

Effects of the low-carbon energy transition on air pollution and health

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Abstract

The transition to a low-carbon energy system could simultaneously mitigate carbon emissions, reduce air pollution and protect human health. Although these potential benefits have been widely acknowledged, major questions remain regarding key factors that determine the impacts of energy strategies on health and health disparities, as well as ways to incorporate health benefits into real-world energy decisions. In this Perspective, we summarize the current understanding and analytical framework related to the pollution and health impacts of the energy transition, discuss the analytical challenges and knowledge gaps in assessing and projecting the magnitude and distribution of the pollution and health impacts, and identify plausible entry points to enhance the real-world relevance of health benefits in decision-making about energy systems. The energy transition will affect pollution and health impacts at the global, national and subnational scales, resulting in complex distributional effects across regions and population groups. Although current analytical frameworks are useful to quantify the general patterns of health benefits, they are often insufficient for characterizing distributional effects, quantifying potential trade-offs, and incorporating considerations of deep and interacting uncertainties. Given the complexity of the actors involved and the policymaking landscape, it will be necessary to make knowledge actionable by, for example, establishing a co-production process between researchers and practitioners.

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Key points

- The transition from a fossil-fuel-heavy to a low-carbon energy system could simultaneously mitigate carbon emissions and reduce the health impacts from air pollution.
- The assessment of health benefits of energy transitions often relies on an integrated modelling framework that couples energy system, air quality and health modelling.
- The scientific community currently has a good understanding of the aggregate health impacts of different energy strategies, whereas the distribution of these impacts across regions and populations is more complicated and remains poorly understood.
- Incorporating health benefits into real-world energy policies will require research efforts to integrate insights from multiple disciplines and a close collaboration between researchers, decision-makers and relevant stakeholders.

Introduction

Stabilizing the global climate system will require transformational changes in energy systems to achieve dramatic reductions in greenhouse gas emissions^{1,2}. As fossil-fuel combustion is a major emission source of both greenhouse gases and air pollutants, efforts to decarbonize energy systems could simultaneously reduce air pollution and related health impacts^{3–5}. In countries such as China and India, mitigating local air pollution has been one of the strongest motivations to shift away from fossil-fuel use^{6,7}. In other countries, the potential co-benefits of improved air quality and reduced health impacts have helped to increase public support for climate and clean-energy policies^{8–10}.

Research efforts over the past decades have improved our understanding of the complex interactions between energy, air pollution and health (Fig. 1). Although energy decisions also have an effect on indoor air pollution^{11,12}, we focus only on the effects on outdoor air pollution, especially ambient fine particulate matter with a diameter of $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and ozone (O₃). The air quality and health benefits from low-carbon energy strategies have been demonstrated and quantified in numerous studies at the global^{4,5,13,14}, national^{15–23} and local^{24–27} levels. In some countries and for some policy choices, the health benefits are likely to be large and might outweigh the policy costs^{14,17,28}.

Despite a growing literature on the health effects of energy transitions, at least two important knowledge gaps remain and require further investigation. First, the impacts of energy transitions on air pollution and health are unevenly distributed across regions and population groups, and energy policies could widen or narrow current disparities. Globally, countries such as China and India currently experience disproportionately higher pollution levels and health impacts owing to high population density and greater dependence on coal^{29,30}. Domestically, exposure disparities sometimes remain large across population groups even in countries with good air quality overall. For example, despite persistent reductions in pollution levels across the USA over the past decades, racial minorities still face disproportionately higher exposure to PM_{2.5} than other population groups^{31–33}. As energy decarbonization reduces pollution levels and health impacts overall, it is important to identify which countries and

population groups will receive more (or less) air-quality benefit, and how decarbonization ambition and technology choices will influence those distributions.

Second, the energy transition could introduce potential trade-offs between climate, health and equity objectives. For example, some low-carbon technologies could mitigate greenhouse gas emissions at the expense of increased emissions of air pollutants. A case in point is scaling up bioenergy for decarbonization, which entails the emission of particulate matter pollution from direct combustion³⁴, while also inducing potential increases in ammonium emissions from expansion of agricultural activities for biofuel production³⁵. In addition, energy decisions sometimes bring air-quality benefits to one region or population while harming others. For example, increasing the adoption of electric vehicles improves air quality in urban centres, but pollution levels might rise in other places owing to increased fossil-fuel-based power generation or battery production activities^{36–39}. Quantifying these trade-offs requires a comprehensive understanding of the complex interactions across regions and sectors. New modelling methods and analytical tools are needed to characterize these system dynamics and related future uncertainties.

In this Perspective, we provide an overview of existing evidence for how energy transitions influence air pollution and health across and within regions. We describe the modelling approaches that are used to assess health benefits and highlight key analytical challenges and uncertainties. We also outline the current policymaking landscape and opportunities for energy, air quality and health, and identify concrete strategies to generate actionable knowledge. Finally, we discuss potential directions for future research.

Impacts of energy transition on air quality and health

Energy transitions take place at global, national and local scales. The resulting changes in energy activities and related emissions will affect the future pattern of pollution. By further considering the size and vulnerability of exposed populations, the associated health effects can vary substantially across regions and population groups. In this section, we summarize key trends and insights at various spatial scales.

The global landscape

Over the past three decades, energy consumption has surged in most low- and middle-income countries, including in Asia (for example, China and India) and in Africa (Fig. 2a). Across these regions, this surge in energy consumption also led to an 82–330% increase in greenhouse gas emissions for the period 1990–2020 (Fig. 2b). Energy consumption in high-income countries/regions, such as the USA and Europe, has largely stabilized (Fig. 2a), owing to a shift from coal to natural gas and renewable energy sources, as well as an overall improvement in energy efficiency⁴⁰. These trends in energy consumption have contributed to 22% and 14% reductions in greenhouse gas emissions for the USA and Europe (respectively) over the period 2000–2020 (Fig. 2b).

The trends for air pollution demonstrate a slightly different pattern to those for energy consumption and greenhouse gas emissions. In general, countries with growing energy consumption tend to simultaneously increase their air pollution, measured, for example, by population-weighted PM_{2.5} concentrations (Fig. 2c). However, in some countries, such as China, ambient PM_{2.5} concentrations decreased by 29% from 1990 to 2020, despite a 2.3-fold increase in energy use and 3.3-fold increase in greenhouse gas emissions over the same period. This decoupling of energy use and air pollution patterns is largely due

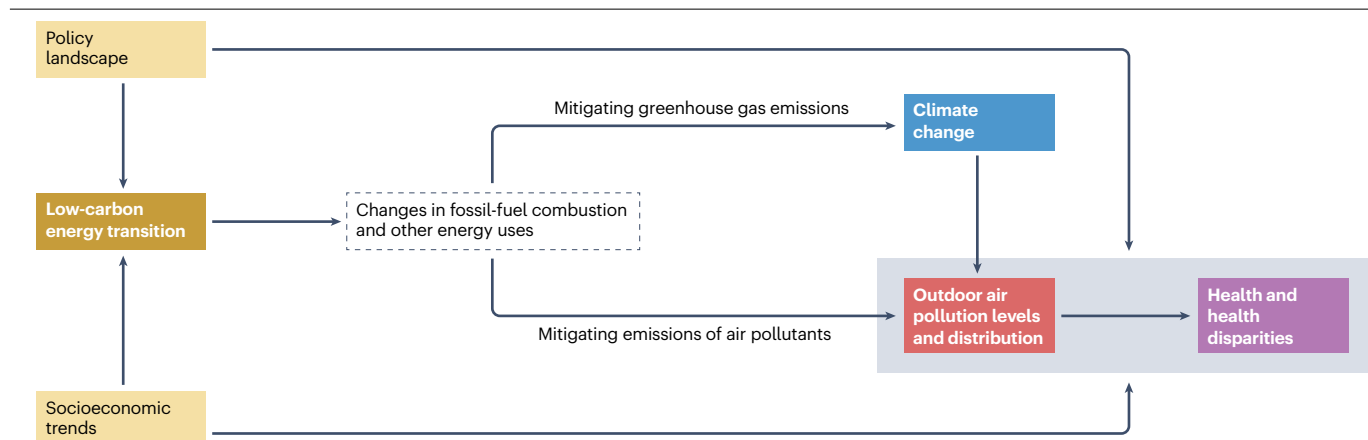


Fig. 1 | The effects of the low-carbon energy transition on outdoor air pollution, health and health disparities. Pollution reduction and health benefits are achieved primarily by reducing air pollutant emissions from fossil-fuel combustion. The impacts on health and health disparities are further

influenced by the policy landscape (such as decarbonization ambition and technology choice) and socioeconomic factors (for example, the size and vulnerability of exposed populations).

