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Targeting net-zero emissions while advancing other sustainable development goals in China

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The global net-zero transition needed to combat climate change may have profound effects on the energy–food–water–air quality nexus. Accomplishing the net-zero target while addressing other environmental challenges to achieve sustainable development is a policy pursuit for all. Here we develop a multi-model interconnection assessment framework to explore and quantify the co-benefits and trade-offs of climate action for environment-related sustainable development goals in China. We find that China is making progress towards many of the sustainable development goals, but still insufficiently. The net-zero transition leads to substantial sustainability improvements, particularly in energy and water systems. However, the co-benefits alone cannot ensure a sustainable energy–food–water–air quality system. Moreover, uncoordinated policies may exacerbate threats to energy security and food security as variable renewables and bioenergy expand. We urge the implementation of pragmatic measures to increase incentives for demand management, improve food system efficiency, promote advanced irrigation technology and further strengthen air pollutant control measures.

In the past few years, many countries have announced their long-term low-emission development strategies, aiming for consistency with the Paris Agreement. But challenges remain as to how to progressively realize their ambitious goals[1]. China has committed to achieving carbon neutrality by 2060. It is not yet clear which greenhouse gases (GHG) will be covered, but even achieving net-zero carbon dioxide (CO_2) emissions, which is the least ambitious, requires a rapid economy-wide transformation, with energy, water, food and air quality systems becoming increasingly interconnected[2]. This requires an integrated approach that considers the interplay between supply and demand, as well as the connections between different systems, to develop cost-effective policy transitions towards the broader sustainable development goal (SDG) agenda and catalyse policymakers and stakeholders to achieve rapid and coordinated change[3,4].

The nexus between SDGs has gained increased attention, as pursuing the net-zero target is anticipated to have substantial social–economic–environmental impacts[5–8]. As suggested in the literature, there are co-benefits of the decarbonization on improving air quality[9,10] and conserving water[11,12]. The negative impact of carbon dioxide removal (CDR) technologies on food security[13], health[14] and water conservation[15] is also identified[16]. Except for some global and European Union model studies that include multiple SDGs and

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sustainability measures[4,17–22], most existing studies focus on a specific part of the SDGs, which may lead to biased results if multiple system interactions are not considered.

As of 2022, China has achieved environment-related SDG targets for 52% (51 out of 98) indicators and has made encouraging progress in food production sustainability, clean energy transition, reduced 2.5-micrometre particulate matter ($PM_{2.5}$) exposure risk and larger forest coverage[23]. Demand and lifestyle changes[24,25], air pollution control measures[7], water management[26] and SDG policy incentives[27] have been proven to affect the cost-effectiveness of the energy–food–water–air quality system transition, but most of the studies are retrospective and static[28–31], with a noticeable absence of dynamic long-term country-level integrated sustainable pathway outlooks as well as assessments of trade-offs and co-benefits of climate action across multiple systems.

Here we develop a bottom-up integrated assessment framework for China's energy–food–water–air quality system to evaluate the co-benefits and trade-offs of the net-zero transition (Extended Data Fig. 1). This study covers 37 official or proxy indicators across environment-related SDGs derived from the SDG target space[32,33], and outline pathways to achieve certain aspects of these SDGs via sustainability measure setting and model framework results. The study presents evidence that climate mitigation is crucial in solving China's environmental challenges; however, co-benefits alone are insufficient to achieve sustainable development of the energy–food–water–air quality system. We highlight the need for additional sector-specific sustainability measures and policies to ensure the net-zero target achieved while making progress in other policy domains of sustainable development as well.

Mitigation pathway to net zero

In this study, we design three core scenarios, 'NDC' (based on updated Nationally Determined Contributions to peak energy-related CO_2 emissions before 2030[34]), 'CN60' (NDC scenario with CO_2 neutrality in 2060) and 'CN60–SDG' (CN60 scenario with additional sustainability measures (Extended Data Table 1)). As China's carbon-neutral pledge does not specify GHG coverage, we assume that it represents net-zero CO_2 emissions from fossil fuel and industrial (FFI) processes in 2060. The comparison of CN60 and NDC reveals co-benefits and trade-offs for the energy–food–water–air quality system induced by the net-zero transition, while the comparison of CN60–SDG and CN60 emphasizes the importance of integrated sustainability measures and policies.

Figure 1 summarizes the relevant indicators for the energy–food–water–air quality net-zero transition. Driven by long-term socio-economic development goals, China's economy is expected to grow with gross domestic product (GDP) per capita exceeding US$22,500 by 2035, and the share of industrial value added in GDP remaining above 30% by 2050 (Fig. 1a). Following the COVID-19 pandemic, China's FFI CO_2 emissions end their volatility and continue rising, expecting to peak around 2025 at ~11 $GtCO_2$. After peaking, based on scenario assumptions that aim for net-zero CO_2 emissions by 2060 and net-zero GHG emissions by 2070, the CN60 and CN60–SDG scenarios have similar emission reduction pathways (Fig. 1b,c). Net-zero target achievement needs widespread use of carbon capture and storage (CCS) and CDR technologies (Supplementary Fig. 2). In 2060, CCS technologies need to capture 1.5 $GtCO_2$, with 1.1 $GtCO_2$ from CDR technologies. Up to 150 $MtCO_2$ would be sequestered through direct air capture and storage (DACS), while bioenergy with CCS (BECCS) for electricity and hydrogen production would contribute to most of the negative emissions (Fig. 1d).

Accelerating energy system decarbonization requires near-term industrial upgrading and energy efficiency improvements. The model results show that China needs to halve its energy intensity by 2035 (Fig. 1e). While renewables have gained momentum, coal, the cornerstone of energy retention, would dominate primary energy through 2035. In 2060, renewables could make up ~66% of the primary energy supply (Fig. 1f). Fuel substitution in the end-use sector would drive greater use of electricity, increasing the share of electricity in the final energy from 25% in 2020 to 59% in 2060 (Fig. 1g). With the growing share of electricity and alternative fuels, oil and gas demands could be cut by >63% after 2050 compared with 2019, leading to lower import dependency and strengthening energy supply security (Supplementary Fig. 3). The CN60–SDG scenario, which incorporates demand management measures such as better load balancing and vehicle to grid (V2G), would result in flatter intraday electricity prices than the CN60 scenario (Fig. 1h). Climate feedback on the energy system also has a crucial role in the transition: in 2060, warmer winters are expected to reduce heating energy consumption by 2.4–11%, while warmer summers are expected to increase cooling energy consumption by 8.6–45% (Supplementary Figs. 4 and 5). Climate feedback could lead to an increase in power sector costs of ~2%, owing to reduced efficiency of solar power and stronger seasonality of water runoff with impacts on hydro production (Supplementary Fig. 6).

Expanding biomass production with food security in mind

The land use system is closely linked to the net-zero transition in both nature-based solutions (forest carbon sinks) and technology-based solutions (BECCS). Demographic change would shape the food system, with demands for biomass putting pressure on the food system after 2060, leading to trade-offs between food security and decarbonization. Enhancing food system efficiency is crucial for achieving net zero while preserving food security and biodiversity.

According to model simulations, China's forest area is steadily increasing owing to continued forest protection and afforestation (Figs. 1i and 2b). Under the CN60 scenario, it is expected to increase by 2.9% in 2030 and 10.6% in 2060 compared with 2020 (Fig. 2a). This increase would contribute to valuable forest carbon sinks that help achieve the net-zero target. In 2030, the CN60–SDG scenario could expand afforestation by 3.34 Mha more than CN60, and forest area increases by 5.2% compared with 2020. Trade-offs between food systems and energy systems would become increasingly evident owing to the massive use of bioenergy for long-term negative emission demand after 2060. The forested areas in the CN60 and CN60–SDG scenarios would exceed those in the NDC scenario. We find that large-scale cultivation of energy crops begins in 2050, covering ~29 Mha by 2100, which is 3% of the national land area. According to our modelling, there is a minor change in the cropland area per capita, but excluding the area for energy crops, the area available for food cultivation in 2100 in the CN60–SDG scenario would be only 65% of that available in 2020, reflecting the savings in cropland due to less food waste, healthier dietary structures and higher crop yields.

In 2020, individual calorie intake averaged 2,700 kcal per day, 23% of which came from animals. In the CN60 scenario, crop consumption is projected to increase by only 2% in 2060 compared with 2020, despite the improvement in living standards, but livestock consumption is expected to grow by >40%. Livestock consumption increases GHG emissions, and feed production crowds out food supplies. By cutting food waste and reducing livestock consumption in CN60–SDG, per capita calorie intake could be maintained at ~3,000 kcal per day in the face of land use resource constraints (Figs. 1k and 2c).

As can be seen in Fig. 2d, the differences between crop supply and demand would not change much over time for all scenarios, and crop supply is expected to be sufficient to meet food demand. Owing to alterations in dietary structure, the CN60–SDG scenario would yield a decrease in livestock demand, subsequently leading to a decline in feed demand.

