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

In the format provided by the authors and unedited

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Supplementary Notes 1 Literature review on synergies between climate change mitigation and air quality improvement

Research on climate-air quality synergies for China mainly focus on transition technology pathways, changes in GHG and air pollutant emissions, mitigation costs, air quality ($PM_{2.5}$ concentrations), and health co-benefits. Many current studies are based on existing data and are therefore mostly retrospective[1]. Most of the studies in this area have explored the impacts of transformations in a single sector (power[2], industry[3-6], rural residential[7] sectors) on air quality. Some of these studies stayed at the level of air pollutant emissions accounting and did not explore $PM_{2.5}$ concentrations and health effects in depth[8].

With the increasing availability of data from CMIP6 and the WHO GBD 2019 version replacing the 2016 version, the research on air quality and health effects in the last two years has been more specific and precise than previously. For example, the 2023 study[9] compared to the 2021 study[10], is a study conducted by the same group using a similar research framework, but with significant updates to the model components.

In addition to methodological advances, there has been an improvement in the characterization of policy and social realities. Studies in the last two years have appeared that consider localized impacts of socio-economic assumptions[8], population size[9], and population aging[11] on the premature deaths attributed to air pollution. Meanwhile, scenarios tailor-made for China's carbon neutrality began to appear, whereas in the past, the 1.5/2-degree target, RCP 1.9/2.6/4.5/7.0, etc., were usually used as the constraints for climate targets.

In terms of future pollution controls, most studies have tended to model two types of strategies, 1) maintaining existing legislation and 2) maximizing technological potential to reduce emissions, although the scenario nomenclature varies in different simulations.

Supplementary Table 3 summarizes representative scientific publications in prestigious journals that address the co-benefits of air quality in China. Compared with the existing studies, this study advances in the following two aspects: 1) the modeling base year is updated to 2019 reflecting the most recent developments, while other studies generally start in 2015; 2) GAINS contains information about costs of control measures, allowing to analyze the cost-benefits of emission control strategies. Since the Cheng et al[9] study was recently published in 2023, we mainly compared our data with its results. The *NDC* scenario in our study does not consider further end-of-pipe measures and mid-century climate goals, which is similar to the *Baseline* definition of Cheng et al. paper. The *CN60* scenario is a scenario that considers climate targets but no further end-of-pollutant management measures, and there is no corresponding scenario in the Cheng et al. paper. The *CN60-SDG* scenario considers both climate targets and further pollutant control measures, and the carbon peak time in this study is around 2025, so it is similar to the *Early peak-net zero-clean air* scenario of Cheng et al. It can be seen that our scenario has slightly higher $PM_{2.5}$ concentrations by 2030, (e.g., 24.7 $\mu g/m^3$ in our study corresponds to 22.1 $\mu g/m^3$ in Cheng et al[9]). The reason occurs to be we consider additional emission sources such as coal-fired power plants and steel capacity built during 2020-2022, and our CO_2 pathways are not as aggressive as that of Cheng et al[9]. For the $PM_{2.5}$ concentration in 2050, the results of Cheng et al[9] are similar to those in our study. The study of Cheng et al[9] on the number of avoided 600,000 premature deaths in 2060 have come up with figures relatively consistent with our study estimating around 620,000 fewer cases in 2050 due to climate measures. Both studies have demonstrated that population ageing is the primary factor of premature deaths increase in the long term and that GHG reduction is critical to reduce the number of premature deaths. By comparing scenarios with and without the addition of pollution control measures, our study emphasizes that end-of-pipe measures not only have a significant near-term impact, but also play an important role in achieving long-term national air quality standards and reducing premature mortality. This is the key takeaway from our study, that carbon neutrality induces health co-benefits, but achieving SDGs still requires additional sector-specific efforts.

Supplementary Notes 2 Explanation of scenario assumptions in the model framework

In the construction of the model framework, some of the technologies, policies, and measures involved in the promotion of emission reduction and the realization of the sustainable development goals cannot be described in detail in the main text due to space constraints, and the assumptions involved in Extended Data Table 1 are explained in detail here.