to the strengthening of pollution-control efforts and the resulting widespread installation of end-of-pipe control measures on vehicles and industrial plants^{41,42}. This example in China demonstrates the importance of combining clean energy and pollution-control policies to mitigate pollution impacts.

Over the past three decades, the health burden from air-pollution exposure has declined in some high-income regions, such as the USA and Europe, owing to a shift away from fossil fuels and the tightening of pollution-control measures on fossil-fuel facilities (Fig. 2d). However, the health burden has been increasing in almost all low- and middle-income countries, including where pollution levels have stabilized or declined (for example, China, India, and other Asian countries) (Fig. 2d). This increase is driven by the drastic sociodemographic changes in these regions, especially population growth, which has increased the size of exposed populations, as well as population ageing, which has increased the population vulnerability to pollution exposure and thus worsened the health impacts. For example, although a reduction in ambient PM_{2.5} level contributed to a 28% decrease in PM_{2.5}-attributable deaths in China from 2004 to 2017, population ageing increased the death burden by 43% during the same period⁴³. Considering the combined impacts from pollution exposure, ageing and other sociodemographic factors, the net effect is a 10% increase in PM_{2.5}-attributable deaths⁴³.

Looking ahead, a clean-energy transition is expected to reduce greenhouse gas and air-pollution levels in most regions. For example, fossil-fuel use and related air-pollutant emissions are projected to decrease in most world regions by 2050 in a low-greenhouse-gas emission scenario (Shared Socioeconomic Pathway SSP1-2.6 scenario that is commonly used by the Intergovernmental Panel on Climate Change and the climate assessment community), leading to widespread reductions in ambient PM_{2.5} concentrations⁴⁴. Quantitatively, from 2015 to 2050, the national average, population-weighted PM_{2.5} concentrations are estimated to decrease by 0–61% across 199 countries⁴⁴. Looking broadly at the literature, potential air-quality benefits from clean-energy transitions are found globally^{3–5,14,44–48} and for specific regions, such as Asia^{16,20,49}, Europe⁵⁰ and Africa⁵¹. Although all countries might benefit, developing countries, which

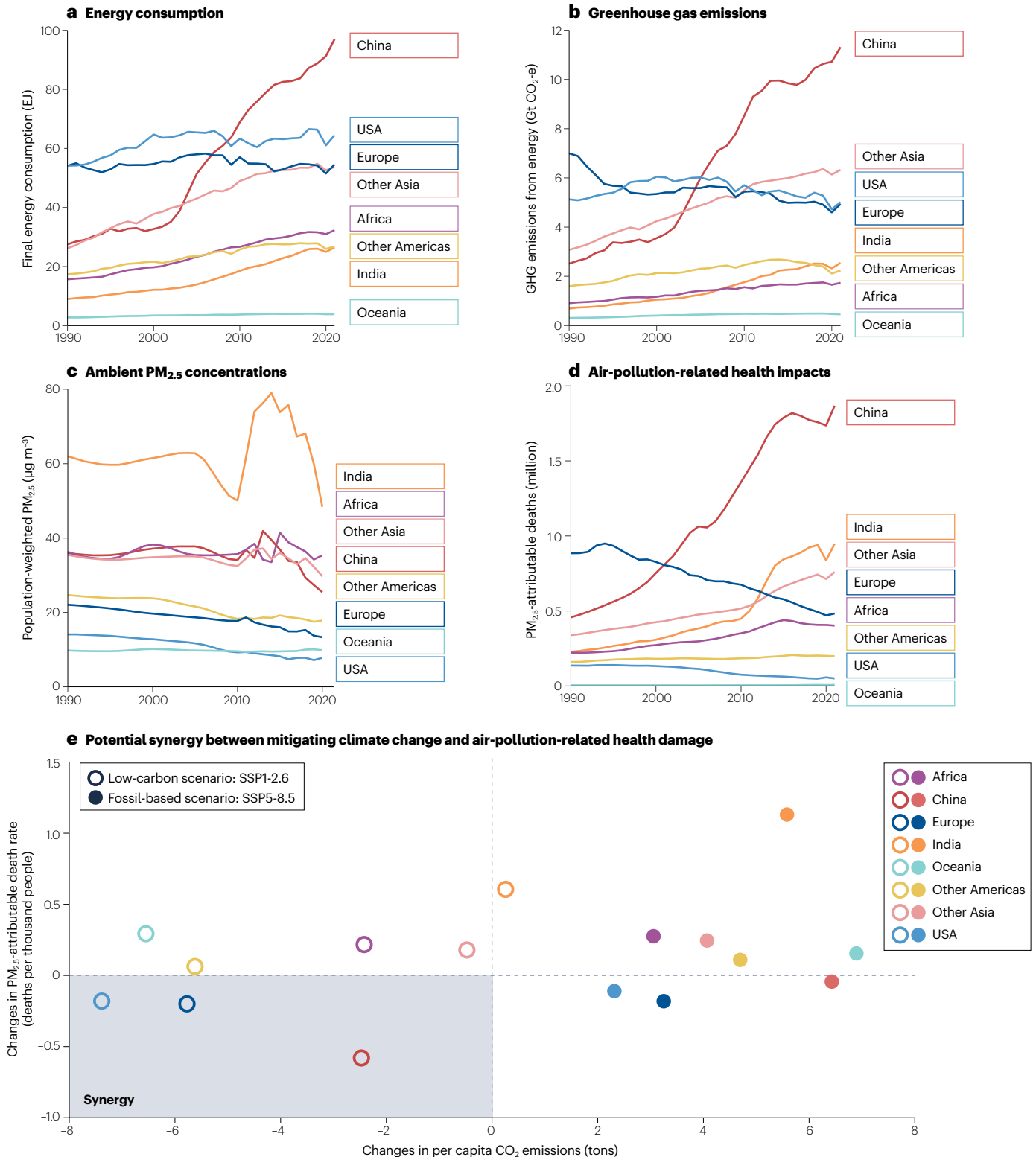
are most heavily reliant on fossil fuels, stand to gain most in terms of air-quality improvements.

We note that some low- and middle-income countries that are expected to experience population growth and ageing, including India and some other Asian countries and various African countries, might still experience an increased risk of health impacts from air pollution despite a cleaner energy system and declining pollution levels in the future (Fig. 2e). For example, in a low-greenhouse-gas emission scenario (SSP1-2.6), the population-weighted PM_{2.5} concentrations in India decrease by 30% between 2015 and 2050, but the resulting PM_{2.5}-attributable death rate is still projected to increase by 37%, owing to an ageing population and insufficient improvement in baseline health conditions⁴⁴. These findings highlight the importance of achieving deep cuts in air pollution to counteract the effects of projected sociodemographic changes in these regions.