To achieve net-zero and even net-negative emissions, biomass is necessary (Fig. 2e). Access to modern energy would reduce the demand for traditional biomass, leading to rapidly declining biomass

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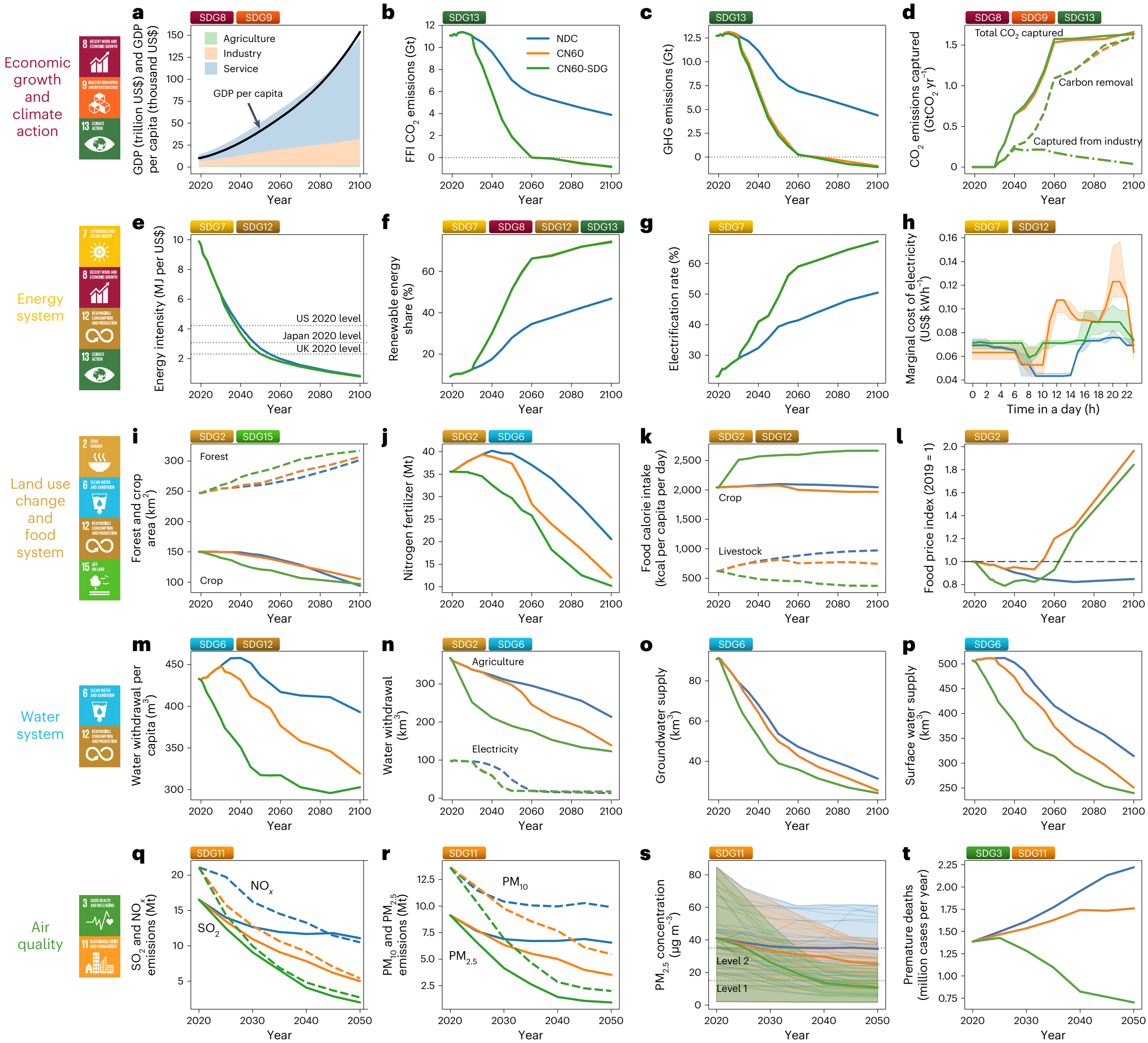

Fig. 1 | Projected evolution of sustainable development indicators in China. **a**, GDP. **b**, FFI CO_2 emissions. The reference scenario (NDC), the net-zero scenario (CN60) and the net-zero with sustainability measures scenario (CN60–SDG) are represented by blue, orange and green, respectively, in this and subsequent panels. **c**, GHG emissions. GHGs in this study comprise CO_2, CH_4 and N_2O emissions and sinks from the fossil fuel, industrial process and AFOLU sector. **d**, CO_2 emissions captured from energy systems. **e**, Energy intensity. **f**, Share of renewable energy in primary energy. **g**, Share of electricity in final energy. **h**, Marginal cost of electricity, reflecting the range of hourly energy prices on a typical summer day from 2035 to 2100, with the thick line being the median value and the range being the 50% confidence interval. **i**, Forest and cropland area. **j**, Nitrogen fertilizer usage. **k**, Food calorie intake. **l**, Food price index. **m**, Water withdrawal per capita. **n**, Water withdrawal in the power and agricultural sectors. **o**, Groundwater supply. **p**, Surface water supply. **q**, SO_2 and NO_x emissions. **r**, PM_{10} and $PM_{2.5}$ emissions. **s**, Population-weighted $PM_{2.5}$ concentration for each province in China (thin line) and for the whole country (thick line). Levels 1 and 2 represent the upper limit of the national first-level standard (15 μg m^{-3}) and the national second-level standard (35 μg m^{-3}) for the annual average $PM_{2.5}$ concentration, respectively. **t**, Annual premature deaths attributable to air pollution. Information on sectoral emission pathways, energy mix and electricity mix can be found in Supplementary Fig. 1. Credit: icons from the United Nations Sustainable Development Goals (https://www.un.org/sustainabledevelopment).

production before 2035 in the NDC scenario. Until 2050, biomass demand could be met through agroforestry residues. After 2060, bioenergy uses would gradually increase to 18 EJ in 2100, with up to 39% from energy crops under the CN60 scenario. The CN60–SDG scenario is expected to conserve biodiversity by avoiding development in biodiversity hotspots while sacrificing only a small amount of biomass supply. The modelling result shows that it is possible to meet the biomass needs for the net-zero goal while minimizing ecological disruption.

Water stress easing but still tight recently

China has long faced challenges related to uneven spatial and temporal water distribution, supply–demand conflicts, inefficient water use and severe water pollution. Solutions to these challenges can be reached through the promotion of climate actions as well as water management policies.

In recent years, water supply in China is ~600 km^3 per year[35]. Intensive economic growth would lead water withdrawals to peak around

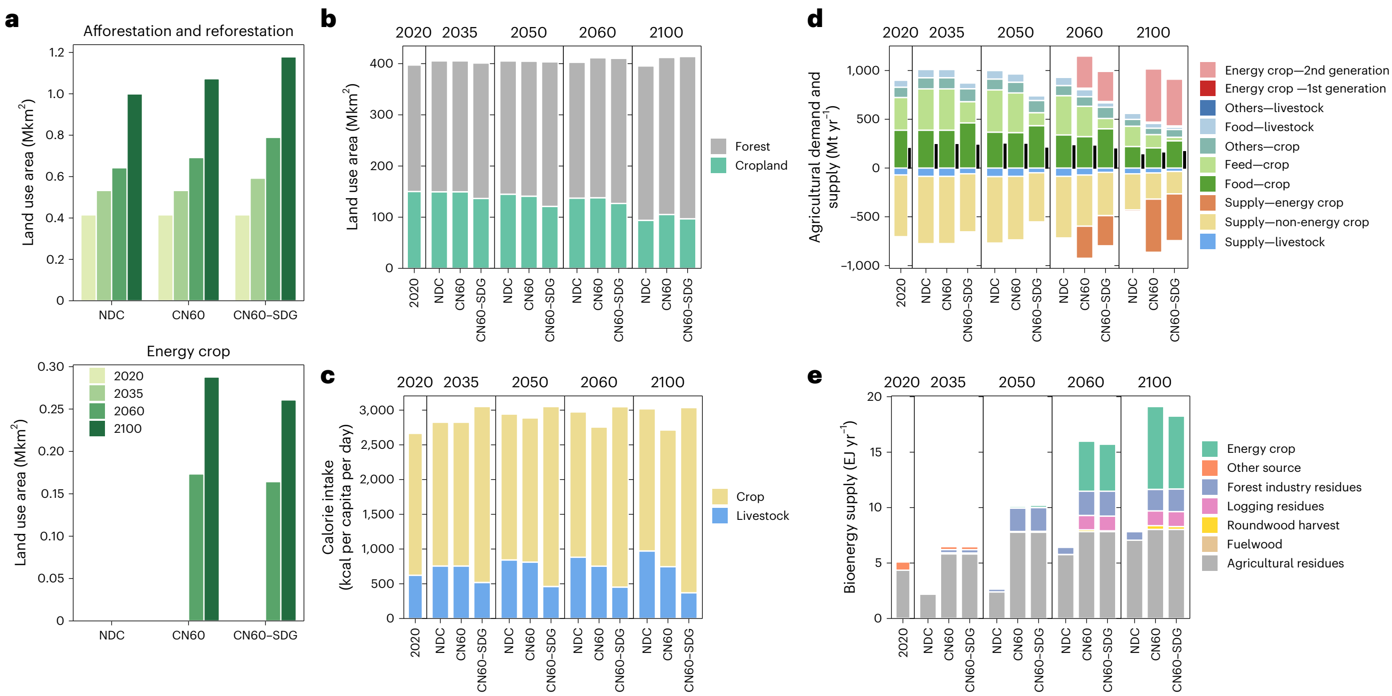

Fig. 2 | Sustainable development of the AFOLU sector in China. **a**, Afforestation and reforestation and energy cropland use. **b**, Land use change. **c**, Dietary structure changes over 2019–2100. **d**, Energy crops, non-energy crops and livestock production and demand. The vertical black bar next to a vertically stacked bar chart represents net values. **e**, Biomass supply for bioenergy by source.

2025 (0.5% larger than today) and remain high until 2030, but thereafter, they would show a notable downward trend thanks to more efficient irrigation and the energy transition towards net zero (Fig. 3). In the CN60–SDG scenario, reducing food waste and constructing high-standard farmland policy would lead to a decline of >30% in irrigation water withdrawals in 2030, compared with a decline of <10% in the CN60 scenario. By 2060 and 2100, the CN60–SDG scenario is expected to save 20% and 5% water, respectively, compared with the CN60 scenario. This reduction is credited to dietary shifts, industrial water efficiency improvement and high-standard farmland construction. The proportion of water supply varies little between seasons, but most artificial recharge for ecological restoration occurs during the winter to maximize ecological benefits.

The agricultural and power sectors are the largest water consumers, currently accounting for 76% of total withdrawals. Nearly half of China's arable land in 2019 was still not irrigated with water-efficient technologies, while 45% of the water-efficient irrigated cropland was served by relatively low-efficiency pipe irrigation[36]. By promoting efficient irrigation technologies, the share of water-efficient irrigated land could reach 74% by 2060, while the share of sprinklers, micro-irrigation and drip irrigation could reach ~70% (Fig. 1n and Supplementary Fig. 7). This reduction would yield near-term co-benefits for groundwater, which is currently being heavily overexploited[37]. In the CN60–SDG scenario, groundwater extraction would be below 80 km^3 by 2025, 5 years earlier than in the CN60 scenario (Fig. 1o).

Our model results reflect the fact that net-zero transition would substantially reduce water withdrawal demand from the energy system, by 38% in 2060 compared with 2019. Declining water consumption for power plant cooling would dominate the achievement of water savings. Supplementary Fig. 8 shows the variation in installed capacity for thermal and nuclear power with different cooling types in each scenario. In 2019, of the 1,204 GW of thermal and nuclear power units included in the statistics, ~14.7% were once-through units, and air-cooling units accounted for only 18.3%. Under the CN60 scenario, thermal and nuclear capacity is expected to reach a low point of ~411 GW by 2055, when the share of once-through units would fall to 5.4% and the share of air-cooling units would reach 25%.