- Early retirement in power and industry: In *CN60* and *CN60-SDG* scenarios, China TIMES 2.0 model allows for the retirement of installed units in the power and industrial sectors after 2035, before the end of their technical lifetime. The plant is assumed to be irrevocably shut down, and therefore fixed O&M costs would no longer occur, and the retirement will recover the salvage value. Whether or not to retire and the amount of early retirement are determined by model cost optimization.
- Price elasticity of demand: Based on the price of the *NDC* scenario in that year, price changes due to carbon emission reductions in *CN60* and *CN60-SDG* scenarios will have an impact on demand. The price elasticity of each energy service demand is from existing literature[12].
- Demand management engagement: Demand-side response technologies such as V2G, load time-shifting, and grid-connected household storage are added to the CN60-SDG scenario, and model optimization determines whether or not these technologies are adopted and the amount of application.
- Sectoral policy-based water saving targets: National water conservation policies for the whole society (16% reduction in water use per GDP in 2025 from 2020), secondary industry (16% reduction in water use per unit of industrial added value in 2025 from 2020), iron and steel (10% reduction in water use per unit of product in 2025 from 2020), chemical industry (5% reduction in water use per unit of product in 2025 from 2020), non-ferrous metals (15% reduction in water use per unit of product in 2025 from 2020), paper making (10% reduction in water use per unit of product in 2025 from 2020), refer to the "14th Five-Year Plan", "Industrial Water Efficiency Improvement Plan", "Regulations on Water Conservation", "National High-standard Farmland Land Construction Plan (2021-2030)".
- High-standard farmland construction plan: By 2022, 67 Mha of high-standard farmland will have been built; by 2025, 72 Mha will have been built and 7 Mha of existing high-standard farmland will have been renovated and upgraded; by 2030, 80 Mha will have been built and 19 Mha of existing high-standard farmland will have been renovated and upgraded. The construction of 73 Mha of new high-efficiency water-saving irrigation will be completed in 2021-2030.
- Avoiding conversion of biodiversity hotspots: We use UNEP-WCMC Carbon and Biodiversity Report to identify highly biodiverse areas. And we consider the area as highly biodiverse where three or more biodiversity priority schemes overlap (Conservation International's Hotspots, WWF Global 200 terrestrial and freshwater eco-regions, Birdlife International Endemic Bird Areas, WWF/IUCN Centres of Plant Diversity and Amphibian Diversity Areas). For these sites, land

use type conversions are prohibited.

- Respect environmental water flow requirements: Environmental flow requirements are estimated using the Pastor's method[13]. The method follows the natural variability of river discharge by adjusting Environmental flow requirements according to the flow season. The method is designed to improve the protection of freshwater ecosystems during low-flow seasons. The Environmental flow requirements are set to 60% of the mean monthly flow during the dry (low-flow) season (December to May) and 30% during the wet (high-flow) season (June to November).

Supplementary Notes 3 China TIMES 2.0 model

The Integrated MARKAL-EFOM System of China 2.0 (China TIMES 2.0), a national energy-environment-economy optimization model, was developed on the basis of China MARKAL[14-16] and China TIMES[17-28] by Tsinghua University. As a bottom-up dynamic linear programming model, the model adopts flexible intervals covering the 2019-2100 simulation period: one-year intervals for the period 2019-2030, five-year intervals for the period 2030-2060, and 15-year intervals for the period 2060-2100, which improves the ability to represent short-term dynamics without increasing excessive computational burden. The model base year is 2019 and is calibrated to the most recent data through 2022. A discount rate of 5% is applied throughout the simulation period.

The model takes a whole energy system view of energy production, conversion, distribution and end-use. The model is divided into five main sectors: energy supply, industry, building, transportation, and agriculture. As for energy supply, China TIMES 2.0 has modeled >100 existing and alternative thermal power units, heat plants and CHP units considering different fuel types (coal, oil, gas, biomass, etc.), unit performance (ultra-supercritical, supercritical, subcritical, high pressure, etc.), unit size (1000MW, 600MW, 300MW, etc.), cooling methods (once-through, recirculating, air-cooled)[28-30]. Based on a unit-level database with multiple cross-checked data, we consider the age, type, capacity factor and cooling method of each existing unit and can guide the early retirement[31,32]. All thermal units consider operational constraints such as ramping and start/stop. Solar, wind, hydro, nuclear, ocean and geothermal power plants are modeled. Sub-annual modeling is performed for distributed PV, centralized PV, BIPV, onshore wind, offshore wind, run-of-river, and dam hydro, based on diurnal and seasonal variations. Hydrogen production, oil refining, cooking, coal chemical industry, petrochemical industry, biomass to oil/gas, are also considered in the energy supply sector. To illustrate variations in power source volatility, we impose the peak load reserve margin constraint. We mandate that the total credible capacity must surpass 10% of the peak load at each timepoint (Supplementary Table 4).