Subnational impacts and environmental justice

In addition to differences between countries, distinct exposure patterns also occur within countries, leading to disparities. In some cases, variations in exposure might be attributable to natural processes, such as topographic or meteorological differences⁵². However, exposure patterns often have a strong economic or social component. Urban areas typically experience worse air quality than rural areas⁵³, but even within a city or small region, differences in exposure can be non-random. For example, in the USA, even as air quality improves over time, the most polluted counties in 1981 remained more polluted in 2016 (ref. 32). The siting of industrial facilities and roadways, among other infrastructure decisions, has led to higher average exposures among specific population subgroups, particularly low-income and minority populations^{31,54–56}. Across the USA, minority populations were exposed to a 0.7–1.4 μg m⁻³ (22–34%) higher annual average PM_{2.5} level than white populations in 2014 (ref. 33). This disparity exists even when controlling for income, indicating that economic status alone does not fully explain the disparities in pollution levels and health impacts³³. Similar findings have also been reported in other parts of the world^{57–59}. For these reasons, addressing disparities in air pollution exposure is a central tenet of the environmental justice movement.

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Given that these distributional effects are highly location-specific and context-specific, below we provide three subnational examples at various spatial resolutions to demonstrate how energy decisions and related policy actions could result in an uneven distribution of health impacts.

First, air-quality benefits are unevenly distributed across provinces or states within a country^{15,17,19,20,28}. These variations are primarily due to differences in energy structures, the availability of renewable resources, subnational policies, and the local implementation of nationwide

Fig. 2 | Historical trends and projected changes in greenhouse gas emissions and air pollution-related health impacts. a–d, Historical trends in energy consumption (part a), energy-related greenhouse gas emissions (part b), population-weighted ambient fine particulate matter with a diameter of $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) concentrations (part c) and $\text{PM}_{2.5}$ -attributable deaths (part d) in major world regions. Data in parts a and b from the International Energy Agency^{133,134}

and in parts c and d from the Health Effects Institute¹³⁵. e, Projected changes in per capita CO_2 emissions and $\text{PM}_{2.5}$ -attributable death rate in 2050 relative to 2015 under a low-greenhouse-gas emissions scenario (Shared Socioeconomic Pathway SSP1-2.6) and a high emissions (fossil-fuel-based) scenario (SSP5-8.5). Data in part e from ref. 44. CO_2 , carbon dioxide; EJ, exajoule.

policies. For example, a clean-electricity transition consistent with deep decarbonization targets is projected to result in different scales of health benefits in different provinces in China. Compared with a baseline scenario of no greenhouse gas emission mitigation efforts, the 2-degree (or 1.5-degree) scenario is projected to result in a reduction in cumulative air-pollution-related deaths for the period 2020–2045 of 50% (or 63%), 53% (or 64%), 48% (or 61%) and 52% (or 62%) in four groups of provinces with low, lower middle, higher middle and high-income levels, respectively⁶⁰ (Fig. 3). This non-linear relationship between province income level and the health benefits of mitigation efforts is because the proportion of coal used to power existing electricity grids, the cost of renewable electricity, and the population patterns are also key determinants of the health benefits. In addition, these factors do not always correlate perfectly with the income level of a province (Fig. 3a).

Second, distributional effects have been examined at a finer spatial resolution, such as at the county level, which offers more valuable insights into environmental justice concerns^{18,61}. For example, an all-of-society decarbonization approach – combining climate and energy policy actions from federal, state and local actors – could reduce $\text{PM}_{2.5}$ -attributable mortality by 13% in United States counties with a low social vulnerability index (SVI) but only by 8.1% in high-SVI counties²³ (Fig. 3b). However, despite the lower percentage reductions in high-SVI counties, the absolute reductions are greater in these counties owing to the greater health burden in the baseline scenario in the absence of policy actions. This finding suggests that the metrics that are used to measure health benefits, such as absolute or percentage changes, can affect conclusions about the effectiveness of policies in delivering health benefits.

Third, some studies at the census-tract level have found that prioritizing the retirement of coal power plants near lower-income and disadvantaged communities can alleviate pollution injustice while achieving similar carbon-reduction targets^{27,62}. For example, retiring Pennsylvania's coal generation by prioritizing plant closures with an equity-oriented approach (that is, first retiring plants close to Environmental Justice Areas (EJAs), which are census tracts defined by the Pennsylvania Department of Environmental Protection) can deliver greater health benefits to the residents living in the EJAs, compared with a least-cost approach (that is, retiring plants with the highest marginal costs of generation)²⁷ (Fig. 3c). Quantitatively, retiring 50% of Pennsylvania's coal generation in 2019 would reduce $\text{PM}_{2.5}$ -attributable deaths in EJAs by 11% with an equity-oriented approach versus 3.4% with a least-cost approach, respectively.

In summary, the subnational impacts of energy transitions on pollution levels and health disparities depend on the specific design of the low-carbon energy transition and its interplay with socioeconomic patterns and broader societal efforts to promote equity. When energy decisions are designed to maximize pollution-reduction benefits in highly polluted, densely populated regions, especially those with many vulnerable populations, greater overall benefits for health and health disparities can be expected.

Analytical approaches and challenges

Methodologically, the impacts of energy decisions or policies on pollution levels and health can be assessed using two types of analysis⁶³. The first type is an ex post assessment, which quantifies the impacts of energy decisions or policies that have already been implemented^{64–66}. The second type is an ex ante assessment, which projects the potential impacts of future decisions and policies^{4,17,26}. Ex post assessments can be conducted either through empirical methods based on observed impacts or through process-based modelling that quantifies the effects of a counterfactual scenario in which such energy decisions were not in place. In comparison, ex ante assessments are almost exclusively performed using process-based modelling, which simulates the cause-and-effect chain from potential policy actions to changes in energy activities and their associated impacts. In this Perspective, we focus on the analytical approaches and challenges associated with ex ante assessments, as they are more relevant for informing the transformational changes required for climate stabilization in the decades to come.

The general analytical framework used to estimate the impacts of energy decisions on air quality and health includes four core steps (Fig. 4): first, assessing the impacts of energy decisions or policies on energy demand and supply technology choices; second, quantifying the impacts of these energy activities on air-pollutant emissions; third, simulating the impacts of emissions on ambient concentrations of air pollutants; and finally, estimating the effects of energy activities on pollution exposure and health outcomes. Below, we outline each step in detail, including the current modelling methods, analytical challenges and key uncertainties.

Quantifying the impacts on energy production and end uses

Energy system models are often used to assess the impacts of energy decisions or policies on energy demand, end uses and production activities. In combination with assumptions on emission factors, many models or modelling frameworks are able to estimate the emissions of air pollutants and greenhouse gases from energy activities^{67,68}. Here, we highlight two key analytical challenges in this step.