Air quality synergies emerging with further measures needed

The net-zero transition is expected to reduce air pollutant emissions by ~70% from 2020 levels through 2050 (Fig. 1q,r). We find that the co-benefit of the net-zero transition on air quality is well pronounced for SO_2 and NO_x, while the $PM_{2.5}$ pollution shows lesser improvement. Nevertheless, the air quality co-benefits of climate action alone cannot ensure satisfactory air quality. It is necessary to pursue stringent air pollution control measures.

Figure 4 depicts the impact of the net-zero transition and end-of-pipe control measures on air quality. Different preset control strategies are adopted to simulate air pollution policies: the NDC scenario and the CN60 scenario apply the current legislation (CLE), while the CN60–SDG scenario applies the maximum feasible reduction (MFR). The control strategy includes application rate assumptions for each type of control measure (Supplementary Data 1–3). Given that most coal-fired power units are undergoing complete ultra-low emission retrofits, the power sector has limited potential for further emission reductions in the future[10]. The industrial sector is currently the largest source of SO_2 emissions with lower application rates of end-of-pipe controls, which suggests a larger scope for co-benefits. NO_x is mainly emitted by the transportation sector, but owing to the increasingly stringent emission standards and alternative energy vehicle deployment, NO_x emissions would drop sharply in all scenarios. Net-zero scenarios could further accelerate NO_x reductions owing to structural changes in transportation by 2040. The building sector currently contributes almost half of $PM_{2.5}$ emissions, from coal and biomass combustion. In the CN60 scenario, the substitution of solid fuels by electricity would lead to a substantial reduction in $PM_{2.5}$ emissions compared with NDC. Additional measures such as replacing conventional electrostatic precipitators with high-efficiency dedusting technologies in the power and industrial sectors could further reduce $PM_{2.5}$ emissions by 80% in 2050.

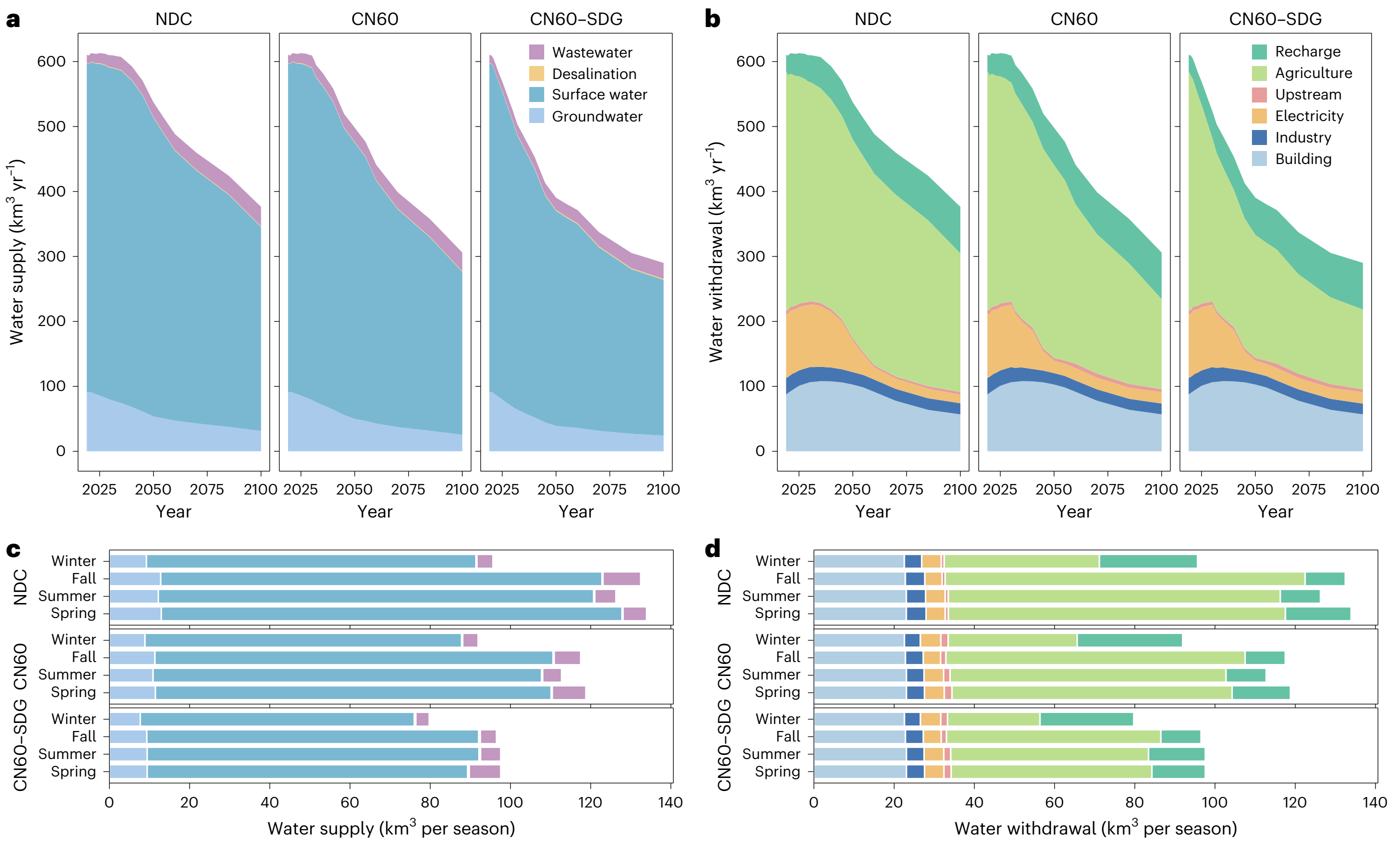

Fig. 3 | Water supply and withdrawal in China. **a**, Water supply by source. **b**, Water withdrawal by sector. **c**, Water supply by season in 2060. **d**, Water withdrawal by season in 2060.

Air quality has improved, with $PM_{2.5}$ concentrations reaching the national second-level standard (35 μg m^{-3}) in 12 out of 31 provinces, but still with concentrations above 50 μg m^{-3} in 6 provinces in 2020 (Fig. 1s). In the NDC scenario, in 2030, 6 more provinces would meet the second-level standard. The co-benefit of the net-zero transition could be notable in 2050, with only 5 provinces having $PM_{2.5}$ concentrations higher than the second-level standard. We find that the CN60–SDG scenario would present considerable air quality improvements with all provinces showing $PM_{2.5}$ concentrations below 50 μg m^{-3} in 2030. Furthermore, by 2050, all provinces could achieve the second-level standard, and 77% of provinces could reach the first-level standard (15 μg m^{-3}). By that time, pollution from anthropogenic sources in China would be minimal, with the main source of $PM_{2.5}$ being natural dust, and the most heavily polluted areas would be in northwestern China (Extended Data Fig. 2).

The net-zero transition would bring substantial health effects, but the upward trend in premature deaths cannot be reversed owing to the increased vulnerability of the aging population[38] (Fig. 1t). Premature deaths attributable to air pollution were 1.4 million per year in 2020. In the CN60 scenario, despite the rapid reductions in fossil fuels and declines in $PM_{2.5}$ emissions and concentrations, this number is expected to rise to 1.8 million per year by 2050. By contrast, the CN60–SDG scenario, with the adoption of enhanced end-of-pipe pollutant management measures, would show a notable decrease in the pollution-driven premature mortality to 0.7 million per year.

The costs and benefits of going net zero and sustainable

From 2019 to 2100, the net-zero transition is projected to require more than US$10.5 trillion in energy system investment in energy supply and demand areas relative to the NDC scenario, with power supply deployment, hydrogen production and energy storage bringing about US$7.4, 1.9, and 1.0 trillion in incremental investment, respectively (Supplementary Fig. 9). Deep electrification in the building sector would require US$1.7 trillion in incremental investment for updating heating, cooking and hot-water devices. The deployment of new energy vehicles beyond policy targets[39], coupled with the rapid decline in their cost[40], and changes in lifestyle such as increased use of public transportation and reduced travel demand, would lead to a US$2 billion reduction in investment in the transportation sector compared with the NDC scenario. After 2060, DACS deployment is expected to require an investment of more than US$100 billion, presenting a huge market opportunity. Industrial and upstream sectors are experiencing investment contractions owing to the phase-out of fossil fuels and demand decreases. Demand management would lower the investment in storage after 2050 by up to 11%.

Figure 5a shows that the marginal CO_2 abatement costs could increase substantially when chasing the net-zero target. Measures to support the sustainable development of the energy–food–water–air quality system would contribute only modestly to the transition burden, resulting in less than a 10% increase.

The spread of renewable energy is projected to reduce marginal electricity costs while increasing storage needs, resulting in differentiated prices at different times (Fig. 5b). Starting in 2040, as the share of renewables in the power system increases, the intraday differences in the generation cost and the grid balancing cost would begin to emerge, and the differences would become apparent in 2050. The power system may experience supply shortages in the evenings, pushing up peak prices. The CN60–SDG scenario would mitigate power imbalances by reducing the load through demand management measures. Marginal hydrogen costs are expected to decrease as renewable energy develops,