For the industrial sector, this study provides process-level modeling of cement[24], glass, steel[22,23,33], Na_2CO_3, NaOH, ammonia, ethylene, paper, non-ferrous metals and non-energy use, and adds the latest production processes for biomass, hydrogen and electricity. China TIMES 2.0 model separately models urban, rural and commercial buildings in five climate zones in China, taking into account the energy demand for heating, cooling, cooking, hot water, refrigerators, other appliances and data centers[25]. It also considers the building envelopes of existing buildings and their renovation options, as well as future ultra-low energy buildings are also considered. The model provides a detailed representation of urban, intercity, and international passenger and freight transportation, including road, water, rail, air, and pipeline, and is broken down into nearly 300 technical entries by fuel and carrier type[26].

The model is designed with 56 timeslices to analyze the energy supply and demand conditions at seasonal-weekly-daily-hourly levels, including all seasons, weekdays, and weekends, four periods in a day (morning, midday, evening and midnight), and separate hourly modeling for a typical summer day.

Supplementary Notes 4 China-TIMES-30PE model

The China-TIMES-30PE model is a provincial energy-environment-economy model developed by Tsinghua University based on the China TIMES and China-TIMES-30P[34-36] framework. The China-TIMES-30PE model analyzes the dynamics of the energy system from 2020 to 2060. For statistical reasons, the Tibet Autonomous Region, Taiwan Province, Hong Kong, and Macao Special Administrative Regions are excluded. The energy balance of every province in China for 2020 serves as the basis for the model. The model depicts the complete energy system, covering power, industry, building, and transportation sectors at the provincial level. The model is functionally designed to provide a comprehensive modeling of bilateral trade links across 30 provinces with regards to electricity, coal, oil, and gas. Therefore, the model can holistically consider socio-economic development, resource endowment, local policy, energy demand changes in different provinces.

The GIS-based renewable energy development analysis module, as an extension of the energy module, contains the renewable energy resource assessment module, the renewable energy development suitability assessment module, and the renewable energy layout analysis module. The module inputs the assessed renewable energy resource data into the resource database of China-TIMES-30PE and evaluates the land suitability for renewable energy development on a grid basis according to numerous factors and obtains a high-resolution picture of China's renewable energy development.

With streamlined timeslice settings, optimized technology modeling, limited external interfaces and reduced simulation horizons, China-TIMES-30PE achieves a globally optimized energy system model of China's provincial portrayals.

Supplementary Notes 5 GAINS-Asia model

Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model was developed by the Pollution Management (PM) Group of International Institute for Applied Systems Analysis (IIASA) to identify strategies to combat air pollution and climate change simultaneously[34,37,38]. Air pollutants (SO_2, NO_X, VOC, PM, NH_3) and GHG (CO_2, CH_4, N_2O and the F-gases) are assessed from their source to their multiple effects. The model projection periods through the year 2050 with 5-year intervals. As a bottom-up air pollution emission and impact model, GAINS provides each region with the potential emission reductions under different scenarios which are supported by >2000 specific emission control measures, estimates costs, and impacts of policy implementation.

Ambient $PM_{2.5}$ concentrations are calculated on a 0.1° grid based on computed pollutant emissions. Atmospheric transfer coefficients are derived from perturbation simulations of the global EMEP chemical transport model, which is run at a resolution of 0.5°. Separate abatement simulations are conducted for urban low-altitude sources at a resolution of 0.1°. To calculate population exposure, GAINS overlay ambient $PM_{2.5}$ with projected population on the same grid.

