAP-China (Chinese version of the Intervention Model for Air Pollution), and BenMAP-CE (Environmental Benefits Mapping and Analysis Program - Community Edition). The comparison covers key dimensions such as scenario drivers, emissions and control costs, air-quality representation, exposure (outdoor and indoor), health outcomes, monetary valuation, and the extent to which economy wide feedbacks can be represented.

IMED|HEL provides internally consistent health and economic damage accounting that is comparable across scenarios, while remaining compatible with external upstream inputs. It can take

Table 1 Comparison of IMED|HEL with existing integrated models for air pollution health and economic co-benefits (China-focused).

Dimension	IMED|HEL	REACH	ABaCAS	GAINS	InMAP-China	BenMAP-CE
Scenario / activity drivers	○	✓	○	—	—	—
Emissions representation	○	○	✓	✓	○ (as input)	—
Control options and abatement costs	○	○	✓	✓	—	—
Air quality representation	○/✓ (can use CTM outputs / concentration fields)	○	○ (often reduced-form/attainment-oriented)	○ (reduced-form / source-receptor type)	✓ (reduced-complexity AQ)	— (takes Δconcentration as input)
Exposure characterization (outdoor)	✓	✓	✓/○	✓/○	✓	✓
Exposure characterization (indoor)	✓	—/○	—/○	—/○	—	—/○
Health outcomes	✓	✓	✓	○/✓ (version-/setup dependent)	✓ (typically via linked HIA)	✓
Monetary valuation	✓ (multi-channel)	○	✓/○	○	○	✓
Economy wide feedback	✓ (via CGE linkage)	○/✓	—	—	—	—

Legend: ✓ = typically built-in / direct output; ○ = sometimes possible via extensions or user implementation; — = not a design focus.
Note: CTM denotes chemical transport model; AQ denotes air quality; HIA denotes health impact assessment; VSL denotes value of a statistical life; COI denotes cost of illness; WTP denotes willingness to pay.

scenario drivers and emissions or air quality fields from other models and then quantify health impacts using established exposure response functions. A key distinction is that it represents both outdoor and household solid fuel related indoor exposure pathways and converts the resulting burdens into multiple economic measures, including medical expenditures, productivity losses, and willingness to pay valuation. When linked to a CGE model, work loss can be mapped to effective labor supply to estimate economy wide outcomes alongside standard health and valuation metrics.

2.3 Uncertainty treatment and reporting in IMED|HEL

Health-impact estimates produced by IMED|HEL are subject to uncertainty arising from multiple stages of the modeling chain, including air-pollution concentration inputs, epidemiological exposure-response relationships, and economic valuation parameters. IMED|HEL addresses these uncertainties by reporting low, central, and high estimates for each health endpoint and aggregating them consistently to country/region totals. In the IMED|HEL implementation, these ranges correspond to uncertainty reflected by the 95% confidence intervals (CIs) of the risk functions used to quantify health effects.

Concentration uncertainty is incorporated by applying an identical health-impact calculation to alternative concentration inputs, so that differences in exposure fields translate into corresponding ranges in estimated impacts. Exposure-response uncertainty is propagated by recalculating each endpoint using the best-estimate relative risks (RR) for the central estimate and the lower/upper bounds of the RR 95% confidence interval for the low/high estimates.

Indoor uncertainty is treated differently because IMED|HEL does not model indoor exposure with a continuous concentration response function. Instead, indoor exposure is represented by a binary classification derived from solid fuel use shares and ventilation coefficients, and endpoint uncertainty is reflected using the reported RR confidence bounds to construct low and high estimates. Valuation uncertainty is then applied consistently across the low, central, and high health outcomes so that monetized impacts capture both health effect and valuation parameter uncertainty.

3 Evolution of IMED|HEL applications: a pollutant policy co-development framework

IMED|HEL applications have expanded along two coupled dimensions, pollutant coverage and policy questions. First, pollutant coverage grew from $PM_{2.5}$ to ozone and then to a joint $PM_{2.5}$ and ozone perspective to avoid improving one pollutant at the expense of another. Second, policy questions expanded from damage accounting to mitigation scenario evaluation and then to synergistic co benefit analysis that links climate and development strategies with air quality, health, and welfare outcomes.

3.1 Pollutant scope expansion

3.1.1 $PM_{2.5}$-focused assessments: establishing a foundational policy-relevant evidence base

Early applications of the IMED|HEL framework were centered on ambient $PM_{2.5}$, reflecting its dominant contribution to air-pollution-related health burden in China and its strong policy salience during the "haze" period. In this initial phase, the key contribution was to establish a consistent concentration-health-macro linkage that could be deployed across spatial scales and, later, across emitting sectors. Methodologically, these studies operationalized $PM_{2.5}$ exposure into a unified set of endpoints that are directly interpretable by decision-makers, most notably work-time loss as a productivity-relevant metric, thereby enabling comparisons of where and why $PM_{2.5}$ matters most. Early applications of the IMED|HEL framework largely centered on $PM_{2.5}$ as the primary exposure metric, using it as an entry point to close the loop from emissions and ambient concentrations to health outcomes and macroeconomic feedbacks. It addressed the dominant driver of air-pollution health burden in China while

demonstrating how health damages can be internalized into economic equilibrium analysis.

A national-to-provincial assessment demonstrated how $PM_{2.5}$-focused modeling can reveal spatial inequality in health-related productivity impacts under realistic future pathways[29]. In the WoPol scenario, where the penetration rate of mitigation technology is fixed at the 2005 level, $PM_{2.5}$ concentrations in 2030 were projected to exceed China's annual standard (35 $\mu g \cdot m^{-3}$) across most province-level regions, implying a substantial nationwide work-time loss of 56.8 h per capita (2.73% of annual work hours). Importantly, the burden was highly heterogeneous. Province-level regions such as Tianjin, Shanghai, Beijing, Hebei, and Henan exhibited particularly high per-capita work-time loss (~75–88 h per capita in WoPol), underscoring that $PM_{2.5}$ is not merely a national-average problem but a geographically concentrated constraint on population health and labor capacity. From a policy perspective, this $PM_{2.5}$-focused evidence base supports a pragmatic sequencing logic, prioritize high-exposure, high-density regions, where health protection and productivity preservation are likely to be most salient and politically actionable, before extending to lower-exposure regions.