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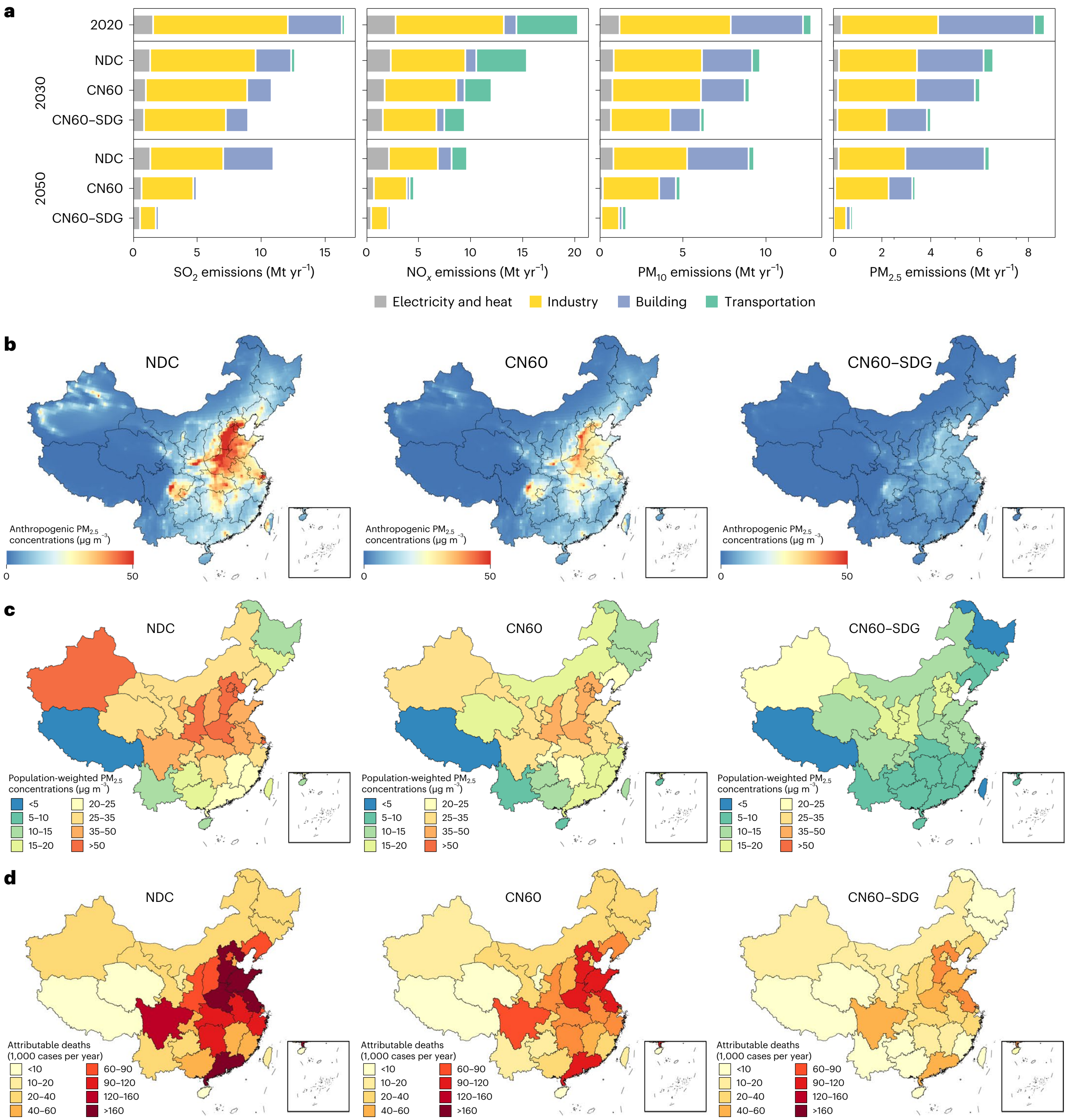

Fig. 4 | Air quality improvement and health benefits in China. a, SO_2, NO_x, PM_{10} and $PM_{2.5}$ emission pathway. **b**, Concentration maps of $PM_{2.5}$ from anthropogenic sources in 2050. **c**, Population-weighted mean provincial $PM_{2.5}$ concentrations in 2050. **d**, Premature deaths due to $PM_{2.5}$ by province in 2050.

especially during daytime with a high solar output, when the cost of hydrogen production would be less than US\$2.5 kg^{-1}.

Figure 5c illustrates the changes in biomass and food prices. Sustainability measures would stabilize food prices and prevent the food price index from increasing by >10% by 2060, compared with 2020.

Climate action combined with further pollution control measures would induce considerable health benefits as well as economic gains. Assuming the value of statistical life to be US\$1 million[9,41], the economic loss from premature deaths due to air pollution could reach 4.4% of GDP in 2050 under the NDC scenario. Net-zero transitions and adding maximized pollutant control measures are projected to reduce the loss to 3.5% and 1.4%, respectively.

The health benefits of the net-zero transition in 2020–2050 would approach US\$2.05 trillion (5% discounted). Synergies between the net-zero transition for air quality improvement would vary between regions. Our result shows that the near-term synergies are concentrated in developing provinces, while notable increases in developed

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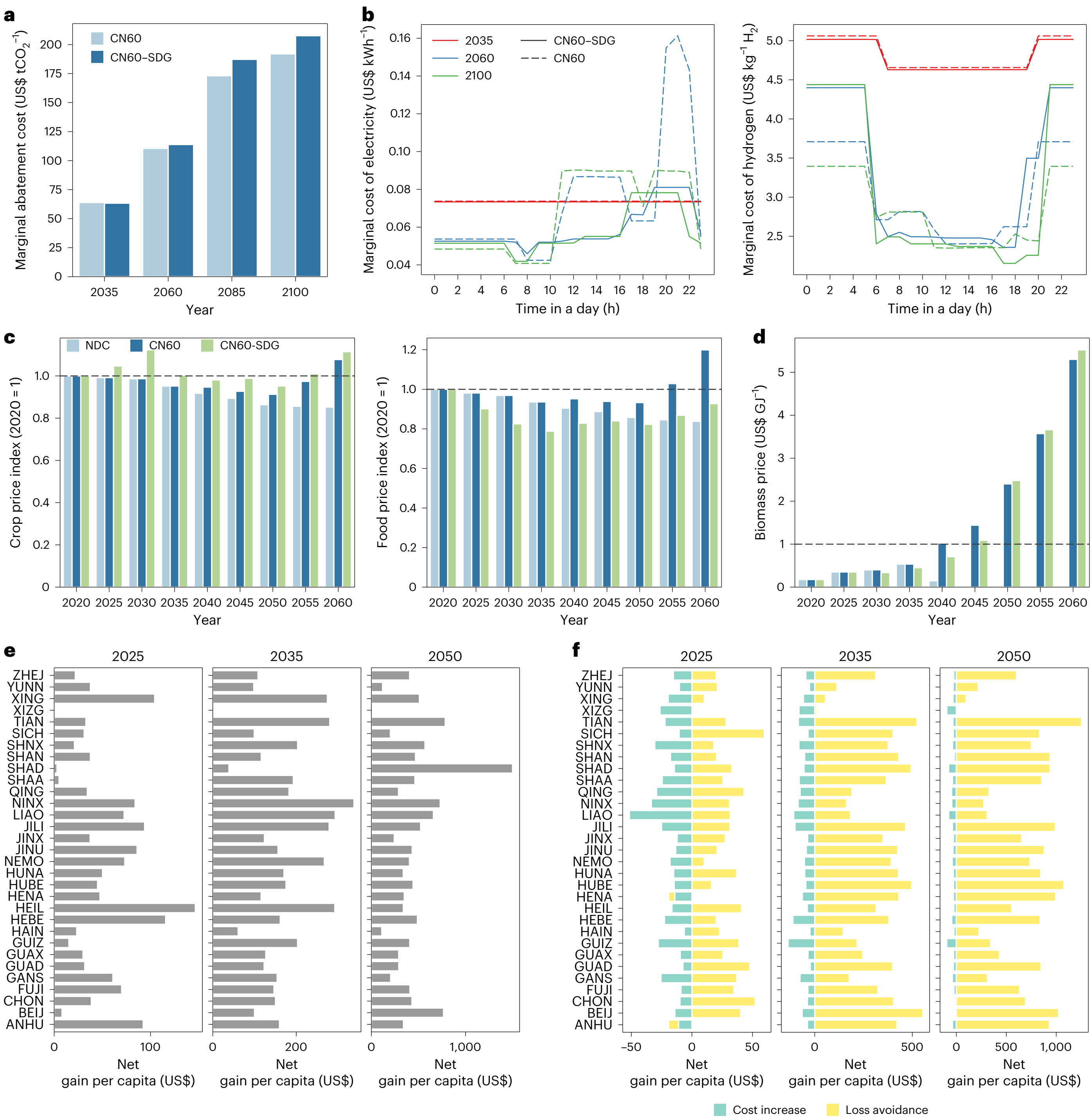

Fig. 5 | Economic analysis of the energy–food–water–air quality system transition in China. a, Marginal abatement cost. **b**, Marginal electricity and hydrogen costs. **c**, Agricultural product price index. **d**, Biomass price. **e**, The health benefits of air quality improvement due to the net-zero transition. **f**, Cost–benefit analysis of stringent air pollution treatment measures. The abbreviations of the provinces are defined in Extended Data Table 2.

provinces and densely populated areas by 2050 are reported (Fig. 5e). Enhanced pollutant control measures would be cost-effective by 2025, with a benefit–cost ratio of ~1.65. Thereafter, the ratio would rise markedly and reach 4.5 (2030), 9.4 (2040) and 22.4 (2050) times the pollutant control spending in that year. The net benefit of control measures in 2020–2050 is projected to be a further US$5.4 trillion (discounted) over the CN60 scenario. The southern provinces could have a better short-term cost–benefit ratio. The cost–benefit ratio would notably increase after 2035 in economically developed areas (Fig. 5f). We also identify that the net benefits per capita and total net benefits of implementing control measures would be greatest in densely populated areas.

Discussion

Model results show that transitioning to a net-zero future in China could result in clear co-benefits in renewable energy (SDG 7), air quality (SDG 11) and forest coverage (SDG 15) by 2030, and more co-benefits in the energy–food–water–air quality system come from the rapid phase-out

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of fossil fuels beyond 2030. Failure to advance sustainable development efforts may pose risks to stable energy and food supplies, as the rapid integration of renewables may lead to recurrent power shortages and electricity price spikes, and land use change may threaten food security. Therefore, although the net-zero target is currently in the spotlight of policymakers and has brought innovative solutions to environmental challenges, the following sector-specific actions are indispensable for breakthrough progress towards a more resilient and sustainable transition.

Risks threatening energy system safety gradually shift from external dependence on fossil fuels to the internal imbalance between supply and demand, especially lack of flexibility. Owing to imperfections in the electricity market and emission trading system, the cost of grid regulation and emission reduction are not effectively shared[42,43]. Moreover, incentives for flexibility resources such as storage and hydrogen are weak[44], and the large amount of coal-fired power plants approved in recent years under the guise of increased flexibility threatens the achievement of both net zero and SDGs. Policymakers need to deepen electricity market reform and establish compensation mechanisms for flexibility resource. Market players need to innovate business models and attract capital to drive infrastructure investment and retrofit at scale. Variable renewable power sources should be equipped with storage of at least 15% of their capacity to improve regulation and expand storage capacity from 2 h to 4 h. It is recommended that the range of consumer tariff changes be extended to encourage time shifting of electricity loads. In addition, subsidies should be provided to incentive V2G and home energy storage feed-in activities to meet power system ramping needs.