First, the choice of the baseline scenario, which represents the conditions that would exist in the absence of specific policy or energy decisions, is crucial for accurately attributing the impacts to the decisions being examined. For example, socioeconomic trends, such as population and economic growth, can change the baseline energy demand independently of the policies or decisions being evaluated. In addition, air-pollution-control policies can reduce the emissions from fossil-fuel use and, in some cases, influence energy technology choices. Although some studies carefully model the role of pollution-control measures and project future changes in air-quality policy ambition and implementation^{69,70}, others make simple assumptions about future emissions, such as emission factors remaining at present-day levels or assuming a linear reduction in future emissions^{20,44,45}. The different assumptions used to design the baseline scenarios will affect the

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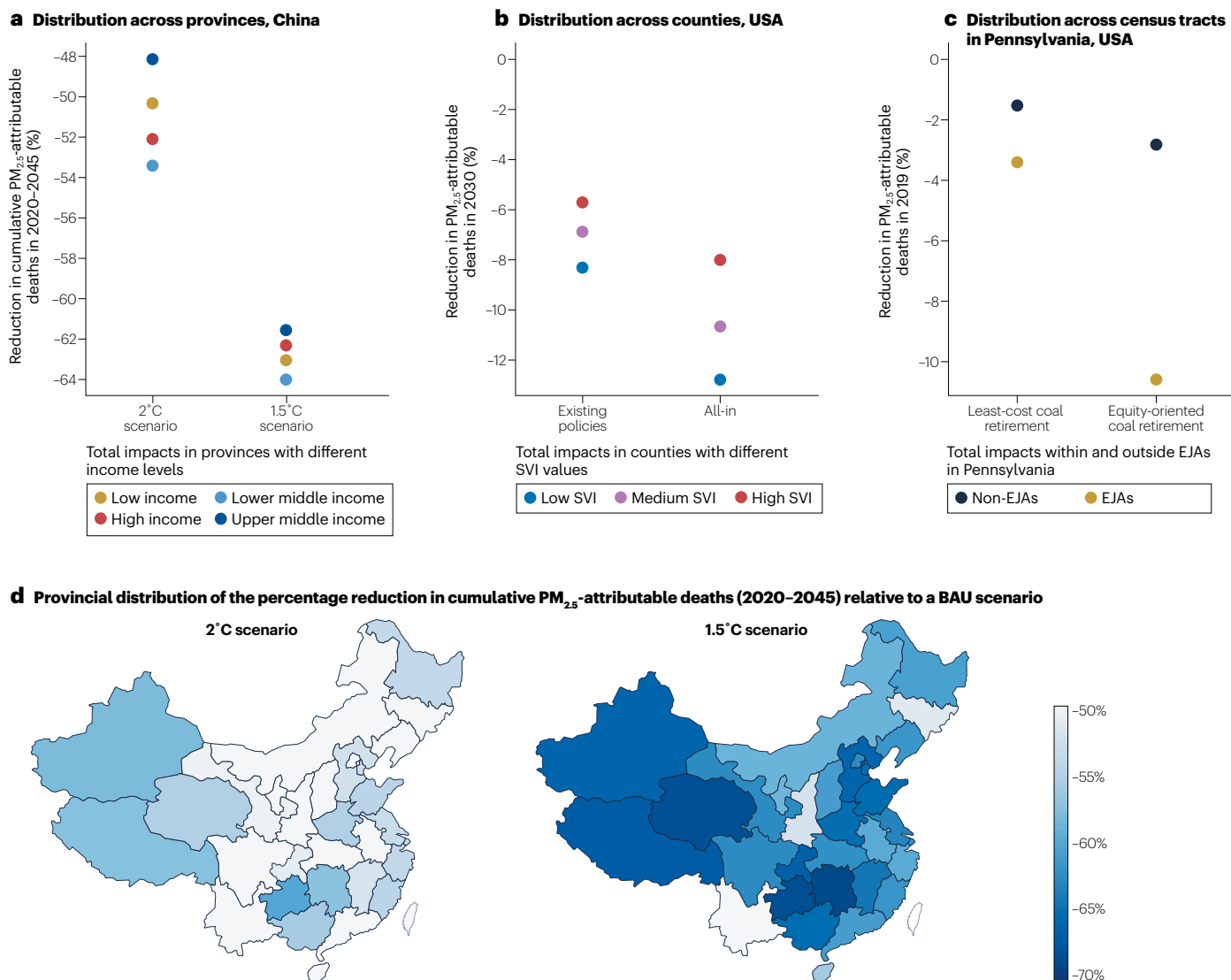


Fig. 3 | Health benefits of clean-energy transitions vary across subnational regions. **a–c.** Percentage reductions in particulate matter with a diameter of $\leq 2.5 \mu m$ ($PM_{2.5}$)-attributable deaths in the clean-energy scenarios compared to a baseline scenario in a province-level analysis for China⁶⁰ (part **a**), a county-level analysis for the USA²³ (part **b**) and a census-tract-level analysis for Pennsylvania, USA²⁷ (part **c**). Health effects vary across Chinese provinces with different income levels, across United States counties with low to high social vulnerability indices

(SVIs, defined by the Agency for Toxic Substances and Disease Registry)¹³⁶, and across Pennsylvania census tracts, defined as Environmental Justice Areas (EJAs) or not, according to the definition from the Pennsylvania Department of Environmental Protection prior to 2023 (ref. 137). **d.** Provincial distribution of the percentage reductions in 25-year (2020–2045) cumulative $PM_{2.5}$ -attributable deaths under the 2 °C and 1.5 °C scenarios, compared to a business-as-usual (BAU) scenario. Data from ref. 60.

estimated magnitude of the energy (and emissions) impacts that can be attributed to the policies or decisions being evaluated.

Second, the choice of suitable energy model types, structures and resolutions depends on the energy decisions of interest and the key mechanisms that are being captured. Energy models vary in their structures and technology representations, such as global versus subnational models, single-sector models versus multi-sectoral integrated assessment models, and short-term operational versus long-term investment models^{71,72}. Key assumptions that determine energy technology deployments also vary across models, such as how

future technology costs are represented (for example, via exogenous assumptions or endogenous innovation) and how technology competition is formulated (for example, based on least-cost principles or also including non-cost, institutional and behavioural factors). These differences between models can have major implications regarding which factors and processes are being represented or omitted, thus influencing the strengths and limitations of the analysis. For example, to assess the air-quality and emissions impacts of electric vehicles, some studies have simulated only national-level patterns of these impacts at an annual or 5-year time step^{38,73,74}, whereas others have

included detailed representation for specific regions at daily or hourly temporal resolution^{75,76}. Some studies rely on exogenous assumptions for transport demand and power grid characteristics^{75,77,78}, whereas others endogenously model the interactions between the transport and power sectors (for example, when and how electricity generation is adjusted to meet the additional demand from electric-vehicle charging)^{79,80}. Some studies directly make assumptions about the future penetration rate of electric vehicles^{21,77,78}, whereas others model how overall decarbonization goals would drive end-use electrification and deliver associated air-quality and health benefits^{17,81}. Carefully choosing the model structure and representations that are suitable for the study is a crucial first step to ensure the validity of the assessment.

Recognizing the importance of model structures, assumptions and baselines, energy modelling studies using different approaches have been compared to identify robust insights across models and the scenario designs that affect the changes to the energy system^{67,68,82}. These multi-model comparisons are valuable for identifying key determinants of emission impacts and highlighting the major assumptions of models that warrant further investigation. In addition, within the energy modelling community, there is also an increasing focus on improving the empirical foundation for modelling of future technology deployment (for example, using historical analogues or experience curves to model the future speed and scale of technology adoption)^{83–85} and to enhance policy realism (for example, modelling the effects of different policy instrument choices, such as mandates, subsidies and taxes, instead of stylized technology strategies)^{23,86}. These efforts have improved the ability of the energy system modelling community to better evaluate the technology and emissions implications of energy transitions.

Quantifying the impacts on fine-scale emissions

Processing and downscaling air-pollutant emission estimates from energy models is often a necessary step towards further assessing the potential impacts on ambient air pollution. Here, we focus on a common workflow that starts by downscaling emissions, and then uses these values as input for air-quality modelling, while recognizing that some studies use an alternative workflow that involves simulating ambient pollution levels at a coarser scale and then downscaling these to subnational or sub-grid levels^{87,88}.

Multi-sectoral energy models typically project emissions at the national or state/provincial level^{67,69,80}, making spatial and temporal downscaling of emission estimates crucial for enabling air-quality simulations. Sectoral energy models project fine-scale emissions for only a single sector (for example, plant-level emissions for the power sector)^{26,27,89}. To accurately simulate air quality, emissions from other

sectors need to be added, because the formation of air pollutants depends on a range of precursor emissions and their interactions, along with local-scale meteorological factors. For example, ammonia emissions from agricultural activities are often not captured by energy models. However, they interact with SO₂ and nitrogen oxides (NO_x) emitted by the energy sector to form secondary aerosols. More generally, most energy models are better at projecting energy-related emissions than land-related emissions. This limitation is important for forward-looking assessment, because wildfire and agricultural emissions will probably have an increasingly important role in determining air quality in the future, especially as energy-related emissions are expected to go down dramatically in a deeply decarbonized world.