To estimate attributable deaths, disease and age-specific attributable fractions are applied to total disease-specific deaths. The PAF calculation utilizes the MR-BRT functions developed for the Global Burden of Disease 2019. Disease-specific baseline mortality is estimated from disease and age-specific shares of total deaths, as reported in the Global Burden of Disease 2019 Study for six causes of death (ischemic heart disease, stroke, COPD, lung cancer, acute lower respiratory infections, and type 2 diabetes) and applied to total deaths as reported/projected in the UN World Population Prospects 2017 revision. According to the UN World Urbanization Prospects 2018, urbanization is seen as a means of redistributing to the exposed population.

GAINS-Asia is a dedicated model version of GAINS for the Asia impact domain, including separate modeling for a total of 24 economies, including China (32 sub-national regions), India (23 sub-national regions), Japan (6 sub-national regions), Thailand (5 sub-national regions). Therefore, the energy use characteristics as well as air pollution and climate policies of different regions can be differentiated in the model. Input data are built on international energy and industry statistics and incorporate data and vetting from each country's government and academic partners.

GAINS-Asia updates control measures, costs, and emission reduction rates regularly to reflect the latest progress[39]. In this study, we utilized emission factors and cost coefficients calibrated specifically for China in 2022 to accurately assess the costs of end-of-pipe control measures. For more information on the emission control measures, application rate and cost settings, the detailed methodology description, please see Supplementary Data 1-3 and the website (https://gains.iiasa.ac.at/models/gains_models4.html).

Supplementary Notes 6 CWatM model

The Community Water Model (CWatM), a spatially explicit, rainfall runoff and channel routing water resources model[40,41], was developed by the Water Security (WAT) Group of IIASA. The CWatM model quantifies water availability, water withdrawals by sector, and the adoption of hydraulic facilities. CWatM model has a spatial resolution of 0.5° and a temporal resolution of daily. More information on the model can be found at website (https://cwatm.iiasa.ac.at).

Since the impacts of climate change due to GHG emissions from other countries are not simulated within the national model, and long-term water model simulations require a global perspective, we have matched the scenarios in this paper with the international unified scenario framework Representative Concentration Pathway (RCP) to correspond to the responsible mitigation efforts. In this study, we used the results of CWatM models run under the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) modeling framework ISIMIP3b, which is a GCM-based quantification of impacts at various levels of climate change. The CWatM model uses bias-calibrated (W5E5 V2.0[42]) CMIP6 climate forcing conditions from 5 earth system models, using the RCP7.0 assumption for the *NDC* scenario and the RCP2.6 assumption for *CN60* and *CN60-SDG* scenarios. Detailed introduction can be viewed at website (https://www.isimip.org/protocol/3/).

The seasonal total runoff and groundwater runoff are used to reflect the supply of water resources in different seasons of the year and the future trend changes of total water resources and distribution. Water quality is not differentiated in this paper.

Supplementary Notes 7 GLOBIOM-G4M model

The Global Biosphere Management Model (GLOBIOM) and Global Forest Model (G4M) were developed by the Biodiversity and Natural Resources (BNR) Program of IIASA to comprehensively represent the evolution of the land use sector[43,44]. GLOBIOM-G4M is a bottom-up model that provides a partial equilibrium result of technological competition in agriculture, forestry, and bioenergy areas. It is based on exhaustive data on land cover, land use, land management, and costs. GLOBIOM-G4M model models commodity markets and international trade in 37 economic regions, and prices are determined at the regional level to establish market equilibrium. To maximize social welfare, land and resources are allocated to different production and processing activities. Spatially explicit Leontief production functions are parameterized for crops, livestock, and forest products using biophysical models such as EPIC, G4M, or RUMINANT models. GLOBIOM-G4M model estimates major variables including supply, demand, prices, land use and GHG emissions from agriculture, forestry, and other land use (AFOLU) sector by 2100 using a recursive dynamic solution method. The methodology article[43], model documentation[45] and the GLOBIOM-G4M model documentation (https://iiasa.github.io/GLOBIOM/) provide more detailed information about GLOBIOM-G4M model.

To better descript biomass supply, GLOBIOM-G4M covers energy crop plantations and biomass feedstock from existing forests for energy use. Land suitability criteria based on drought, temperature, elevation, population, and land cover data are used to determine the potential for expanding energy plantation areas. A detailed description of the forest sector and its supply chain is provided by GLOBIOM-G4M. The model focuses on the types of biomass feedstocks that can be used for energy use and includes five primary wood products and eight final products.