Demand-side actions are essential for achieving the net-zero target while improving the sustainability of the land (food) system. Halving food waste from 27% (ref. 45) by 2030 and shifting dietary structure towards less animal-sourced food can reduce cropland occupation and GHG emissions without lowering calorie intake, and free up ~10 Mha of cropland for afforestation. Entrepreneurs and policymakers are promoting change through initiatives such as the 'Clean Plate Campaign' and 'Anti-Food Waste Act', but incentives are still necessary to encourage continued lifestyle changes.

To facilitate water saving, it is necessary to establish the binding assessment indicators for recently enacted 'Water Conservation Regulation'. In areas with severe water shortages or overexploited groundwater, mandatory construction of water metering facilities for agricultural irrigation is recommended. The undergoing promotion of high-standard farmland is expected to improve water-use efficiency[46], but the efficiency of water-saving irrigation technologies varies widely. To better cope with the water scarcity, advanced irrigation technologies such as sprinklers and drip irrigation should be adopted more in this promotion.

Given the current spatial pattern of industrial production and not sufficient rate of controls for $PM_{2.5}$ emissions[47], it is recommended to scale up the application of high-efficiency dedusting options particularly in developing and densely populated provinces. Rapidly replacing traditional biomass and bulk coal with electricity in the residential sector is recommended to substantially reduce ambient as well as indoor air pollution. China's air quality standards are currently lagging far behind the guideline values of major developed countries and the World Health Organization[48]; therefore, we propose to update air quality standards and monitoring and evaluation systems based on the health protection principle to synergize health-driven air pollution and climate change management.

China has legislation adopted in the areas of energy, food, water and air pollution. However, there is currently no specific law regulating the legal responsibilities and obligations of stakeholders regarding climate change[49]. In addition, policies and regulations do not emphasize the synergy of the goals and policies of the various systems and domains[50]. We recommend accelerating legislation to address climate change, clarifying the GHG coverage of climate targets and strengthening regional, sectoral and policy synergies between climate targets and other SDGs. In addition, we strongly call for the inclusion of co-benefits as a necessary component of national commitments, reporting mechanisms such as the NDCs of the Paris Agreement and the Voluntary National Review report on the implementation of the 2030 agenda for sustainable development.

Overall, our modelling framework integrates the energy–food–water–air quality system and covers many aspects of the relevant SDGs, and at the same time, it represents a big step forwards to assessing sustainable scenarios and long-term transition pathways at the national level. However, the coverage of sustainability targets and indicators is still undeniably inadequate and, particularly the representation of the social dimensions of the SDGs, such as gender gaps, inequality, impacts on different population groups and governance capacity, is still underdeveloped. Methodologically, this study achieves multi-model interconnection, but model assumptions are not guaranteed to be fully consistent across models owing to differences in modelling approaches and data sources. Climate feedback is introduced through external inputs rather than coupling within the framework. Future study could also improve the connection between an integrated assessment model and an earth system model, and increase the representation of region heterogeneity in the model to obtain more coherent modelling.

Moving from modelling exercises to sustainable change practices requires cross-sectoral collaboration, systems-oriented decision-making and public engagement to address institutional and socio-cultural barriers. To achieve net zero, the transition involves promoting immature technologies such as BECCS, enforcing variable renewables in the electricity supply, managing new material demand and massive fossil fuel infrastructure decommissioning. Technical and socio-political feasibility concerns still exist regarding whether these changes can become a reality.

Despite these limitations, this study examines in quantitative terms implications of China's net-zero transition for the energy–food–water–air quality system and explores sustainability measures to increase co-benefits and reduce trade-offs, providing a vision for China and other climate-aware economies to move towards sustainable development.

Methods

Energy–food–water–air quality assessment framework

This study is based on the interconnection of the national energy system model (China The Integrated MARKAL-EFOM System version 2.0, China TIMES 2.0)[51–62], the provincial energy system model (China The Integrated MARKAL-EFOM System 30-Province Enhanced version, China-TIMES-30PE)[63–65], the land use simulation model (Global Biosphere Management Model-Global Forest Model, GLOBIOM-G4M)[24,66,67], the water management model (Community Water Model, CWatM)[68,69] and the air quality model (Greenhouse Gas and Air Pollution Interactions and Synergies for Asia version 4, GAINS-Asia 4)[38,63,70] to form an integrated energy–food–water–air quality assessment framework (Extended Data Fig. 3). Detailed descriptions of the individual models are included in Supplementary Notes 3–7.

The China TIMES 2.0 model and the GLOBIOM-G4M model are linked through the biomass variables and constructed to be integrated in the emulator[66]. This emulator presents a lookup table model emulation of the GLOBIOM-G4M regarding potential reductions of GHG from the Agriculture,Forestry and Other Land Use (AFOLU) sector and land-based biomass potential for bioenergy production. The lookup table shows 84 scenarios resulting from a combination of 7 biomass prices (in US$ GJ^{-1}: 0, 3, 5, 8, 13, 30 and 60) and 12 GHG prices (in US$ tCO_2e^{-1}: 0, 10, 20, 50, 100, 200, 400, 600, 1,000, 1,500, 2,000 and 3,000), trajectories quantified in GLOBIOM-G4M. This table is quantified for two sets of scenarios: considering selected sustainable development measures (scenSDGs) and without considering them (scenBASE). The GLOBIOM-G4M model combines China, Japan and South Korea into the East Asian region; data are downscaled based on the share of each country's land area when using the lookup table. The downscaling method according to land area ignores the heterogeneity between countries, but the bias from the downscaling method is limited by the fact that China's land area makes up the majority of the region, and by the subsequent calibration exercise with the statistics. China TIMES 2.0 provides GHG prices (marginal abatement costs) and biomass prices to GLOBIOM-G4M to determine the supply function of biomass and, furthermore, to quantify the cost-optimal land use pattern. GLOBIOM-G4M inputs the supply curves of the different types of biomass resources into China TIMES 2.0 as the upper limit of the resource potential and cost of the biomass resources. The GLOBIOM-G4M model generates the development pathway of crops and livestock, which in turn can drive the irrigation water demand of the China TIMES 2.0 model for subsequent calculation of water consumption in the agricultural sector. The results generated by GLOBIOM-G4M, including the emissions produced by the AFOLU sector and the forest carbon sinks, are integrated into the China TIMES 2.0 model GHG accounting. When using the GLOBIOM-G4M emulator in China TIMES 2.0, a single discrete land use scenario can be used individually or multiple scenarios can be linearly combined to create a smoother transition dynamic. This study refers to the model connection approach of the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGEix) and GLOBIOM model; more information on the GLOBIOM-G4M emulator can be found in the MESSAGEix–GLOBIOM documentation (http://data.ene.iiasa.ac.at/message-globiom).

The CWatM model is soft-linked to the China TIMES 2.0 and GLOBIOM-G4M[71]. The CWatM model uses localized climatic conditions from Global Climate Model (GCM) projections from Climate Model Intercomparison Project Phase 6 (CMIP6) to simulate changes in aggregated runoff and other hydrological parameters. Before inputting the results of CWatM into the models, we compare the water supply data generated by the model from 2000 to 2015 with the water resources bulletin issued by the Ministry of Water Resources of China, and select the scaling factor that minimizes the sum of squared errors[35]. Environmental flows, using Pastor's method[72] that assigns different retention weights to environmental flows in the wet (30%) and dry (60%) seasons, are deducted from the runoff. After harmonizing the CWatM results with the official historical water resources data, we use the CWatM model results as the upper limit of future water resources for each category. We aggregate the monthly data over time to the year, and the resulting data serve as the basis for water availability for agricultural production in the GLOBIOM-G4M model. The results generated under the five climate forcings are fed into China TIMES 2.0 after a multi-model averaging process and spatial aggregation to river basins and provinces. The monthly total runoff, surface water runoff and groundwater runoff from the CWatM simulation are clustered into four seasons and, after subtracting environmental flows, are used as the upper limit of each type of water supply for China TIMES 2.0. China TIMES 2.0 has built-in water resource extraction technologies that incorporate historical infrastructure inventory and stepwise investment cost settings. China TIMES 2.0 can optimize water infrastructure investments and water supply patterns with the objective of minimizing costs. Also, for the power output of hydropower plants, the seasonal ratio is determined according to the runoff volume (assuming that most hydropower plants have intra-seasonal regulation capacity of the supporting reservoirs). As for water consumption and water withdrawal, China TIMES 2.0 calculates the amount of water withdrawal (consumption) for each activity by setting the water withdrawal (consumption) coefficient for each technology in the water use sector, thus covering the entire water supply and water use chain. The seasonal distribution for irrigation water demand is determined by the proportion of potential irrigation withdrawals in the four seasons from the CWatM simulation. Potential irrigation water use is derived by multiplying crop yields by crop-specific water demand coefficients. The actual irrigation water use is then derived from the irrigation techniques in China TIMES 2.0.

China TIMES 2.0 is linked to GAINS-Asia through the outputs of China-TIMES-30PE downscaled to the provincial level and followed by the implementation of activity projections into GAINS-Asia. The China-TIMES-30PE and China TIMES 2.0 models form a two-tier computational architecture to downscale the pathways from the national level to the provincial level, which improves the plausibility and accuracy of local air pollutant modelling. China TIMES 2.0 and China-TIMES-30PE share the same source of energy data calibration (China Energy Statistics Yearbook), fuel and sector definitions. Assumptions in the two models for national GDP, population, industrial structure and urbanization rate remain the same. The aggregate national CO_2 mitigation pathway of China-TIMES-30PE is derived from China TIMES 2.0. The two models have comparable aggregate national energy service demands, including the production of major industrial products and transportation turnover. The upper limits of resource potential and supply curves for centralized PV, rooftop PV, and onshore wind and offshore wind power plants in China TIMES 2.0 are derived from the renewable energy development analysis module developed based on the GIS system embedded in the China-TIMES-30PE model. A soft link between China-TIMES-30PE and GAINS-Asia has been established by using the GAINS data explorer, which is based on a set of mapping matrixes linking energy variables with the GAINS sectors and activities and fuels[63] (Supplementary Table 1). After inputting the primary energy supply by fuel and final energy consumption by sector and fuel calculated by China TIMES 2.0, downscaled by China-TIMES-30PE, GAINS-Asia can generate air pollutant emissions under different end-of-pipe control measure scenarios. Also, the $PM_{2.5}$ concentration map of the 0.1° grid, the number of excess deaths and ambient $PM_{2.5}$ concentrations by province weighted by population are available. In this study, CLE scenarios and MFR scenarios are used to show the synergistic effect of CO_2 reduction and the maximum air quality improvement potential.