City-scale applications further refined the policy insight by showing that $PM_{2.5}$ impacts in megacities can be large even when local governance is strong, because urban air quality is shaped by both local sources and regional transport. For Shanghai[30], an uncontrolled 2030 scenario suggested $PM_{2.5}$-attributable mortality of 192,400 cases and a work-time loss of 72.1 h per capita annually, highlighting that $PM_{2.5}$ burdens can remain substantial in economically advanced urban areas. City-level $PM_{2.5}$ risk management cannot be fully understood without a regional lens, because the determinants of exposure extend beyond administrative boundaries. This insight is critical for interpreting why apparently similar local policies may yield divergent outcomes across cities, even under comparable economic development levels.

The $PM_{2.5}$-focused phase also evolved from "where is the burden" to "which sources drive the burden," using sector attribution to create more actionable evidence. A provincial analysis of China's road transport sector estimated that[31], without additional control measures, transport-related $PM_{2.5}$ pollution could lead to 177.50 thousand deaths in 2030, increase morbidity risk by 0.40%, and cause 2.23 h per capita work-time loss. These results illustrate a second-order refinement within the $PM_{2.5}$-focused line of work, beyond identifying spatial hotspots, IMED|HEL applications began to identify sector-specific leverage points and their regional heterogeneity, which is essential for designing targeted interventions and anticipating uneven benefits across province-level regions.

Overall, the $PM_{2.5}$-focused literature provides a coherent first-stage narrative of IMED|HEL applications, (i) establishing a policy-relevant health-and-productivity evidence base at national and subnational scales, (ii) revealing that large-city $PM_{2.5}$ risks are intrinsically linked to regional transport, and (iii) moving toward sector-resolved attribution to improve actionability. This progression sets the foundation for the next stages of model application, expanding the pollutant scope to ozone and ultimately addressing multi-pollutant interactions. The key studies reviewed in this section are synthesized in Table 2.

Table 2 Key studies supporting $PM_{2.5}$-focused assessments.

Study	Scope	What it adds to the IMED|HEL evolution
Xie et al. (2016)[29]	China | provincial level | $PM_{2.5}$ | reference vs. 2005-level technology penetration vs. current air pollution policies | to 2030	First integration of $PM_{2.5}$ into the IMED|HEL framework to jointly quantify health impacts and macroeconomic consequences establishing the $PM_{2.5}$-centered "health-economy loop" as the baseline for later extensions.
Wu et al. (2017)[30]	China (Shanghai) | city case | $PM_{2.5}$ | business as usual vs. Intended Nationally Determined Contributions socioeconomic pathways combined with no control, local control, and coordinated control | to 2030	Extends $PM_{2.5}$-focused assessment from provincial scale to the megacity scale, strengthening the policy-relevance of IMED|HEL at the urban scale
Tian et al. (2018)[31]	China | provincial level | road transport sector focus | $PM_{2.5}$ | business as usual vs. current legislation vs. zero road transport emission vs. moderate technology control vs. strict technology control | 2015–2030	Evolves $PM_{2.5}$-focused applications from "where the burden is" to "which sector drives the burden," enabling sector-targeted policy levers and province-level heterogeneity.

3.1.2 Introducing ozone: from single-pollutant assessment to regime-aware policy signals

As China's air-quality management progressed from particulate-focused control to multi-pollutant governance, IMED|HEL was extended to explicitly represent ground-level ozone exposure and its distinct health and economic implications. This extension is not a simple "pollutant add-on", O_3 introduces a fundamentally different atmospheric behavior from $PM_{2.5}$, requiring the framework to interpret policy outcomes through photochemical regimes and metric choices.

Scenario based national simulations[32] illustrate why introducing O_3 reshapes the interpretation of "policy effectiveness." Under WoPol scenario, daily maximum 8-hour O_3 concentrations are projected to be higher in southwestern and northwestern provinces (Sichuan, Qinghai, Gansu) and lower in eastern China. More importantly, the framework shows a non-linear and sometimes counterintuitive response of O_3 to precursor reductions, even when precursor emissions are reduced substantially, the daily maximum 8-hour O_3 concentration decreases only marginally in many province-level regions (often <10%), and can increase in major metropolitan regions such as Beijing, Shanghai, and Guangdong. This divergence reflects regime dependence in which large urban clusters are often VOC limited, so cutting NO_x can weaken ozone removal and lead to higher O_3, an insight that would be missed if the model stayed focused only on $PM_{2.5}$.

A further methodological refinement enabled by IMED|HEL's O_3 integration is the explicit diagnosis of natural-background constraints on mitigation potential. By using a zero-anthropogenic-emission experiment to define "natural background" O_3, province-level regions can be grouped by the fraction of O_3 attributable to natural sources. In "natural-dominated" province-level regions

(human contribution <20%), reductions under a policy scenario are not significant, implying that O_3-related damages there are hard to mitigate through standard emission-control interventions alone. This regime-aware decomposition strengthens the model's policy relevance, it shifts the interpretation of results from "uniform national control" toward region-specific strategies, where some province-level regions require more targeted precursor management while others may face structural limits driven by background O_3 and long-range transport.

The O_3 extension also generates policy-relevant health and economic contrasts. The national assessment finds that, while total O_3-attributable mortality is smaller than that from $PM_{2.5}$, it is still substantial, and its distributional pattern differs, daily maximum 8-hour O_3 tends to be higher in less-populated western province-level regions, leading to relatively high per-capita burdens in some less-developed regions. For example, under a 2030 policy scenario, total mortality is estimated at 0.49 million from O_3 versus 2.43 million from $PM_{2.5}$, while per-capita morbidity and expenditure can be higher for O_3 due to endpoint composition (bronchodilator usage). Consistent with these health patterns, macro indicators such as GDP losses are projected to be modest in percentage terms (about 0.034% without strengthened controls and 0.030% with controls nationally in 2030), yet the study emphasizes that O_3 can become a non-negligible economic burden for low-income residents in western province-level regions.