In addition, quantifying the distributional effects requires major advances to characterize fine-scale emissions in relation to sociodemographic patterns as well as infrastructure siting and retirement decisions. Historically, pollution hotspots have coincided with the locations of heavily polluting industrial and electricity facilities, leading to exposure inequities, as many of these facilities were sited close to disadvantaged communities. The location of future pollution hotspots will similarly depend on the technology choices and siting decisions made today. For example, retiring highly polluting coal power plants near disadvantaged communities could help to mitigate pollution-exposure disparities and improve equity outcomes^{27,61,62,90}. Conversely, building new bioenergy facilities or adding carbon capture and storage might increase air-pollutant emissions^{69,91}. Ensuring that the energy transition does not exacerbate exposure disparities would require such facilities to be sited away from disadvantaged communities.

The spatial relationships between polluting energy infrastructure and sociodemographic patterns are crucial determinants of future disparities in pollution exposure and health impacts. However, existing assessments often rely on simple assumptions. For example, many studies downscale future emissions based on historical patterns^{19–21,44,92}, which can create inconsistencies between fine-scale socioeconomic projections and new energy investment locations. Future emissions are beginning to be treated in a more sophisticated way in some studies, for example, by considering the emission patterns associated with different coal-power-plant retirement decisions that consider the size and vulnerability of populations living close to the power plants, as well as the costs, age and operational details of the power plants and transmission grids^{27,61,93}. Further research is needed to study this issue in a more systematic way.

Quantifying the impacts on ambient air pollution

Air-quality models are often used to simulate changes in ambient concentrations of air pollutants, especially PM_{2.5} and ozone, based

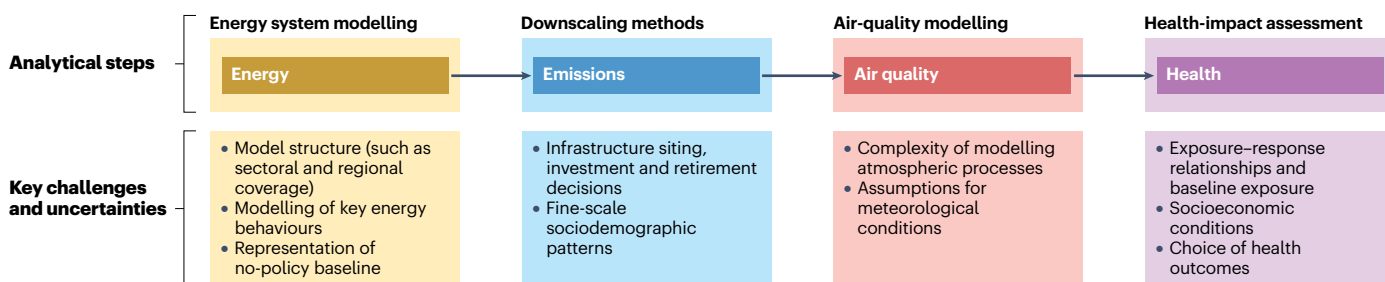


Fig. 4 | Overview of the integrated modelling approach. The analytical steps and key challenges and uncertainties in quantifying the effects of the energy transition on air quality and health are depicted.

on fine-scale emissions data. As in the discussion above about energy model structures and assumptions, the choice of air-quality models and their underlying assumptions can affect the results for the simulated air-quality impacts. Atmospheric chemistry and transport models serve as the central analytical tool for simulating the magnitude and distribution of air pollution in various energy strategy scenarios. Complex models are sometimes used to carefully simulate the physical and chemical processes in the atmosphere at fine spatial and temporal scales, such as WRF-Chem or CMAQ at the regional scale^{17,20,21,77} and GEOS-Chem or Earth system models at the global scale^{5,44,90}. By contrast, reduced-complexity models have frequently been used to assess changes in annual concentrations of PM_{2.5} and, in some cases, ozone, including InMAP, ISRM and other response-surface models at the regional scale^{27,49,74,94–98} and TMS-FASST at the global scale^{14,45,47,48}. Although these simpler models enable rapid analyses of pollution impacts and facilitate the assessment of differences across multiple energy scenarios, they are limited in the types of pollutant they can accurately simulate and the temporal resolution they can reliably provide; for example, annual results are often more available and credible than monthly or daily results. Furthermore, reduced-complexity models often perform less well when applied to different meteorological years (for example, if the model was developed using 2005 meteorological conditions but is then applied to a different year in the assessment) or when non-marginal changes in emissions are present. Although bias-correction methods have been developed and applied in some analyses^{99,100}, reduced-complexity models should be approached with caution and their validity assessed on a case-by-case basis. For example, reduced-complexity models are generally better at capturing the relative differences across energy scenarios than they are at simulating the absolute impacts.

Another key assumption that can substantially change simulated pollution patterns is projected future meteorological conditions. For example, ozone pollution might increase in a warmer world^{101–103}, whereas the effects of future meteorological conditions on ambient PM_{2.5} are predicted to be more mixed and location-dependent^{103–105}. Notably, local meteorological conditions are affected by future climate patterns, which in turn are influenced by global greenhouse gas emissions resulting from energy transitions worldwide. To date, the impacts of multi-scale energy transitions on air quality – through changes in both emissions and meteorological conditions – have not been systematically examined and are an important area for future research.

Quantifying the impacts on health exposure and outcomes

Assessing the impact of specific energy policies or decisions on human health requires an estimate of population exposure to air pollution (or changes in exposure) with and without policy implementation, typically based on the results of air-quality simulations. Assessment of health impacts must also take into account the size of the exposed population, the baseline incidence rate of the relevant diseases, and concentration–response relationships, which quantify how disease or mortality rates (the ‘response’) change as a result of altered estimated concentrations.

Assessment of health impacts is subject to a few general analytical challenges¹⁰⁶. First, estimating the baseline exposure level at fine spatial scales often involves combining data from multiple sources, including ground-based measurements, satellite data and the results of simulations. Despite substantial efforts to retrieve and estimate surface air-pollution concentrations and population exposure levels^{99,107,108}, considerable uncertainties remain. At the global scale, more

pollution data are available for higher-income than for lower-income countries/regions; credible baseline exposure assessments for African countries and some Asian countries remain challenging¹⁰⁹. At the sub-national scale, ground measurements are typically more concentrated in urban areas with high pollution levels, whereas rural areas and those downwind of polluting facilities often lack sufficient data¹¹⁰. This imbalance in data availability makes it difficult to quantify disparities in baseline exposure between urban and rural areas, which serves as the basis for evaluating the effectiveness of energy decisions.

Large uncertainties in concentration–response relationships (or exposure–response relationships) is another general challenge related to assessing health impacts. These relationships are derived from studies with different experimental designs (for example, cohort studies or cross-sectional studies) and focused on different regions (for example, more studies in developed countries than in developing countries), different population groups (for example, all-age, adult populations or specific age groups) and causes of mortality (for example, all-cause or cause-specific)^{111,112}. The numerical values of the exposure–response relationships thus vary substantially across studies. Multiple meta-analyses have attempted to synthesize and combine the evidence from various studies¹¹². However, the generalizability of these exposure–response relationships to a different region or population group is still up for debate^{111,113}, and further evidence is needed from epidemiological studies.