Climate feedback modelling

Climate change leads to temporal and spatial changes in temperature and hydrology, which profoundly affects the heating and cooling demand, renewable energy output, water supply and cooling technologies for power generation, thus having an impact on both the supply and demand side of the energy system[26,73,74]. As this study focuses on China, the climate actions of other countries are outside the model boundary, but the climate impacts are caused by GHG emissions emitted globally. In the field of climate change assessment, the representative concentration pathway (RCP) framework provides estimates of future temperature increases and CO_2 concentration pathways to standardize scenario design across different global modelling groups. RCP 2.6 is a concentration pathway consistent with the Paris agreement, corresponding to a greater than 67% likelihood of achieving the 2-degree target by the end of the century. On the other hand, RCP7.0 represents a concentration pathway that lacks policy measures, with a greater than 50% likelihood of holding temperature rise to 4 °C, which is used as a baseline. Therefore, we assume that the net-zero scenarios (CN60 and CN60–SDG) form the climate change impacts according to the RCP 2.6 pathway, while the reference scenario (NDC) forms the climate change impacts with the RCP 7.0 pathway. This allows us to use the existing earth system model results to portray climate impacts in the national model. Based on the results of the Inter-Sectoral Impact Model Intercomparison Project 3b simulation round (ISIMIP3b), this study can consider the seasonal variability and volume trends of water runoff. As a result, there will be a difference in the quarterly output of hydroelectric power. The heating and cooling needs of the residential and commercial sectors depend heavily on the number of heating degree days (HDD) and cooling degree days (CDD). In this study, 18 °C and 26 °C are chosen as thresholds to form HDD-18 and CDD-26 values for five climate zones (Extended Data Table 2) in China (severe cold, cold, cold winter and cool summer, cold winter and warm summer, and mild) based on historical data and predictions under RCP2.6, which in turn change cooling and heating energy demands.

Sustainable development consideration

The SDGs are organized into three dimensions: biosphere, society and economy, and SDG 17, which helps the world work together to achieve the SDGs. More than one-third of SDG indicators are environmentally relevant, and there are relatively fair methods and indicators for quantifying and monitoring[75]. In this paper, the focus is on the nexus of the energy–food–water–air quality systems toward the net-zero target. Owing to lack of instrumental capacity, this study focuses on the national-level context and is not representative of progress on SDG 1, 4, 5, 14, 16 and 17. We consider multiple indicators for achieving sustainable development in China, apart from SDG 14, 16 and 17 related to oceans, peace and partnerships, respectively. SDG 1 (no poverty), SDG 4 (quality education) and SDG 5 (gender equality) are not SDGs directly related to the environment and will also be excluded. In addition to examining the impacts of net-zero policies, more importantly, we introduce measures to enhance the sustainability of energy–food–water–air quality systems in a dedicated scenario, thereby emphasizing the needs and benefits in implementing sector-specific sustainability efforts while meeting climate goals.

To assess the impact of net-zero transition and sustainability measures on environment-related SDGs, we screen indicators based on the following six principles: (1) quantifiable: clear, model-measurable indicators that can be analysed quantitatively; (2) scalable: applicable indicators for country- and region-level assessments; (3) path dependent: indicators should be able to be monitored consistently beyond 2030; (4) actionable: viable policy and measures can be shown to influence these indicators; (5) environmentally relevant: indicators should be closely linked to the energy–food–water–air quality system that is the focus of the study; and (6) data available: indicators have valid data for tracking progress. Details of the mapping of these sustainability indicators to SDG targets and indicators can be found in Supplementary Table 2.

China has made a lot of efforts in sustainable development, among which SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action) and SDG 15 (life on land) are partially involved in this study. The study explores the co-benefits and trade-offs of the net-zero transition on other sustainability indicators, as well as integrated decarbonization solutions under multiple sustainability constraints. The net-zero transition leads to industrial upgrading and energy technology changes that reduce water use for industry and cooling for power generation, but the effect is also diminished by the intense water consumption of bioenergy crops. The reduction in fossil fuel combustion reduces local air pollutant emissions and thus improves air quality, resulting in substantial synergistic effects. The sustainable net-zero scenario CN60–SDG sets constraints on the undernourishment rate, animal-based calorie intake limit, protected area ratio, environmental water flow limit, local air pollutant end-of-pipe treatment technology promotion and active supply–demand interactions, thereby enhancing the harmonization and sustainability of the systems in the transition process. Rural clean energy access also receives attention. In 2030, the share of traditional biomass and bulk coal used for heating, cooking and hot water in rural residential buildings is constrained to decline by at least 70%, 40% and 40% compared with 2020, and the downward trend continues, with all accounting for less than 5% of the demand for energy services by 2050.

Scenario definition

In this study, one reference scenario and two GHG mitigation scenarios are proposed. The reference scenario, NDC, considers near-term energy and climate policies released by 2022, and is in line with China's 14th Five-Year Plan and Vision 2035, and includes China's updated NDCs, that is, China to achieve energy-related CO_2 peaking by 2030. The NDC scenario is constrained to a monotonic decline in CO_2 emissions after peaking, forming a transition path that minimizes total system cost while meeting energy demand and system balance constraints. The two net-zero scenarios (CN60, CN60–SDG) are both designed to address China's carbon neutrality target, following the emission path of the NDC scenario until 2030, after which both CO_2 and GHG emissions are constrained to decline year by year. As China has not officially stated whether the carbon neutrality target is for CO_2 or all GHGs, in this paper, we assume that China's carbon neutrality target in 2060 is net zero for FFI CO_2 and that net zero for GHG is assumed to be achieved in 2070, based on the results of the studies that show that net zero for GHG is usually 10 years later than net zero for CO_2 (ref. 76). Cumulative emissions for 2020–2100 are the same for two net-zero scenarios (CN60, CN60–SDG) with RCP2.6 compliance (230 $GtCO_2$ for CO_2 emissions). With the inclusion of the emission-related constraints described above, the model is optimized to form a transition pathway that extends to 2100. The 'SDG' suffix represents the addition of energy-, water-, food- and air-quality-related constraints to meet sustainable development requirements.

For CN60 and CN60–SDG scenarios, the China TIMES 2.0 model allows the early retirement of thermal power units without CCS and high-energy-consuming industrial capacity. Price elasticities of demand are also introduced to reflect the impact of price changes on demand in the CN60 and CN60–SDG scenarios. On an annual scale, price elasticity reflects a decrease in demand as the cost of abatement increases; on a sub-annual scale (only in the CN60–SDG scenario), it reflects the demand management resources available for load shedding.

For the CN60–SDG scenario, GLOBIOM-G4M applies the scenSDG constraints (assumptions for targeted measures consistent with sustainable development) to achieve sustainable development in 2030 in the four dimensions of food (SDG 2), dietary patterns (SDG 12), biodiversity conservation (SDG 15) and irrigation water use (SDG 6) and extrapolates the measures to 2100 with the same effort. Specifically, these four dimensions are the following: (1) meets the minimum calorie intake standard and maintains the undernutrition rate below 1% by 2030, without any subsequent worsening; (2) reduces livestock calorie intake through a dietary shift to 500 kcal per capita per day and halving food waste by 2030; (3) increases the share of protected areas to 17% and avoids the conversion of biodiversity hotspots to achieve the biodiversity target by 2030; and (4) respects environmental water flow requirements for freshwater ecosystem protection. For the NDC and CN60 scenarios, GLOBIOM-G4M uses scenBASE constraints to maintain current trends to 2100. The GLOBIOM model is optimized to obtain the evolutionary path of the land sector that maximizes total social welfare. More information and sensitivity test results can be found in a previous study[66] and model documentation[67].

GAINS-Asia uses the MFR strategy in the CN60–SDG scenario to fully leverage existing end-of-pipe treatment measures in contrast to the CLE reduction strategies in the NDC and CN60 scenarios, maintaining current pollution control efforts. A pollutant control strategy is a combination of the end-of-pipe treatment measures that can be applied to a given region, a given energy technology activity and a given fuel. Supplementary Data 1 and 2 contain all assumptions about CLE and MFR strategies. The application rates of emission control measures in the key areas of the energy system for the three scenarios in 2020, 2030 and 2050 are summarized in Supplementary Data 3.

China TIMES 2.0 introduces demand management measures such as home storage feed-in, V2G and load time shifting to mitigate the flexibility risk on the power system in the CN60–SDG scenario. The amount of water withdrawal per unit of industrial added value is set according to the 14th Five-Year Plan. The decline in water withdrawal per unit of product for iron and steel, non-ferrous metals, papermaking and chemicals is bound according to the National Industrial Water Efficiency Improvement Plan. In the CN60–SDG scenario, the lower limit of the proportion of water-saving irrigated cropland is stipulated with reference to the National High-Standard Farmland Construction Plan[46]. A scenario summary can be found in Extended Data Table 1.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The historical socio-economic data used in this study are from the World Bank, the International Monetary Fund and the National Bureau of Statistics of China. The base year (2019) energy data are based on the energy balance in 'China Energy Statistics Yearbook 2020', and reference is made to publicly available data from the International Energy Agency and the China Electricity Council. Cost projections are available in Supplementary Data 4. Unit-level data for the power sector were obtained from the Global Coal Plant Tracker (July 2022)[77] and integrated with cooling technology and capacity factor data for each unit from the China Electricity Council[78]. The scenario data for the CWatM model are available via ISIMIP at https://data.isimip.org/. GLOBIOM-G4M emulation data are also open source and available via GitHub at https://github.com/iiasa/GLOBIOM-G4M_LookupTable. The inputs related to the GAINS-Asia model can be obtained for free by registering on the official website (https://gains.iiasa.ac.at/models/gains_models4.html).

Code availability

The China TIMES 2.0 and China-TIMES-30PE models are based on the TIMES framework, which is open source and available via GitHub at https://github.com/etsap-TIMES/TIMES_model. GAINS-Asia v4.03 provides the online simulation platform, which can be accessed after user registration at https://gains.iiasa.ac.at/models/gains_models4.html. CWatM v1.06 is also an open-source model and is available via GitHub at https://github.com/iiasa/CwatM. The open-source version of the GLOBIOM-G4M model is under preparation. Potential collaborators may be given access to pre-release versions after communicating with the GLOBIOM modelling team. In this study, commercial software such as VEDA 2.0, GAMS 39.3, CPLEX 22.1.0, Gurobi 10.0.1 and ArcGIS Pro 3.2.2 is used. Public software such as Python 3.11 and R 4.2.2 is used for data processing and result visualization.