Taken together, incorporating O_3 marks a clear evolution of IMED|HEL from pollution damage quantification to regime-aware policy diagnostics. These insights provide the conceptual bridge to the next stage of model development, co-considering $PM_{2.5}$ and O_3 jointly. The key study reviewed in this section are synthesized in Table 3.

Table 3 Key study supporting O_3-inclusive assessment.

Study	Scope	What it adds to the IMED|HEL evolution
Xie et al. (2017)[32]	China | provincial level | O_3 (daily max 8-h metric emphasized) | reference vs. 2005-level technology penetration vs. current air pollution policies vs. more aggressive air pollutant control | to 2030	First integration of O_3 into the IMED|HEL-type integrated assessment to evaluate O_3-related health and economic impacts at the provincial level

3.1.3 Joint $PM_{2.5}$-O_3 control: avoiding "one-pollutant wins, the other rebounds"

With the inclusion of ozone, IMED|HEL applications moved from single pollutant assessment to a policy-relevant joint control framing, recognizing that $PM_{2.5}$ and O_3 differ in formation chemistry, spatial patterns, and controllability. A key step in this evolution is the explicit side-by-side quantification of health and macroeconomic impacts from both pollutants under consistent assumptions at China's provincial level, enabling policymakers to see where $PM_{2.5}$ dominates the burden and where O_3 becomes an increasingly important policy challenge. In this comparative application[33], eastern province-level regions show more severe losses from $PM_{2.5}$ and thus larger gains from mitigation, whereas lower-income western province-level regions bear relatively heavier health and economic burdens from O_3, highlighting an environmental-inequality dimension that cannot be captured by $PM_{2.5}$-focused analysis.

Real-scenario results further clarify why a "$PM_{2.5}$-first" strategy can be insufficient for long-term air-quality management. Under WoPol scenario, $PM_{2.5}$ pollution is estimated to cause ~2.0% GDP loss, 210 billion CNY in health expenditure, and ~10,000 billion CNY in monetized life loss, while ozone contributes ~0.09% GDP loss (78 billion CNY), 310 billion CNY in health expenditure, and ~2300 billion CNY in life loss (2.7% of GDP). Although the overall health and economic impacts of O_3 are smaller than $PM_{2.5}$ in aggregate, the study emphasizes that O_3 is much more difficult to mitigate, motivating an explicit policy recommendation for joint $PM_{2.5}$-O_3 reduction rather than sequential or isolated control.

The joint-control message is strengthened by the chemical nonlinearity of ozone. Strategies optimized for $PM_{2.5}$ do not automatically deliver O_3 benefits, so precursor coordination (NO_x, VOC and CH_4) becomes central to avoiding O_3 rebounds while still achieving $PM_{2.5}$ reductions.

Joint control also becomes more salient when air-pollution policy is evaluated together with climate-oriented transitions. In the Asian co-benefits assessment[34], climate mitigation can substantially reduce $PM_{2.5}$ concentrations (~30 $\mu g \cdot m^{-3}$ reductions for eastern China and northern India in 2050), but ozone responses are less uniform; ozone concentrations can even increase in central and eastern China under climate mitigation in 2050. This reinforces a joint $PM_{2.5}$-O_3 governance implication, decarbonization or energy transition pathways may deliver strong $PM_{2.5}$ gains, yet still require targeted O_3-oriented precursor management to ensure that overall population exposure improves across pollutants.

Taken together, the IMED|HEL evolution toward joint $PM_{2.5}$-O_3 control shifts the policy question from "how much $PM_{2.5}$ can be reduced" to "how to design multi-precursor, region-specific strategies that reduce $PM_{2.5}$ while preventing O_3 increases." Conceptually, this aligns with the idea that controlling primary emissions such as NO_x and VOC can reduce both $PM_{2.5}$ and O_3, making joint-control policies a natural bridge toward the later discussion of coordinated mitigation benefits. The key studies reviewed in this section are synthesized in Table 4.

Table 4 Key studies supporting joint $PM_{2.5}$-O_3 control.

Study	Scope	What it adds to the IMED|HEL evolution
Xie et al. (2018)[34]	Asia | regional/sub-regional | $PM_{2.5}$ + O_3 | no climate mitigation vs. 3.4 $W \cdot m^{-2}$ climate mitigation, each evaluated with and without air-pollution health feedback | to 2050	Establishes an early joint pollutant perspective under climate-driven transitions, mitigation yields large $PM_{2.5}$ reductions, but O_3 responses can be weaker or even increase regionally
Xie et al. (2019)[33]	China | provincial level | $PM_{2.5}$ vs. O_3 | reference vs. 2005-level technology penetration vs. current air pollution policies vs. more aggressive air pollutant control | to 2030	Provides the explicit $PM_{2.5}$-O_3 "joint governance" rationale within integrated assessment

3.2 Policy scope expansion

3.2.1 Damage accounting: translating health burden into economic loss

A core contribution of IMED|HEL is that it does not stop at reporting health endpoints (mortality and morbidity), but systematically converts them into economic losses that are compatible with macroeconomic accounting. In practice, the model's "damage accounting" is organized around three linked valuation channels, (i) direct medical expenditure, (ii) productivity loss through reduced effective labor supply, and (iii) willingness-to-pay (WTP) based valuation of risk reductions, typically operationalized via the value of a statistical life (VSL). This structure allows the same health burden estimates to be expressed both as market impacts and as broader welfare-relevant metrics.

The first channel, health expenditure, converts morbidity outcomes into additional healthcare costs by multiplying endpoint counts with disease-specific treatment prices. These prices are not assumed uniform, they are estimated as a function of provincial GDP per capita, enabling spatially differentiated medical costs that better reflect regional income and healthcare price structures. Additional medical spending is treated as a household budget reallocation, more expenditure on medical services implies less consumption of other goods, so health shocks propagate into the economy through changes in the consumption bundle rather than being recorded as a purely external cost item.