In addition to these common challenges related to assessing health impacts, a few additional challenges exist that are particularly relevant to assessing energy decisions. First, socioeconomic conditions serve as both drivers of upstream energy decisions and determinants of downstream health impacts. In practice, energy models often utilize exogenous economic and population projections to estimate future patterns of energy demand; some models also account for heterogeneous energy consumption patterns among different population groups (for example, across income levels or between urban and rural populations)^{114,115}. These socioeconomic factors influence energy technology choices and, consequently, future patterns of emissions and pollution. The same factors also directly affect health outcomes by determining the size and vulnerability of the populations exposed to pollution. For example, large disparities are found in the exposure of urban and rural populations to ambient PM_{2.5} in China⁵³. In addition, population ageing is a key determinant of future health burdens related to pollution exposure^{43,44}. Although the complex connections between energy decisions and socioeconomic factors are starting to be recognized^{44,82}, these interactions warrant further investigation to ensure that internally consistent assumptions are used throughout the assessment of energy production and consumption, emissions, air quality and health impacts.

Second, exposure to air pollution affects a wide range of health outcomes, including short-term morbidity and long-term mortality. Consequently, conclusions regarding the effectiveness of energy policies or decisions can vary depending on the chosen health outcomes. For example, ambient PM_{2.5} generally has a larger impact than ozone on long-term mortality, but ozone can have a larger effect than PM_{2.5} on some short-term outcomes, such as certain respiratory problems¹¹¹. Furthermore, different energy strategies have varying potential to mitigate the precursor emissions that form ambient PM_{2.5} versus ozone. For example, replacing solid fuels with electricity for cooking and heating reduces emissions of black carbon (often referred to as soot), thereby lowering primary PM_{2.5} concentrations. By contrast, scaling up electric-vehicle adoption can help to avoid the NO_x emissions from

gasoline and diesel combustion, which reduces the precursor emissions for both PM_{2.5} and ozone. Thus, the decision of which energy policies or decisions and related health outcomes to examine determines the most suitable modelling approach for the analytical task.

Characterizing uncertainties in an integrated modelling framework

Assessing the health effects of energy transitions requires an integrated modelling framework that connects the four steps from energy policies or decisions and emissions to air quality and health. The uncertainties in each of the four steps can propagate through a long cause-and-effect chain simulated by this integrated modelling framework, from ‘upstream’ health drivers (for example, energy strategies that change air-pollutant emissions) to ‘downstream’ health exposures (for example, exposure to ambient particulate matter) and outcomes (for example, premature deaths). Some uncertainties, such as those related to demographics, can affect both upstream drivers and downstream impacts.

Importantly, these various types of uncertainty also have different natures and therefore require different mathematical representations¹¹⁶. Analytically, some of these are parametric uncertainties (for example, choice of exposure–response relationships, sociodemographic projections and meteorological conditions), whereas others are structural uncertainties (for example, which energy model and air-quality model structures are being used). Conceptually, each of these uncertainties is located somewhere on a continuum from well characterized (shallow) uncertainty to difficult-to-characterize (deep) uncertainty¹¹⁷. Shallow uncertainty can be represented by joint probability distributions over a known set of possible scenarios or situations. For example, the uncertainties related to exposure–response relationships and present-day exposure levels are relatively well characterized, thanks to the growing empirical evidence and observational data in this space. By contrast, representing unknown futures for energy transitions results in deep uncertainties, where “the system model and the input parameters to the system model are not known or widely agreed on by the stakeholders to the decision”¹¹⁸. For example, long-term sociodemographic trends, energy technology costs, and energy policy choices involve deep uncertainties that are challenging to characterize.

Conventional uncertainty-quantification methods such as Monte Carlo simulations are useful to represent well characterized uncertainties. However, deep uncertainties and the interactions between social and technical uncertainties present new analytical challenges for their incorporation into assessments of the health impacts of energy transitions. To address this challenge, exploratory modelling based on large-scale scenario ensembles offers a promising way to identify robust energy strategies that can yield health benefits across a range of plausible futures^{45,119}. The scenario ensemble approach can sample a wide range of socioeconomic and technical uncertainties to characterize how they propagate through a highly interconnected, multi-sector system to influence air quality and health. When combined with scenario discovery approaches such as classification tree regression, the scenario ensemble approach enables the identification of the key conditions leading to undesirable outcomes, such as technology choices that are most likely to worsen air quality or widen health disparities in a wide range of future ‘states of the world’. For example, a coupled climate–energy–health model has been used to assess the health effects across countries of a global carbon price in nearly 30,000 future states of the world⁴⁵, revealing consistent health co-benefits in most highly polluted countries. However, for a few less

polluted countries, a carbon price can increase the mortality risks in some of the states of the world owing to emissions increases from bioenergy use and land-use changes. In this modelling analysis, these potential health co-harms are largely driven by the scale and method of deforestation⁴⁵.

Given the complexity of the underlying mechanisms and uncertainties in an integrated modelling framework, efforts to identify robust energy strategies can enhance the decision relevance of their impact assessments for air quality and health. Applying advanced methods related to trade-off analysis in the energy and health contexts will be valuable for comparing and informing different energy strategy designs. Potential approaches include ‘modelling to generate alternatives’¹²⁰, which can aid in identifying a portfolio of near-least-cost solutions with better health and equity outcomes, as well as multi-objective robust decision-making methods¹²¹, which can explore trade-offs and assess robustness in selected scenarios. In addition, innovative visualization and storytelling techniques can facilitate communication of the results with decision-makers, thereby improving the usefulness of these studies¹²². For example, different narratives exist about the energy transition, such as that it will improve energy resilience, achieve health benefits or mitigate climate change. Using different narratives to communicate the research findings could improve the connection with the motivations and interests of real-world decision-makers and stakeholders.

Incorporating health benefits into energy policy decisions

Policy actions to facilitate the shift away from fossil-fuel-based energy provide an avenue to simultaneously achieve climate, air quality and health objectives. It is often not straightforward to categorize a policy as solely climate-focused or energy-focused. For example, in countries such as China and India, the clean energy transition has been driven primarily by local concerns about air pollution and health rather than by global climate priorities^{6,7}. In addition, many countries have embraced green industrial policy as a key near-term strategy to mitigate climate change¹²³. These policies place special emphasis on local employment, health and other socioeconomic benefits, by promoting domestic manufacturing and clean energy investments. Therefore, the resulting health benefits are viewed as the primary policy goal in some cases, and a co-benefit in other contexts.

Here, we adopt a broad definition of clean energy policies based on the anticipated policy outcomes (for example, when clean energy technologies are supported, either directly or indirectly) rather than the stated policy objectives that facilitate the adoption of such policies (for example, achieving climate, air quality or energy goals). In this section, we first summarize the potential for health benefits from clean energy policies and then discuss ways to generate actionable knowledge that can facilitate the integration of health benefits into energy policy decisions.