The GLOBIOM-G4M model offers a detailed analysis of GHG mitigation options for the AFOLU sector. The model includes four different crop management systems and livestock species in the crop and livestock sector, enabling it to explicitly represent structural changes in the agricultural sector under climate policy. Agricultural producers can reallocate production to more productive areas within a region. The model presents various mitigation options, such as anaerobic digesters and animal feed supplements. It includes information on the potential for mitigation, costs, and impacts on productivity. Mitigation options are implemented as additional management activities, characterized by GHG reductions, productivity changes, and economic costs. If the economic benefits of an option exceed its costs, it is applied to the system. G4M considers diverse options to reduce the impact of forestry on the environment. These options include reducing deforestation, increasing afforestation, adjusting the rotation length of managed forests, changing the ratio of inter-felling to final felling, adjusting the intensity of harvesting, and changing the location of harvesting. The model calculates the best combination of measures for the economy. Introducing a GHG price gives value to forest carbon sinks, which reduces deforestation and increases afforestation.

Supplementary Table 1 Fuel and sectoral mapping of the GAINS-Asia model and the China TIMES 2.0 (China-TIMES-30PE) model. OS – Biomass fuels; HC – Hard coal; BC – Brown coal; DC – Derived coal; GAS – Gaseous fuels; MD – Diesel; GSL – Gasoline; HF – Heavy fuel oil; ELE – Electricity; HT – Heat; H2 – Hydrogen; GTH – Geothermal. The numbers at the end indicate different grades of fuel.

China TIMES 2.0 China-TIMES-30PE				GAINS-Asia 4.0					
Sector		**Fuel**		**Fuel**	**Sector**				
Primary Energy	Electricity	Biomass	w/ CCS	OS1 OS2	Existing Power Plants w/o CCS (PP_EX_L) (PP_EX_S) (PP_EX_OTH)	New Plants w/o CCS (PP_NEW) (PP_NEW_L)	Advanced Plants w/o CCS (PP_MOD) w/ CCS (PP_MOD_CCS)	IGCC Plants w/o CCS (PP_IGCC) w/ CCS (PP_IGCC_CCS)	Diesel Engines (PP_ENG)
			w/o CCS	OS1 OS2					
		Coal	w/ CCS	HC1 HC2 HC3 BC1 BC2 DC					
			w/o CCS	HC1 HC2 HC3 BC1 BC2 DC					
		Gas	w/ CCS	GAS					
			w/o CCS	GAS					
		Oil	w/ CCS	MD GSL LPG HF					
			w/o CCS	MD GSL LPG HF					
		Geothermal		GTH					
		Hydro		HYD					
		Nuclear		NUC					
		Ocean		OTH					
		Solar		SPV STH					
		Wind		WND					