The second channel translates morbidity and premature mortality into productivity loss. IMED|HEL first aggregates work loss days (WLD) from morbidity and from chronic mortality within working ages (typically 15–65), then normalizes them into an annual per capita work loss rate (WLR). This WLR is then directly embedded into the CGE module by reducing effective labor supply, ensuring that health damages affect production, income, and prices through general equilibrium mechanisms rather than via a simple partial-equilibrium "lost wages" calculation.

The third channel provides a complementary welfare-oriented valuation using WTP/VSL, monetizing the value of avoided mortality risk in addition to market impacts captured through medical spending and labor supply.

Because these components are computed within a consistent accounting framework, IMED|HEL can report damage in multiple policy-facing metrics, including medical spending, labor and productivity impacts, GDP and welfare changes, and VSL based life loss valuation, while keeping the translation from health burden to economic loss transparent and comparable across studies.

3.2.2 Mitigation scenarios: end-of-pipe vs. structural transition

Within IMED|HEL applications, mitigation scenarios are designed not merely to generate alternative concentration pathways, but to distinguish policy levers that operate through different mechanisms. A recurring and policy-relevant contrast is between (i) end-of-pipe controls, which reduce emissions by upgrading abatement technologies while largely preserving underlying activity patterns, and (ii) structural transition, which reduces emissions by changing the drivers of pollution, through shifts in energy use, technology choice, and sectoral structure. This scenario architecture enables clearer interpretation of which policy type is binding at different stages of air-quality governance.

End-of-pipe mitigation scenarios often vary the penetration and effectiveness of abatement technologies across sectors and province-level regions, creating a baseline counterfactual with weak controls and one or more policy cases with strengthened controls. A representative design fixes mitigation-technology penetration at an early-year level as a "no additional control" counterfactual, then contrasts it with a "current policy" case and a more stringent package that further tightens controls[33]. This configuration directly supports policy inference about the marginal health and economic value of tightening standards, without conflating results with broader changes in development pathways.

A more advanced version of end-of-pipe scenario design brackets ambition using multiple tiers, ranging from controls fixed at base-year levels, to compliance with current legislation, and further to maximum feasible reduction, so that analysts can identify when technology-driven control begins to saturate. Evidence from Sichuan case study illustrates why such tiering matters[35], under a 2035 policy setting, moving from legislation-level controls to maximum feasible reduction yields only a limited additional improvement in provincial mean $PM_{2.5}$ reduction (from about 1.7 $\mu g \cdot m^{-3}$ to 2.6 $\mu g \cdot m^{-3}$), indicating diminishing marginal returns as end-of-pipe technologies approach their feasible limits. Moreover, the same analysis shows that even under the strictest end-of-pipe package, population-weighted $PM_{2.5}$ exposure remains high (reported around 58 $\mu g \cdot m^{-3}$ in 2035), implying that technology upgrades alone may be insufficient to deliver exposure-oriented improvements in dense population and industrial areas.

Structural transition scenarios, in contrast, represent mitigation through technology substitution and system reconfiguration rather than add-on abatement. A sector-focused illustration comes from a transport electrification policy experiment in the Beijing-Tianjin-Hebei region[36], which contrasts futures with and without electric-vehicle policies to isolate the impact of a technology shift. Under the electric vehicle policies scenario, $PM_{2.5}$ emissions decline by 11.38% (Beijing), 15.12% (Tianjin), and 22.27% (Hebei) by 2030, alongside reductions in average $PM_{2.5}$ concentration of roughly 18.84%, 20.04%, and 19.57%, respectively. These exposure changes translate into measurable health benefits in the same policy horizon, including approximately 23.5 million morbidity cases avoided and 4.6 thousand premature deaths avoided.

Taken together, the mitigation-scenario literature within IMED|HEL demonstrates an evolution from simply asking "how much can pollution be reduced under stronger controls" to a more decision-relevant question, which policy lever is binding in a given region or sector. End-of-pipe scenarios reveal where marginal gains diminish under very high stringency, while structural transition scenarios identify leverage points where technology substitution can deliver large concentration and health improvements. The key studies reviewed in this section are synthesized in Table 5.

3.2.3 Synergistic co-benefits: integrating air-quality gains into climate and development strategies

Synergistic co-benefits constitute a defining application frontier of IMED|HEL, rather than treating air-quality improvement as an incidental outcome of decarbonization, the framework quantifies how climate- and development-driven structural changes simultaneously reshape pollutant concentrations, health burden, and macroeconomic welfare. This synergy-oriented line of work evolved from regional, target based mitigation assessments toward place based and technology-portfolio analyses, enabling policy appraisal in terms that are jointly environmental ($PM_{2.5}/O_3$),

Table 5 Key studies supporting mitigation scenarios.

Study	Scope	What it adds to the IMED|HEL evolution
Xie et al. (2019)[33]	China | provincial level |$PM_{2.5}$ + O_3 | reference vs. 2005-level technology penetration vs. current air pollution policies vs. more aggressive air pollutant control | to 2030	Provides a tiered end-of-pipe scenario structure, supporting interpretation of marginal gains from increasing end-of-pipe stringency without changing the broader development pathway.
Zhang et al. (2021)[35]	China (Sichuan) | province | $PM_{2.5}$ | end-of-pipe tiers (fixed controls vs. current legislation vs. maximum feasible reduction) | to 2035	Demonstrates diminishing marginal returns of end-of-pipe tightening near technical maximum, motivating the policy insight that end-of-pipe measures may be necessary but not sufficient for large exposure reductions in dense regions.
Ma et al. (2021)[36]	China (BTH) | regional (Beijing/Tianjin/Hebei) | transport electrification (EV policy) | $PM_{2.5}$ | with-EV-policy vs. without-EV-policy scenarios | to 2030	Represents a sectoral structural transition scenario through transport eclectrification, showing that technology substitution can yield sizeable reductions in PM2.5 and substantial health benefits.

health (mortality/morbidity), and economic (medical spending, labor supply, and monetized welfare).