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Author contributions

S.Z., W.C., Q.Z., V.K., E.B., P.R., M.A. and K.R. conceived and designed the study. S.Z., W.C., V.K. and E.B. developed the framework. S.Z. and W.C. formulated the China TIMES 2.0 model. Q.Z. and W.C. conducted downscaling work with the China-TIMES-30PE model. S.Z., W.C., Q.Z., V.K., E.B., P.R., M.A. and K.R. conducted the data search. S.Z., Q.Z., E.B., B.N. and P.R. conducted the simulations. S.Z., W.C., Q.Z., V.K., E.B., P.R., M.A. and K.R. conducted the analysis. S.Z. wrote the first draft of this article. S.Z., W.C., Q.Z., V.K., E.B., P.R., M.A. and K.R. contributed to the revision and improvement of the article.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-024-01400-z.

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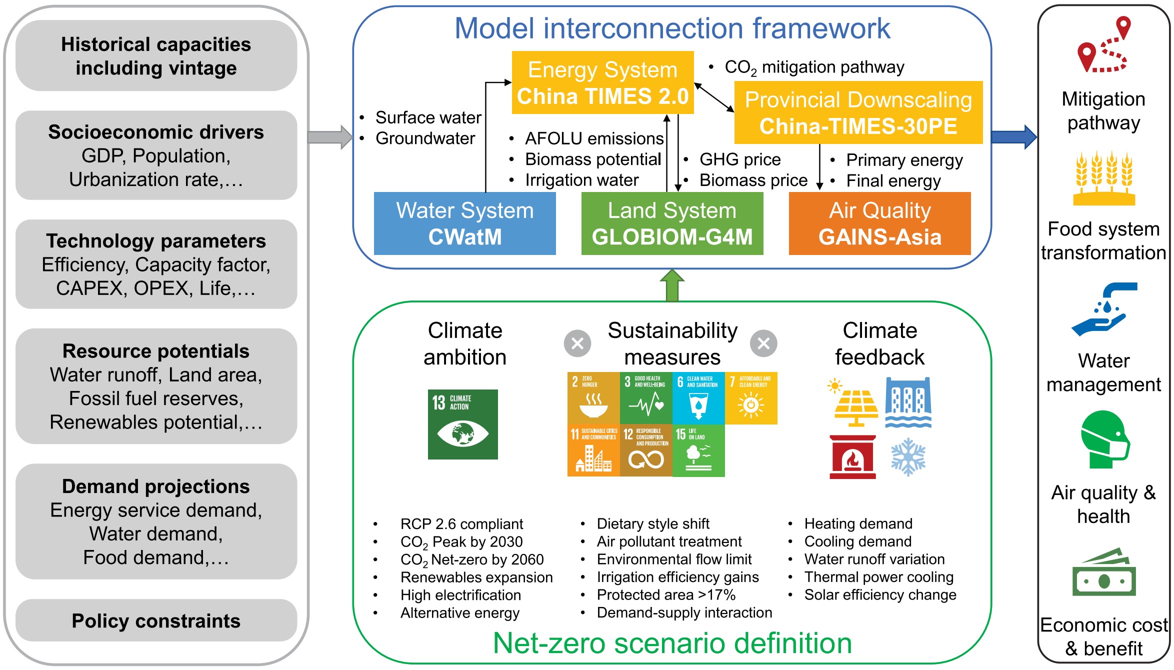
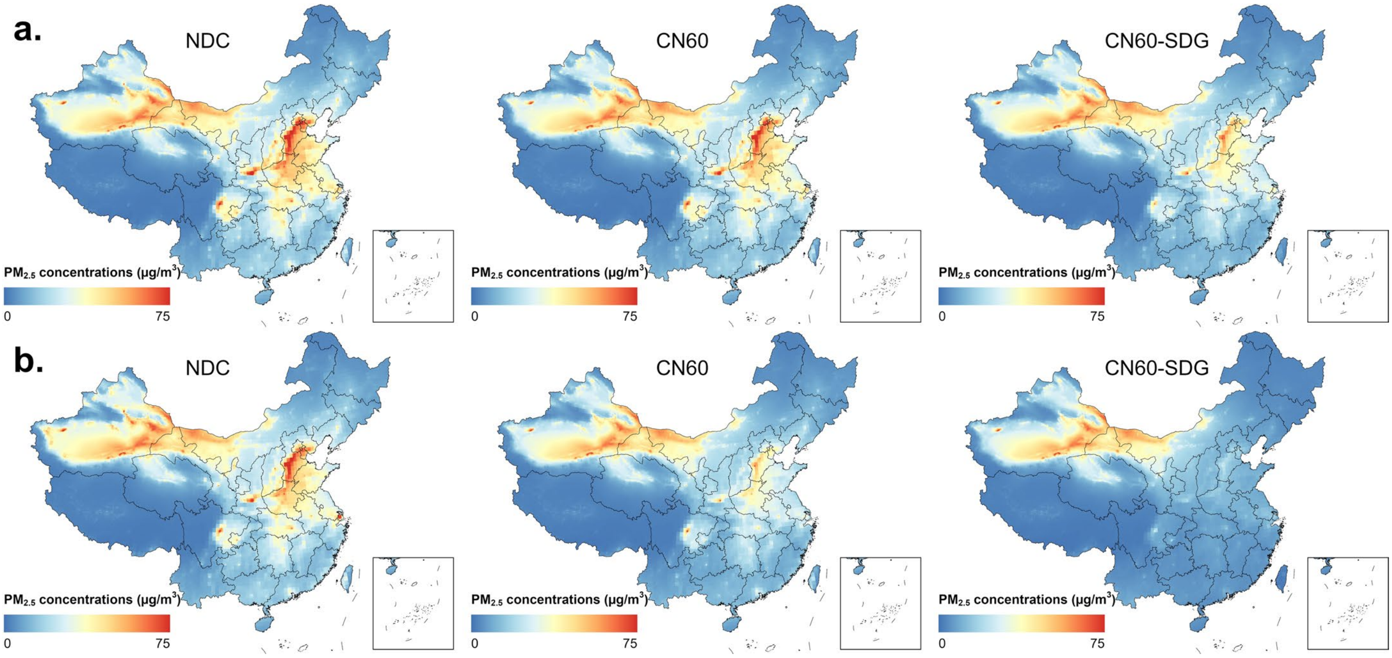


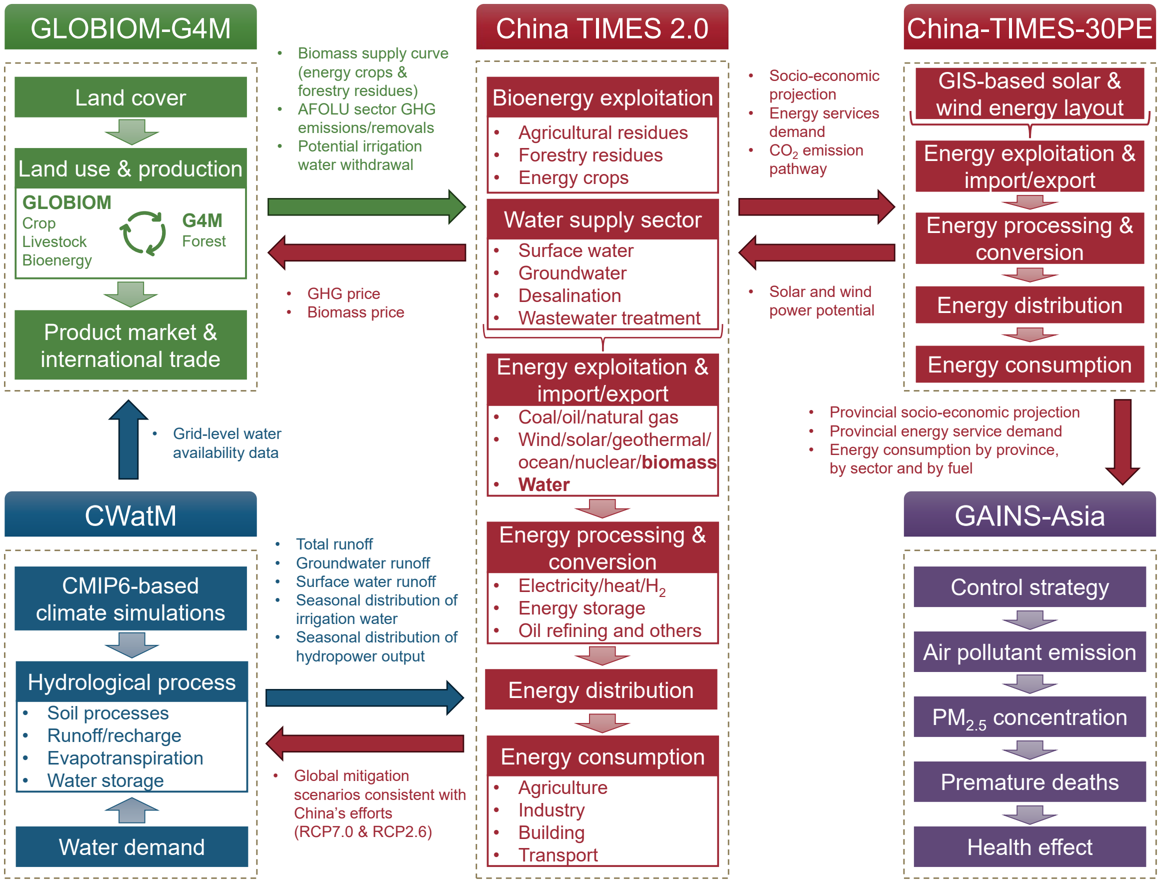
Extended Data Fig. 1 | Overall analysis framework for this study. The schematic diagram shows the input & output, scenario definition and model linkage relationships for this study. The research work is centered on the energy system model China TIMES 2.0, with bi-directional soft links to the land use model GLOBIOM-G4M, and model data interaction with the water model CWatM. The China TIMES 2.0 model passes CO_2 mitigation pathways into the China-TIMES-30PE model, thus downscaling to the provincial level and then connecting to the air quality model GAINS-Asia 4. By combining the sustainability constraints with the climate mitigation targets, the three scenarios in this study fully reflect the synergistic effects of climate action and can also indicate solutions for the integrated transition of China's energy-food-water-air quality system. Credit: icons from the United Nations Sustainable Development Goals (https://www.un.org/sustainabledevelopment).