Primary Energy	Gases	Biomass		OS1 OS2	Fuel Production & Concersion: Combustion (CON_COMB)	Own use of energy sector and losses during production, transmission & distribution of final product (CON_LOSS)			
		Coal		HC1 HC2 HC3 BC1 BC2 DC					
		Gas		GAS					
		Oil		MD GSL LPG HF					
Primary Energy	Liquids	Biomass		OS1 OS2					
		Coal		HC1 HC2 HC3 BC1 BC2 DC					
		Gas		GAS					
		Oil		MD GSL LPG HF					
Primary Energy	Solids	Biomass		OS1 OS2					
		Coal		HC1 HC2 HC3 BC1 BC2 DC					
		Gas		GAS					
		Oil		MD GSL LPG HF					
Primary Energy	Hydrogen	Biomass		OS1 OS2					
		Coal		HC1 HC2 HC3 BC1 BC2 DC					
		Gas		GAS					
		Oil		MD GSL LPG HF					
Final Energy	Commercial	Electricity		ELE	Services (DOM_COM) + Domestic others (DOM_OTH)				
		Gases		GAS					
		Heat		HT					
		Hydrogen		H2					
		Liquids		MD GSL LPG HF					
		Other		GTH					
		Solids	Biomass	OS1 OS2					
			Coal	HC1 HC2 HC3 BC1 BC2 DC					
Final Energy	Residential	Electricity		ELE	Residential (DOM_RES)	Residential Lighting (DOM_LIGHT)			
		Gases		GAS					
		Heat		HT					
		Hydrogen		H2					
		Liquids		MD GSL LPG HF					
		Other		GTH					
		Solids	Biomass	OS1 OS2					
			Coal	HC1 HC2 HC3 BC1 BC2 DC					
Final Energy	Transportation	Freight	Electricity	ELE	Cars (TRA_RD_LD4C)	Light-Duty Cars (TRA_RD_LD4T)	Buses (TRA_RD_HDB)	Heavy-Duty Trucks (TRA_RD_HDT)	2-Wheelers (TRA_RD_LD2) 4-Wheelers (TRA_RD_M4)
			Gases	GAS	Agriculture (TRA_OT_AGR)	Offroad Machinery and Construction (TRA_OT_CNS)	Offroad 2-&4- Wheelers (TRA_OT_LD2) (TRA_OT_LB)	Rail (TRA_OT_RAI)	Domestic Aviation (TRA_OT_AIR)
			Hydrogen	H2	Inland Navigation (TRA_OT_INW)	Maritime (TRA_OTS)			
			Liquids – Biomass	(included in other oil products)					
			Liquids – Oil	MD GSL LPG HF					
			Other	HC1 HC2 HC3 BC1 BC2 DC					
		Passenger	Electricity	ELE					
			Gases	GAS					
			Hydrogen	H2					
			Liquids – Biomass	(included in other oil products)					
			Liquids – Oil	MD GSL LPG HF					
			Other	HC1 HC2 HC3 BC1 BC2 DC					
Final Energy	Industry	Electricity		ELE	Paper & Pulp (IN_PAP_OC)	Iron & Steel (IN_ISTE_OC)	Chemical Industry (IN_CHEM_OC)	Non-Ferrous Metals (IN_NFME_OC)	Other Industry (IN_OTH_OC)
		Gases		GAS	Paper & Pulp Boilers (IN_PAP_BO)	Non-Metallic Minerals (IN_NMM_OC)	Chemical Industry Boilers (IN_CHEM_BO)	Conversion Sector Boilers (IN_CON_BO)	Other Industry Boilers (IN_OTH_BO)
		Heat		HT					
		Hydrogen		H2					
		Liquids		MD GSL LPG HF					
		Other		GTH STH					
		Solids	Biomass	OS1 OS2					
			Coal	HC1 HC2 HC3 BC1 BC2 DC					