At the regional scale, scenario based mitigation under an explicit temperature goal shows that health and welfare gains can rival or even exceed mitigation costs[34]. Under a 2 °C mitigation pathway for Asia, air-pollution reductions were projected to prevent about 0.79 million premature deaths by 2050, with monetized mortality benefits on the order of USD 2.8 trillion, compared with an estimated mitigation cost of USD 840 billion.

A second methodological advance is the explicit treatment of cross-border spillovers and multi-pollutant complexity, especially for ozone[37]. Using an integrated chain that links mitigation policy to atmospheric chemistry and then to health valuation, one assessment of China's stringent climate mitigation showed that ozone concentration declines could avoid approximately 15,800 ozone-related premature deaths globally in 2030 and 35,550 in 2050, with over three quarters of the avoided deaths occurring within China and additional benefits accruing to downwind regions.

As the literature matured, synergy assessments increasingly emphasized policy packages and temporal distribution of costs and benefits, rather than single levers. A national renewable energy deployment analysis[38] projected substantial co-benefits by the middle of the century, avoiding 0.6 million premature deaths, 151 million morbidity cases, and 111 million work loss days in 2050, while highlighting a key policy tension in which net benefits can be negative in earlier years because of high upfront investment but become strongly positive by 2050. This finding turns "co-benefits" into a financing and sequencing question, policies that deliver long-run health and productivity dividends may still require near term investment mechanisms to bridge the cost-benefit timing gap.

Synergy studies also expanded from "average benefits" toward equity and affordability considerations, especially in household energy transitions[39]. A rural cooking-and-heating decarbonization pathway projected that $PM_{2.5}$ concentrations in most province-level regions would decline, with particularly notable reductions in northern China, yielding roughly 75,500 avoided $PM_{2.5}$-associated premature deaths nationwide by 2050 and concentrating the majority of benefits in northern province-level regions. At the same time, the analysis reported large cumulative transformation costs through mid century. It found that monetized health benefits can offset these costs in most province-level reigons. In lower development regions, the benefits may not fully cover the costs. This suggests a need for (i) targeted subsidies, (ii) fiscal support or transfers, and (iii) policy design that makes synergy socially attainable as well as technically feasible.

Most recently, synergy analysis has moved toward portfolio optimization, identifying which combinations of mitigation technologies maximize joint air quality and health economic gains under climate constraints. A multi-model study[40] evaluating alternative technology bundles found that a combination of end-of-pipe measures, renewable energy, and electrification delivered the largest air-quality improvements by 2050, whereas carbon capture and storage (CCS) pathways produced comparatively modest air quality and cumulative mortality improvements. By explicitly comparing bundles under a consistent climate target and translating concentration changes into avoided deaths and economic loss, such work demonstrates how IMED|HEL can inform not only "how much" to mitigate, but also "how" to prioritize technology mixes for maximum synergistic value.

Collectively, these studies show that IMED|HEL enabled synergy analysis has progressed along three policy-relevant dimensions, (i) from single region to cross-border and multi-pollutant accounting, (ii) from static benefit statements to dynamic assessments that reveal cost-benefit timing and regional heterogeneity, and (iii) from evaluating isolated interventions to optimizing portfolios under climate constraints, while retaining health and economic valuation as central decision metrics. The key studies reviewed in this section are synthesized in Table 6.

Across applications, IMED|HEL has progressed from $PM_{2.5}$-focused burden quantification to ozone and ultimately joint $PM_{2.5}$-O_3 interpretation, while expanding policy questions from damage accounting to mitigation design and synergistic co-benefits under climate and development strategies. Collectively, the evidence shows that health impacts are economically material, geographically and sectorally heterogeneous, and sensitive to both pollutant chemistry and the choice of policy lever. These application patterns provide a basis for interpreting what model "improvements" over time actually changed in results, and for deriving robust policy lessons about joint pollutant management, regional coordination, and transition sequencing.

4 Discussion

4.1 Core strengths and innovations of the IMED|HEL framework

The IMED|HEL model provides a comprehensive framework for integrated health impact assessment by embedding population health directly into environmental and economic policy analysis. Unlike traditional models that treat health effects as external or secondary, IMED|HEL integrates health outcomes into the core structure of scenario design and evaluation. This enables decision-makers to assess policies not only by their environmental performance, but also by their consequences for human well-

Table 6 Key studies supporting synergistic co-benefits.

Study	Scope	What it adds to the IMED|HEL evolution
Xie et al. (2018)[34]	Asia | regional/sub-regional | climate mitigation pathway | $PM_{2.5}$ + O_3 | no climate mitigation vs. 3.4 $W{\cdot}m^{-2}$ climate mitigation, each evaluated with and without air-pollution health feedback | to 2050	Establishes the co-benefits framing at a regional scale, showing that monetized health benefits can exceed mitigation costs under a climate target, helping position health benefits as a core pillar of climate-policy appraisal.
Wang et al. (2022)[37]	Global (with China as main contributor) | multi-region | climate mitigation pathway | O_3 | new policies scenario vs. China-only 2°C consistent climate mitigation, with all other countries remaining on the new policies scenario | 2030 and 2050	Extends synergy analysis to ozone and transboundary spillovers, quantifying how China's mitigation yields avoided O_3 mortality both domestically and downwind, adding a cross-border, multi-pollutant policy justification.
Xie et al. (2023)[38]	China | sub-national regions | renewable energy expansion (structural transition) | $PM_{2.5}$ | stated policy vs. below 2° C | 2017, 2030 and 2050	Demonstrates that synergistic benefits are regionally uneven and time distributed (near term costs vs. long-term gains), shifting co-benefits from a "headline number" to a sequencing/financing question for transition policy design.
Ma et al. (2023)[39]	China | provincial/national | rural household energy transition (structural transition) | $PM_{2.5}$ | business as usual vs. carbon neutrality | to 2060	Adds an equity lens to synergy, co-benefits are large but concentrated, implying policy needs for targeted support so that health gains are achievable across regions.
Zhao et al. (2024)[40]	China | national/provincial | technology portfolio comparison | $PM_{2.5}$ + O_3 | reference vs. end-of-pipe-only vs. thermal power electrification with CCS vs. primary electrification vs. enhanced electrification | to 2050	Advances from "evaluate a pathway" to "optimize a portfolio", identifies which technology mixes maximize joint air quality and health gains under climate constraints, supporting actionable prioritization.

being and economic resilience. Health gains are systematically monetized through statistical life valuation, productivity loss, and medical costs, allowing for more comprehensive cost-benefit analysis and transparent policy prioritization.