Potential for health benefits from clean-energy policies

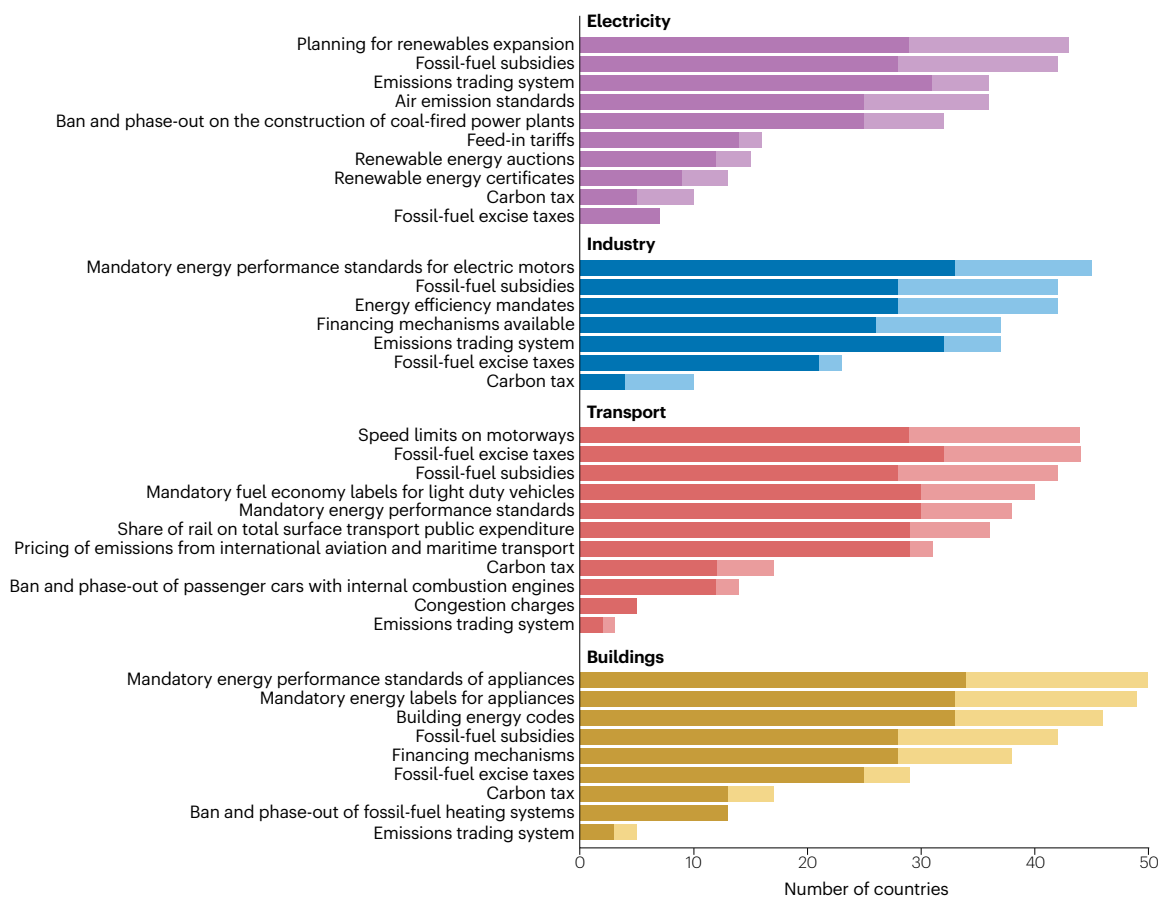
Over the past decades, the adoption of clean-energy policies by governments has been on the rise in nearly all countries¹²⁴. Based on a data set covering 52 countries (Climate Actions and Policies Measurement Framework database)¹²⁴, all of these countries, which include developed and developing economies, have adopted a wide range of clean-energy policies at present (Fig. 5a). Despite some exceptions, such as fossil-fuel subsidies, most policies are designed to support and promote low-carbon energy use and enhance energy efficiency. These policies span one

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or more emitting sectors and include both command-and-control measures, such as emission standards and technology mandates, and market-based policies, such as subsidies and carbon pricing. These

trends suggest that there is considerable potential for health benefits from current policy actions, because greater clean-energy use often implies reduced (or avoided) air pollution from fossil-fuel use.

a Number of countries that have adopted each type of policy instrument by 2020



b Synergistic programmes between energy, health and equity under the United States Inflation Reduction Act

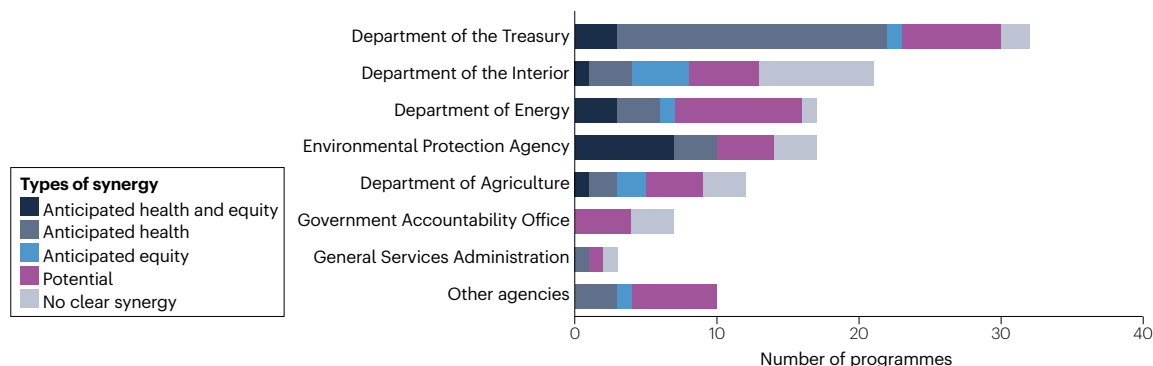


Fig. 5 | Clean-energy policies and programmes adopted globally.

a, The number of countries that have adopted various types of climate and energy policy by 2020. The darker and lighter colours indicate developed economies and developing, transitioning economies, respectively. Data from ref. 124; original data from the Organisation for Economic Co-operation and Development (OECD) Climate Actions and Policies Measurement Framework database, which includes 52 countries. **b**, Categorization of United States federal programmes under the Inflation Reduction Act based on whether they explicitly include health as a programme objective or not. A programme is labelled as

having ‘anticipated’ synergy when health or equity are mentioned explicitly as a primary goal of the programme. The synergy of a programme is labelled ‘potential’ when the benefits depend on the details of implementation; for example, many programmes include a loose guideline that they will give high priority to low-income communities, but achieving equity-improving outcomes depends on successfully directing more funding to these communities during the implementation process. The raw data are from the Inflation Reduction Act tracker¹³⁸. Detailed labelling and justifications are included in ref. 126. Part **b** adapted with permission from ref. 126, Elsevier.

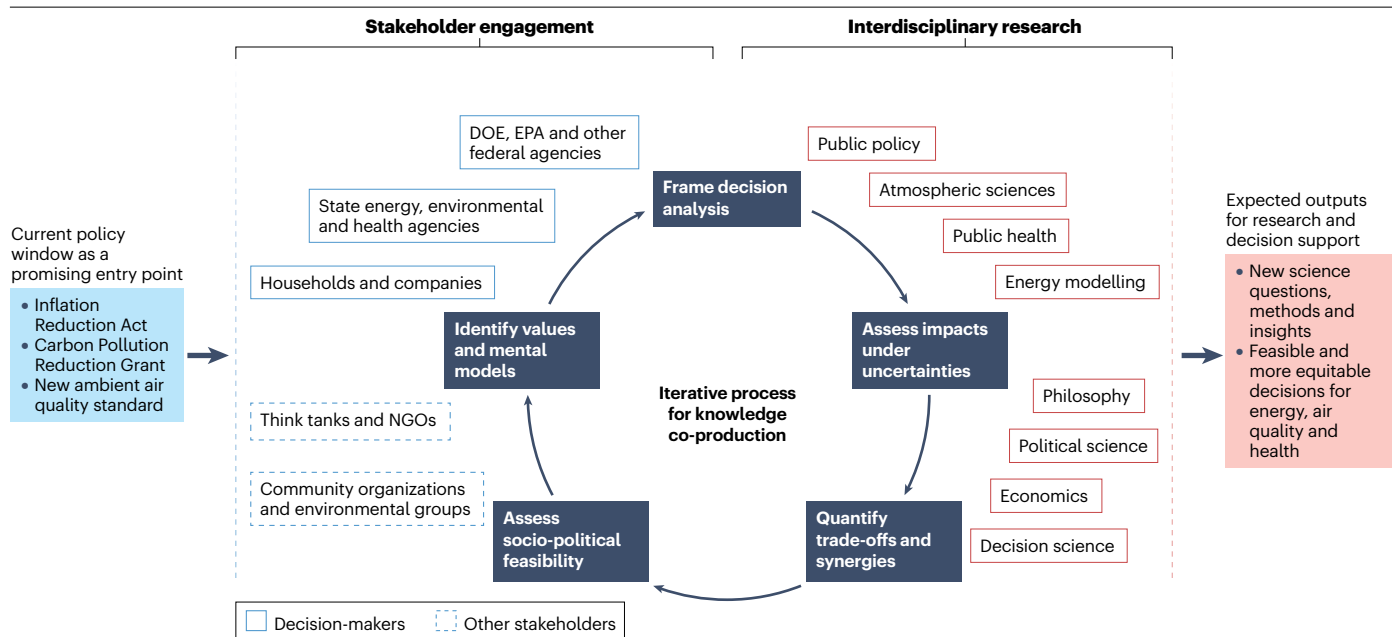


Fig. 6 | An iterative process for knowledge co-production to integrate health benefits into energy decisions. The United States Inflation Reduction Act and other recent actions are used as examples of this process. The process is inspired