https://doi.org/10.1038/s41893-024-01400-z



Extended Data Fig. 2 | Concentrations maps of $PM_{2.5}$ from natural and anthropogenic sources in 2030 and 2050. The figure shows the concentration maps of $PM_{2.5}$ from natural and anthropogenic sources for the years 2030 and 2050. **a** Concentrations maps of $PM_{2.5}$ from natural and anthropogenic sources in 2030, **b** Concentrations maps of $PM_{2.5}$ from natural and anthropogenic sources in 2050.

https://doi.org/10.1038/s41893-024-01400-z



Extended Data Fig. 3 | Multiple model interconnection mechanism. The figure shows the interconnection framework of the national energy system model (China TIMES 2.0), the provincial energy system model (China-TIMES-30PE), the land use simulation model (GLOBIOM-G4M), the water management model (CWatM), and the air quality model (GAINS-Asia 4).

https://doi.org/10.1038/s41893-024-01400-z

Extended Data Table 1 | Summary of scenario definition and model assumption

Model	Assumption	NDC	CN60	CN60-SDG
China TIMES 2.0	Energy and climate policies released before January 1, 2022 (except net-zero)	√	√	√
China TIMES 2.0	FFI CO_2 peaks by 2030	√	√	√
China TIMES 2.0	Monotonic downward constraints on CO_2 and GHG after peaking	√	√	√
China TIMES 2.0	FFI CO_2 net-zero by 2060		√	√
China TIMES 2.0	GHG (CO_2, CH_4, N_2O) net-zero by 2070		√	√
China TIMES 2.0	FFI CO_2 cumulative emission constraints for 2020-2100 (230 $GtCO_2$)		√	√
China TIMES 2.0	Climate feedback under RCP7.0	√		
China TIMES 2.0	Climate feedback under RCP2.6		√	√
China TIMES 2.0	Early retirement in power and industry		√	√
China TIMES 2.0	Price elasticity of demand		√	√
China TIMES 2.0	Demand management engagement (household storage feed-in, V2G, load time-shifting, etc.)			√
China TIMES 2.0	Sectoral policy-based water saving targets			√
China TIMES 2.0	High-standard farmland construction plan			√
GAINS-Asia	Current legislation reduction (CLE) strategy	√	√	
GAINS-Asia	Maximum feasible reduction (MFR) strategy			√
GLOBIOM-G4M	No additional sustainability measure (scenBASE)	√	√	
GLOBIOM-G4M	Meet the minimum calorie intake standard			√
GLOBIOM-G4M	Undernutrition rate below 1% by 2030			√
GLOBIOM-G4M	Animal calorie intake to 500 kcal/capita/day by 2030 and halve food waste by 2030			√
GLOBIOM-G4M	Increase protected area share to 17% by 2030			√
GLOBIOM-G4M	Avoiding conversion of biodiversity hotspots			√
GLOBIOM-G4M	Respect environmental water flow requirements			√
CWatM	Climate related forcing under RCP7.0	√		
CWatM	Climate related forcing under RCP2.6		√	√

The table displays a summary of scenario definitions and model assumptions. RCP - Representative Concentration Pathway. Refer to the Scenario definition section and Supplementary Notes 2 for more details.

https://doi.org/10.1038/s41893-024-01400-z

Extended Data Table 2 | Climate zones and provincial abbreviations for the 31 provincial administrative regions of mainland China

Climate Zone	Province	Abbreviation
Severe cold area (SC)	Heilongjiang	HEIL
Severe cold area (SC)	Jilin	JILI
Severe cold area (SC)	Liaoning	LIAO
Severe cold area (SC)	Inner Mongolia	NEMO
Severe cold area (SC)	Gansu	GANS
Severe cold area (SC)	Qinghai	QING
Severe cold area (SC)	Xinjiang	XING
Severe cold area (SC)	Tibet	XIZG
Cold area (C)	Beijing	BEIJ
Cold area (C)	Tianjin	TIAN
Cold area (C)	Hebei	HEBE
Cold area (C)	Shanxi	SHNX
Cold area (C)	Shandong	SHAD
Cold area (C)	Shaanxi	SHAA
Cold area (C)	Ningxia	NINX
Cold area (C)	Henan	HENA
Hot summer and cold winter area (HSCW)	Jiangsu	JINU
Hot summer and cold winter area (HSCW)	Anhui	ANHU
Hot summer and cold winter area (HSCW)	Shanghai	SHAN
Hot summer and cold winter area (HSCW)	Zhejiang	ZHEJ
Hot summer and cold winter area (HSCW)	Jiangxi	JINX
Hot summer and cold winter area (HSCW)	Sichuan	SICH
Hot summer and cold winter area (HSCW)	Chongqing	CHON
Hot summer and cold winter area (HSCW)	Guizhou	GUIZ
Hot summer and cold winter area (HSCW)	Hubei	HUBE
Hot summer and cold winter area (HSCW)	Hunan	HUNA
Hot summer and warm winter area (HSWW)	Fujian	FUJI
Hot summer and warm winter area (HSWW)	Guangxi	GUAX
Hot summer and warm winter area (HSWW)	Guangdong	GUAD
Hot summer and warm winter area (HSWW)	Hainan	HAIN
Mild area (M)	Yunnan	YUNN

The table illustrates the climatic zones and provincial abbreviations for the 31 provincial administrative regions of mainland China in this study.

nature portfolio

Corresponding author(s): Wenying Chen; Volker Krey

Last updated by author(s): May 28, 2024

Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No specific software was used for data collection. The various data sources were gathered from the web, books, reports , databases, or directly provided by collaborators.
Data analysis	China TIMES 2.0 model and China-TIMES-30PE model are based on TIMES framework, which is open source and available at GitHub (https://github.com/etsap-TIMES/TIMES_model). GAINS-Asia v4.03 provides the online simulation platform, which can be access after user registration at IIASA's website (https://gains.iiasa.ac.at/models/gains_models4.html). CWatM v1.06 is also an open-source model and can be found at GitHub (https://github.com/iiasa/CwatM). Commercial software such as VEDA 2.0, GAMS 39.3, CPLEX 22.1.0, Gurobi 10.0.1, ArcGIS Pro 3.2.2 are used. Public software such as Python 3.11 and R 4.2.2 are used for data processing and result visualization.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The historical socioeconomic data used in this study are from the World Bank, the International Monetary Fund, and the National Bureau of Statistics of China. The base year (2019) energy data are based on the energy balance in “China Energy Statistics Yearbook 2020”, and reference is made to publicly available data from the International Energy Agency and the China Electricity Council. Cost projections are available in Supplementary Data 4. Unit-level data for the power sector was obtained from the Global Coal Plant Tracker (July 2022) and integrated with cooling technology and capacity factor data for each unit from the China Electricity Council. The scenario data for the CWatM model is from ISIMIP and is available in the repository at https://data.isimip.org/. GLOBIOM-G4M emulation data is also open source and can be download from GitHub (https://github.com/iiasa/GLOBIOM-G4M_LookupTable). The inputs related to the GAINS-Asia model can be obtained for free by registering on the official website (https://gains.iiasa.ac.at/models/gains_models4.html).

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	N/A
Reporting on race, ethnicity, or other socially relevant groupings	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

This study is an assessment of the energy-food-water-air quality nexus in China under the carbon neutrality goal within a unified framework. The modeling framework analyzes the synergies and potential tradeoffs of the net-zero transition through the coupling of energy model, land use model, water model, and air quality model.

Research sample

Follows is the main sources of each component input:

China TIMES 2.0 and China-TIMES-30PE:
China Energy Statistics Yearbook 2020
Global Coal Plant Tracker (July 2022)
Database of National Bureau of Statistics of the People's Republic of China

CWatM:
Climate forcing-Intersectoral Impact Model Intercomparison Project (ISIMIP)

GLOBIOM:
Frank S, Gusti M, Havlík P, Lauri P, DiFulvio F, Forsell N, Hasegawa T, Krisztin T, Palazzo A, and Valin H (2021). Land based climate change mitigation potentials within the agenda for sustainable development. Environmental Research Letters. Volume 16(2)024006.

GAINS-Asia 4.0:
GAINS technical reports at https://gains.iiasa.ac.at/models/gains_tech_reports.html

Sampling strategy	This paper does not deal with sampling-related data processing operations.
Data collection	Data came from external sources
Timing and spatial scale	The temporal scale of China TIMES 2.0 is of 1 year time-steps during 2019-2030, 5 year time-steps during 2030-2060 and several 15 year time-steps after 2060. In each milestone year (typical median year of the period), there are 56 time slices representing the entire year, modeled up to the hour. China TIMES 2.0 spatial scale is for the entire mainland China. The building sector took into account the five main climate zones of China. Data at finer scales (province, county, grid) are aggregated to the national level (except for the building sector)/climate zones (building sector). The temporal scale of China-TIMES-30PE is of 5 year time-steps during 2015-2060. In each milestone year (median year of the period), there are 20 time slices representing the entire year. The spatial scale of China-TIMES-30PE is 30 provinces (except Tibet) in mainland China. Data at finer scales (county, grid) are aggregated to the provincial level. The temporal scale of CWatM is of monthly time-steps during 2015-2100. In our study, the data were aggregated seasonally, with March-May in the spring, June-August in the summer, September-November in the fall, and December-February in the winter. CWatM has a spatial resolution of 0.5° grid and was clustered to the China region in this study. The temporal scale of GLOBIOM is of 10 year time-steps during 2000-2100. The GLOBIOM spatial resolution is 2° grid and this paper focuses on the East Asia region (China, Japan, South Korea). Data in this study are scaled according to land area and harmonized with official data. The temporal scale of GAINS-Asia 4.0 is of 5 year time-steps during 2015-2050. The spatial scale of GAINS-Asia 4.0 is 31 provinces of mainland China, Taiwan, Hong Kong and Macao, as well as other countries and regions in Asia.
Data exclusions	No data were excluded
Reproducibility	The results can be reproduced in full with the same model version and data inputs.
Randomization	Not relevant as we did not collect data ourself
Blinding	Not relevant as we did not collect data ourself

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

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Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A