A distinctive innovation of IMED|HEL lies in its explicit treatment of both ambient and indoor air pollution within a unified framework. By differentiating exposure pathways and incorporating population heterogeneity, such as age, gender, solid fuel use, and ventilation conditions, the model enables a more equity-sensitive estimation of health risks. This feature is particularly relevant for developing countries, where indoor sources remain a major and often under-addressed driver of disease burden. Furthermore, the inclusion of delayed health responses, such as long-term reductions in chronic disease following intervention, adds important temporal realism for long-term scenario evaluation.

The model has also demonstrated strong adaptability across geographic and policy contexts, from national-level assessments to localized analyses in cities and province-level regions. Its consistent performance in simulating health burdens and economic impacts under varying energy, environmental, and socioeconomic conditions confirms its empirical scalability and practical relevance. Whether used to evaluate Beijing-Tianjin-Hebei's coal-to-electricity transition or rural household energy shifts, IMED|HEL has proven both precise and policy-responsive, supporting integrated, health-centered environmental governance.

4.2 Cross-cutting insights from the evolution of IMED|HEL applications

Across the IMED|HEL literature, three changes stand out as the primary drivers of "new" findings, (i) what pollutants are explicitly modeled, (ii) how policy levers are represented, and (iii) how economic meaning is assigned to health outcomes.

First, the pollutant dimension evolved from $PM_{2.5}$ dominance to multi-pollutant realism. Early studies were $PM_{2.5}$-centric and delivered a clear message, $PM_{2.5}$ creates large, spatially heterogeneous health and productivity burdens under realistic development pathways. As ozone was incorporated, the interpretation of "effective policy" became more nuanced. O_3 introduced chemistry-driven nonlinearity and background constraints, which means that reducing precursors does not guarantee peak O_3 reductions. The move to joint $PM_{2.5}$-O_3 assessment therefore represents more than a broader scope; it changes the decision criterion from "maximize $PM_{2.5}$ reduction" to "maximize net population exposure improvement across pollutants," thereby preventing policy designs that inadvertently trade $PM_{2.5}$ gains for O_3 deterioration.

Second, the policy dimension evolved from descriptive damage assessment to decision-oriented scenario experimentation. Early applications demonstrated that pollution damages are not peripheral externalities but economically material through channels such as medical expenditure, work-time loss, and welfare valuation. Subsequent scenario studies improved policy usefulness by separating mitigation levers. End-of-pipe controls can deliver near term reductions but may exhibit diminishing marginal returns as technical feasibility is approached, while structural transitions can unlock larger reductions by changing emission drivers, though their effectiveness depends on system conditions such as the upstream energy mix. The most recent synergy-oriented studies then broadened the policy question again, evaluating transition pathways and technology portfolios under climate constraints and explicitly comparing costs with health and welfare gains across time, regions, and pollutants.

Third, the economic interpretation of health outcomes became more policy-salient by moving from single-metric reporting to multi-metric valuation. By translating health burdens into (a) market-consistent macroeconomic impacts and (b) welfare-relevant monetization, IMED|HEL applications enabled a more complete appraisal of why and where health benefits matter. This dual accounting also explains why some studies emphasize GDP effects while others emphasize monetized mortality benefits, the differences often reflect the chosen valuation lens.

These evolutions support several cross-cutting policy insights that are consistent across diverse applications:

1. Multi-pollutant governance is necessary for robust performance. Policies optimized for $PM_{2.5}$ improvement alone may not control ozone effectively; joint $PM_{2.5}$-O_3 evaluation reduces the risk of unintended trade-offs and highlights where precursor coordination is essential.

2. Policy effectiveness is region-specific and often requires coordination beyond administrative boundaries. City and regional applications repeatedly show that local outcomes depend on

transported pollution and regional precursor regimes, implying that governance design can be as important as local technology choice.

3. End-of-pipe controls are necessary but not sufficient for long-run exposure reduction in many settings. As technical abatement approaches feasible maxima, marginal gains can shrink; structural transition levers then become increasingly important, but must be evaluated as system interventions.

4. Synergistic co-benefits reshape the economic case for climate and development strategies. When health benefits are valued consistently, they can materially change the perceived net benefits and timing of transition pathways, supporting the rationale for more ambitious action while also highlighting financing and equity needs where benefits and costs are unevenly distributed.

In sum, the IMED|HEL application literature has progressed from establishing a credible $PM_{2.5}$-centered damage baseline to delivering multi-pollutant, policy actionable insights about mitigation design and synergy. The most durable contribution is not any single numeric estimate, but a coherent interpretive framework. Health impacts can be quantified in economically meaningful terms, they vary systematically by pollutant chemistry and regional context, and they can decisively influence the ranking and timing of air-quality and climate strategies when integrated into decision making.

4.3 Limitations of the IMED|HEL model

While the IMED|HEL framework provides a robust and integrated tool for assessing the health and economic impacts of air pollution, several limitations should be acknowledged. These include uncertainties in the characterization of exposure, particularly for indoor air pollution, which relies on simplified assumptions about fuel use, ventilation, and household behavior. The exposure-response functions used in the model also involve uncertainty, especially at high pollution levels where non-linear effects may occur. In addition, the model does not fully account for differences in population vulnerability or disparities in access to healthcare. Finally, empirical validation of the full modeling chain remains limited, so results should be interpreted with caution when applying the model to new regions or policy settings.