by the literature on knowledge co-production^{132,139} and risk management¹⁴⁰ and adapted for energy, air-quality and health decisions. DOE, Department of Energy; EPA, Environmental Protection Agency; NGO, non-governmental organization.

Although clean-energy policies generally yield climate and health benefits, the scale of the benefits depends largely on specific details regarding the policy goal, design and implementation. For example, renewable energy policies designed to maximize the climate benefits from wind-power and solar-power generation will be different from those aimed at maximizing health benefits. Climate-benefiting policies would concentrate the deployment in regions with high carbon-intensive power generation, whereas health-benefiting policies would also take into account population density and the vulnerability of exposed communities¹²⁵.

Here, we use United States federal programmes under the Inflation Reduction Act as an example to illustrate the importance of policy design and implementation¹²⁶ (Fig. 5b). Although the new 2025 federal administration has proposed major changes to government spending, including pausing some Inflation Reduction Act funds, the Inflation Reduction Act still represents the largest investment by the United States Congress to date in low-carbon energy, by providing substantial tax credits and financing to businesses and individuals for adopting clean technologies. In particular, some Inflation Reduction Act programmes explicitly mention health as one of the primary programme goals, which is reflected in their resource allocation criteria (these programmes are labelled ‘Anticipated health’ in Fig. 5b). Other programmes either omit these considerations or include only vague guidelines that might not be straightforward to enforce, such as prioritizing disadvantaged communities when possible (these programmes are labelled ‘Potential’ in Fig. 5b). These examples emphasize the importance of policy design and implementation details to transform the potential health benefits of clean-energy policies into tangible benefits on the ground.

More generally, aligning policy actions in energy, climate and health requires new partnerships and collaborations, which might

not be prevalent or standard at present. For example, inter-agency collaboration will be crucial to pursue joint efforts and align the timelines of distinct policy actions. At the federal level, cooperation between the United States Environmental Protection Agency and Department of Energy could enhance the integration of air-quality and health goals into energy policies. At the state level, establishing interagency initiatives and public-private partnerships can help to identify synergistic programmes that align with local priorities and administrative capacity. In addition, given that energy decisions could affect multiple states and that air pollution travels across state boundaries, existing programmes and regulations that promote cross-state collaboration, such as the [Regional Greenhouse Gas Initiative](#) and the [Cross-State Air Pollution](#), provide useful platforms with which to engage multiple states and explore ways to improve policy coordination. Although these examples are focused on the USA, improving coordination between government agencies and across states/provinces is also important for other countries with different institutional environments to integrate health benefits into energy decisions.

Actionable knowledge for complex decision-making

In addition to the analytical challenges discussed above, incorporating health benefits into real-world energy-policy decision-making presents challenges related to institutional and sociopolitical factors^{126–129}. The policymaking process for energy, air quality and health are often led by different government agencies and stakeholders. The policy design (for example, using incentives versus penalties) and their framing (for example, emphasizing climate versus health benefits), along with their distributional impacts, strongly affect the sociopolitical feasibility of various policy instruments and measures^{130,131}. Generating actionable knowledge in this area thus requires a multidisciplinary approach that combines insights from energy modelling, atmospheric sciences,

public health, economics, and the political and behavioural sciences. It also requires close collaboration with societal stakeholders to identify what is socially desirable and politically feasible.

The distinct characteristics of this problem highlight the need for knowledge co-production, defined as “an iterative and collaborative process involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future”¹³². Here, we use the USA as an example to illustrate key elements of a plausible knowledge-production process (Fig. 6). The Inflation Reduction Act provided an opportunity to initiate knowledge co-production for integrated energy, air-quality and health decisions. Other synergistic initiatives include the [Climate Pollution Reduction Grants](#), which emphasize air-quality benefits, and the recently tightened National Ambient Air Quality Standards (NAAQS) for particulate matter. Researchers could make use of these to address the immediate decision needs of state and local stakeholders. For example, model assessments that compare siting decisions of industrial facilities and technology choices for energy supply and consumption could help to optimize air-quality benefits while considering cost-effectiveness, distributional effects and other objectives. It is also crucial to strategically organize initial efforts to develop sustainable, long-term partnerships. In addition to exploring what is possible in the near term, a forward-looking perspective focused on defining a course of future actions will be instrumental in promoting air quality and health in long-term energy planning.

Recognizing that effective knowledge co-production needs to be context-specific and goal-oriented, countries and regions need to identify promising opportunities aligned with their policy agenda and near-term priorities. In China, the strong push for green technologies such as electric vehicles and renewable electricity presents a valuable policy window in which to pursue health benefits. In India, the urgent need for cleaner cooking and heating solutions to combat air pollution could serve as an entry point to accelerate the energy transition. The key to developing actionable solutions lies in engaging with societal actors who understand real-world barriers, as well as incorporating interdisciplinary research insights that are grounded in local conditions and contexts.

Conclusions

Transitioning to a low-carbon energy system can simultaneously mitigate carbon emissions, reduce air pollution and protect human health. Although the potential health benefits have been identified at local, national and global scales, knowledge gaps and analytical challenges remain at every stage of assessing the air-quality and health effects of energy transition – ranging from energy and air-quality modelling to health and disparity assessments. To understand the impacts on health disparities in addition to aggregate patterns, we must better characterize the complex cause-and-effect relationships between energy decisions, emissions, air pollution levels and health impacts, including cross-regional and sectoral impacts, as well as appropriately represent the uncertainties related to future trends in technology and socioeconomic aspects.

Energy decision-making in the real world requires a careful balance of multiple policy priorities while navigating complex institutional and sociopolitical challenges. Two areas of future effort are particularly crucial for improving the policy relevance of research studies. First, there is a need to shift from assessing general policy strategies to evaluating specific policy design and implementation questions. By improving the policy realism in the assessments, researchers can provide

more direct and actionable insights to support the decision-making process. Second, co-producing knowledge with decision-makers and relevant stakeholders is essential for addressing energy policy issues characterized by complex design questions and uneven impacts across regions and interest groups. Engaging closely and interactively with stakeholders to frame the problem and conduct analyses is the key to aligning research efforts with concrete decision needs on the ground.

Data availability

All the data used to generate Figs. 2, 3, and 5 are available in the following Zenodo repository: <https://doi.org/10.5281/zenodo.15466238>.

Code availability

All the codes used to generate Figs. 2, 3 and 5 are available in the following Zenodo repository: <https://doi.org/10.5281/zenodo.15466238>.

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Author contributions

W.P., M.B. and N.S. conceptualized the paper. W.P., J.S., C.C.M. and H.L. analysed the data and generated the figures. W.P., J.S. and C.C.M. wrote the first draft. All authors reviewed and revised the paper.

Competing interests

The authors declare no competing interests.

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