4.4 Future research directions

Future work on the IMED|HEL framework could focus on improving exposure characterization, expanding health endpoints to capture better climate related risks such as heat stress and wildfire smoke, and enhancing empirical validation through collaboration with public health data sources. Broader geographic application beyond China and exploration of new policy domains, would further strengthen the model's relevance and adaptability to global sustainable development challenges.

5 Conclusions

This study introduces the IMED|HEL framework, an integrated assessment approach that links air-pollution and climate policy scenarios to population exposure, health outcomes, and economic impacts. By combining atmospheric modeling outputs with health risk assessment and economic valuation, IMED|HEL provides a consistent pathway from emissions to monetized health damages.

The core contribution of IMED|HEL lies in its ability to translate health impacts into policy-relevant economic metrics. Mortality, morbidity, productivity loss, and healthcare expenditure are quantified within a unified accounting structure, allowing health outcomes to be directly compared across regions, pollutants, and policy scenarios. This approach moves policy evaluation beyond concentration based indicators toward outcome-oriented assessment grounded in population well being.

By embedding health impacts within environmental economic analysis, IMED|HEL expands the informational basis for air quality and climate decision making. The framework enables clearer comparison of policy trade offs and supports strategies that explicitly account for health alongside environmental and economic objectives, contributing to more coherent and human-centered policy design.

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Author contribution statement

Jiayi Li is responsible for conceptualization, investigation, writing – original draft, writing – review & editing, visualization. Yang Xie is responsible for conceptualization, writing – review & editing, supervision, funding acquisition.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] IPCC. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

[2] Wang, Y. L., Wild, O., Chen, X. S., Wu, Q. Z., Gao, M., Chen, H. S., Qi, Y., Wang, Z. F. (2020). Health impacts of long-term ozone exposure in China over 2013–2017. *Environment International*, 144: 106030.

[3] Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525(7569): 367–371.

[4] Xie, R., Sabel, C. E., Lu, X., Zhu, W. M., Kan, H. D., Nielsen, C. P., Wang, H. K. (2016). Long-term trend and spatial pattern of $PM_{2.5}$ induced premature mortality in China. *Environment International*, 97: 180–186.

[5] Khomenko, S., Cirach, M., Pereira-Barboza, E., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., de Hoogh, K., Hoek, G., Nieuwenhuijsen, M. (2021). Premature mortality due to air pollution in European cities: a health impact assessment. *The Lancet Planetary Health*, 5(3): E121–E134.

[6] Dedoussi, I. C., Eastham, S. D., Monier, E., Barrett, S. R. H. (2020). Premature mortality related to united states cross-state air pollution. *Nature*, 578(7794): 261–265.

[7] Turner, M. C., Jerrett, M., Pope, C. A., Krewski, D., Gapstur, S. M., Diver, W. R., Beckerman, B. S., Marshall, J. D., Su, J., Crouse, D. L., et al. (2016). Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical*

Care Medicine, 193(10): 1134–1142.

[8] Arjomandi, M., Balmes, J. R., Frampton, M. W., Bromberg, P., Rich, D. Q., Stark, P., Alexis, N. E., Costantini, M., Hollenbeck-Pringle, D., Dagincourt, N., et al. (2018). Respiratory responses to ozone exposure. MOSES (the multicenter ozone study in older subjects). *American Journal of Respiratory and Critical Care Medicine*, 197(10): 1319–1327.

[9] Yang, Y., Qi, J. L., Ruan, Z. L., Yin, P., Zhang, S. Y., Liu, J. M., Liu, Y. N., Li, R., Wang, L. J., Lin, H. L. (2020). Changes in life expectancy of respiratory diseases from attaining daily $PM_{2.5}$ standard in China: a nationwide observational study. *The Innovation*, 1(3): 100064.

[10] Guan, W. J., Zheng, X. Y., Chung, K. F., Zhong, N. S. (2016). Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. *The Lancet*, 388(10054): 1939–1951.

[11] Faustini, A., Stafoggia, M., Colais, P., Berti, G., Bisanti, L., Cadum, E., Cernigliaro, A., Mallone, S., Scarnato, C., Forastiere, F. (2013). Air pollution and multiple acute respiratory outcomes. *European Respiratory Journal*, 42(2): 304–313.

[12] Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., Lam, K. B. H., Mortimer, K., Asante, K. P., Balakrishnan, K., Balmes, J., et al. (2014). Respiratory risks from household air pollution in low and middle income countries. *The Lancet Respiratory Medicine*, 2(10): 823–860.

[13] Rajagopalan, S., Al-Kindi, S. G., Brook, R. D. (2018). Air pollution and cardiovascular disease: JACC state-of-the-art review. *Journal of the American College of Cardiology*, 72(17): 2054–2070.

[14] Bhatnagar, A. (2022). Cardiovascular effects of particulate air pollution. *Annual Review of Medicine*, 73: 393–406.

[15] Al-Kindi, S. G., Brook, R. D., Biswal, S., Rajagopalan, S. (2020). Environmental determinants of cardiovascular disease: lessons learned from air pollution. *Nature Reviews Cardiology*, 17(10): 656–672.

[16] Liang, F. C., Liu, F. C., Huang, K. Y., Yang, X. L., Li, J. X., Xiao, Q. Y., Chen, J. C., Liu, X. Q., Cao, J., Shen, C., et al. (2020). Long-term exposure to fine particulate matter and cardiovascular disease in China. *JACC Journals*, 75(7): 707–717.

[17] Yao, M. Y., Niu, Y., Liu, S. C., Liu, Y. M., Kan, H. D., Wang, S. X., Ji, J. S., Zhao, B. (2023). Mortality burden of cardiovascular disease attributable to ozone in China: 2019 vs 2050. *Environmental Science & Technology*, 57(30): 10985–10997.

[18] Sakhvidi, M. J. Z., Yang, J., Lequy, E., Chen, J., de Hoogh, K., Letellier, N., Mortamais, M., Ozguler, A., Vienneau, D., Zins, M., et al. (2022). Outdoor air pollution exposure and cognitive performance: findings from the enrolment phase of the CONSTANCES cohort. *The Lancet Planetary Health*, 6(3): E219–E229.

[19] Zhang, X., Chen, X., Zhang, X. B. (2018). The impact of exposure to air pollution on cognitive performance. *Proceedings of the National Academy of Sciences of the United States of America*, 115(37): 9193–9197.

[20] Graff Zivin, J., Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, 102(7): 3652–3673.

[21] Hoffmann, B., Rud, J. P. (2024). The unequal effects of pollution on labor supply. *Econometrica*, 92(4): 1063–1096.

[22] World Health Organization. (2024). Ambient (outdoor) air pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[23] Li, M. W., Zhang, D., Li, C. T., Mulvaney, K. M., Selin, N. E., Karplus, V. J. (2018). Air quality co-benefits of carbon pricing in China. *Nature Climate Change*, 8(5): 398–403.

[24] Markandya, A., Sampedro, J., Smith, S. J., Van Dingenen, R. V., Pizarro-Irizar, C., Arto, I., González-Eguino, M. (2018). Health co-benefits from air pollution and mitigation costs of the paris agreement: a modelling study. *The Lancet Planetary Health*, 2(3): E126–E133.

[25] Huang, X. Y., Peng, W., Zhao, A., Ou, Y., Kennedy, S., Iyer, G., McJeon, H., Cui, R., Hultman, N. (2025). Substantial air quality and health co-benefits from combined federal and subnational climate actions in the United States. *One Earth*, 8(3): 101232.

[26] Chang, S. Y., Yang, X., Zheng, H. T., Wang, S. X., Zhang, X. L. (2020). Air quality and health co-benefits of China's national emission trading system. *Applied Energy*, 261: 114226.

[27] Zhang, D., Wang, Q. Y., Song, S. J., Chen, S. M., Li, M. W., Shen, L., Zheng, S. Q., Cai, B. F., Wang, S. H., Zheng, H. T. (2023). Machine learning approaches reveal highly heterogeneous air quality co-benefits of the energy transition. *iScience*, 26(9): 107652.

[28] Lin, J. T., Du, M. X., Chen, L. L., Feng, K. S., Liu, Y., V. Martin, R., Wang, J. X., Ni, R. J., Zhao, Y., Kong, H., et al. (2019). Carbon and health implications of trade restrictions. *Nature Communications*, 10(1): 4947.

[29] Xie, Y., Dai, H. C., Dong, H. J., Hanaoka, T., Masui, T. (2016). Economic impacts from $PM_{2.5}$ pollution-related health effects in China: a provincial-level analysis. *Environmental Science & Technology*, 50(9): 4836–4843.

[30] Wu, R., Dai, H. C., Geng, Y., Xie, Y., Masui, T., Liu, Z. Q., Qian, Y. Y. (2017). Economic impacts from $PM_{2.5}$ pollution-related health effects: a case study in Shanghai. *Environmental Science & Technology*, 51(9): 5035–5042.

[31] Tian, X., Dai, H. C., Geng, Y., Wilson, J., Wu, R., Xie, Y., Hao, H. (2018). Economic impacts from $PM_{2.5}$ pollution-related health effects in China's road transport sector: a provincial-level analysis. *Environment International*, 115: 220–229.

[32] Xie, Y., Dai, H. C., Zhang, Y. X., Hanaoka, T., Masui, T. (2017). Health and economic impacts of ozone pollution in China: a provincial level analysis. *Atmospheric Chemistry and Physics*, https://doi.org/10.5194/acp-2017-849.

[33] Xie, Y., Dai, H. C., Zhang, Y. X., Wu, Y. Z., Hanaoka, T., Masui, T. (2019). Comparison of health and economic impacts of $PM_{2.5}$ and ozone pollution in China. *Environment International*, 130: 104881.

[34] Xie, Y., Dai, H. C., Xu, X. H., Fujimori, S., Hasegawa, T., Yi, K., Masui, T., Kurata, G. (2018). Co-benefits of climate mitigation on air quality and human health in Asian countries. *Environment International*, 119: 309–318.

[35] Zhang, S. L., Wu, Y. Z., Liu, X. R., Qian, J., Chen, J. H., Han, L., Dai, H. C. (2021). Co-benefits of deep carbon reduction on air quality and health improvement in sichuan province of China. *Environmental Research Letters*, 16(9): 095011.

[36] Ma, C. N., Madaniyazi, L., Xie, Y. (2021). Impact of the electric vehicle policies on environment and health in the Beijing–Tianjin–Hebei region. *International Journal of Environmental Research and Public Health*, 18(2): 623.

[37] Wang, Y. S., Xie, M. J., Wu, Y. Z., Zhang, X., Wang, M. H., Zhang, Y. Q., Xie, Y. (2022). Ozone-related co-benefits of China's climate mitigation policy. *Resources, Conservation and Recycling*, 182: 106288.

[38] Xie, Y., Xu, M., Pu, J. L., Pan, Y. J., Liu, X. R., Zhang, Y. X., Xu, S. R. (2023). Large-scale renewable energy brings regionally disproportional air quality and health co-benefits in China. *iScience*, 26(8): 107459.

[39] Ma, T., Zhang, S. L., Xiao, Y. L., Liu, X. R., Wang, M. H., Wu, K., Shen, G. F., Huang, C., Fang, Y. R., Xie, Y. (2023). Costs and health benefits of the rural energy transition to carbon neutrality in China. *Nature Communications*, 14(1): 6101.

[40] Zhao, M. D., Xie, Y., Xu, M., Weng, Z. X., Hanaoka, T., Zhang, Y. Q., Tong, D. (2024). Optimizing air quality and health co-benefits of mitigation technologies in China: an integrated assessment. *Environmental Science and Ecotechnology*, 22: 100454.