Main socio-economic indicators and industrial product data

China TIMES 2.0		GAINS-Asia 4.0
GDP|MER		GDP
Population	Rural	POP
	Urban	
Value Added	Agriculture	VA_AGR
	Commercial	VA_TERT
	Industry	VA_CONSTR VA_ENER VA_IND
Electricity Production		ELE
Cement Production		PR_CEM
Steel Production		PR_CAST PR_CAST_F PR_EARC PR_PELL PR_PIGI PR_PIGI_F PR_SINT PR_SINT_F

Supplementary Table 2 Summary of SDG targets and indicators addressed in this study. Table containing mapping of model variables to SDG targets and indicators. The mapping refers to existing studies on the SDG target space[46] and target implementation[47]. The Type column indicates whether the indicator is the result of an endogenous output or an exogenous input constraint, or the result of an endogenous optimization with an exogenous bound constraint.

SDG	Target	Indicator	Definition	Type	Correspondence with SDG targets or indicators and other notes
		Under-nourishment	Under-nourishment rate	Constraint of *CN60-SDG*	● Exactly SDG target 2.2 ("end all forms of malnutrition") ● Exactly SDG indicator 2.1.1 ("prevalence of undernourishment") ● Minimum total calorie intake that limits under-nourishment below 1% by 2030 ● Under-nourishment are calculated based on the FAO methodology[48] as applied
		Health diets	Animal calorie intake is limited to 500 kcal capita^{-1} day^{-1} by 2030	Constraint of *CN60-SDG*	● An aspect of nutritious food and is relevant to SDG target 2.1 ("safe, nutritious and sufficient food") ● Overweight is a form of malnutrition and relevant for SDG target 2.2 ("end all forms of malnutrition") ● Dietary preferences for livestock products are based on the USDA recommendations[49] for healthy diets
		Agricultural product price	Crop and food price index with respect to 2020	Endogenous output	● A factor in food access and an aspect of ensuring SDG target 2.1 ("ensure access by all people") ● Exactly SDG indicator 2.c.1 ("food price anomalies")
		High-standard farmland	Share of high-standard farmland	Constraint of *CN60-SDG*	● Exactly SDG target 2.4 ("implement resilient agricultural practices") ● Efficient irrigation requirements are related to SDG target 6.4 ("increase water-use efficiency") ● According to the National High-standard Farmland Construction Plan (2021-2030), 71.7 and 80 Mha of high-standard farmland will be built by 2025 and 2030 ● Construction of 7.3 Mha of additional efficient water-saving irrigation from by 2030
		Premature mortality from $PM_{2.5}$	Premature mortality from $PM_{2.5}$ exposure	Endogenous output	● Exactly SDG indicator 3.9.1 ("mortality rate attributed to the air pollution") ● Obtained from atmospheric chemistry and source-receptor relationship matrices within GAINS-Asia
		Water withdrawal by sector	Water withdrawal for building, power, industry, and agriculture sectors	Endogenous output	● Reduced water withdrawal for the same service or demand which indicate SDG target 6.4 ("increase water-use efficiency across all sectors") ● Only water quantity is considered, not water quality
		Groundwater exploitation	Groundwater exploitation for use	Endogenous output	● Addressing groundwater over-pumping corresponds to SDG target 6.4 ("ensure sustainable withdrawals and supply of freshwater") ● Maintain the same cost structure of surface water and groundwater supplies as that in 2020
		Water intensity	Water withdrawal intensity	Constraint of *CN60-SDG*	● Reduced water withdrawal per capita which indicate SDG target 6.4 ("increase water-use efficiency across all sectors") ● Economy-wide water withdrawal intensity, industry water withdrawal intensity limits by sector, in accordance with 14th Five-Year Plan and Action Plan for Industrial Water Efficiency Improvement

SDG	Target	Indicator	Definition	Type	Correspondence with SDG targets or indicators and other notes
		Fertilizer use	Nitrogen fertilizer use	Endogenous output	● Contribute to water pollution and are related to SDG target 6.3 ("improve water quality by reducing pollution")
		Wastewater management	Wastewater treatment	Constraint of *CN60-SDG*	● Exactly SDG target 6.3 ("halving the proportion of untreated wastewater") ● Constraints on doubling wastewater treatment capacity
		Environmental flow	Ensure environmental flow and give priority to water demand in other sectors	Constraint of *CN60-SDG*	● A proxy indicator for SDG target 6.6 ("protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes") ● Water withdrawals do not jeopardize ecosystem services and environmental flows[50]
		Modern energy access	Final energy from traditional biomass and bulk coal in rural residential sector	Endogenous output, and additional constraint of *CN60-SDG*	● A proxy indicator for SDG target 7.1 ("affordable, reliable and modern energy services") ● Particularly relevant for SDG indicator 7.1.2 ("population with primary reliance on clean fuels") ● For *CN60-SDG*, in 2030, the share of traditional biomass and bulk coal in rural residential sector is constrained to decline by at least 70%, 40%, and 40% compared to 2020, and the downward trend continues, with all accounting for less than 5% of the demand for energy services by 2050.
		Energy cost	Marginal supply costs for electricity and hydrogen	Endogenous output	● A proxy indicator for SDG target 7.1 ("affordable, reliable and modern energy services") ● Featuring intraday supply cost fluctuations
		Electrification rate	Share of electricity in final energy consumption	Endogenous output	● A proxy indicator to SDG indicator 7.1 ("proportion of population with access to electricity")
		Renewable energy share	Share of renewable energy in primary energy supply	Endogenous output	● Exactly SDG target 7.2 ("share of renewable energy in the energy mix") ● Exactly SDG indicator 7.2.1 ("renewable energy share in total final energy consumption")
		Energy efficiency	Energy intensity (ratio of primary energy to GDP)	Endogenous output	● Exactly SDG indicator 7.3.1 ("energy intensity measured in terms of primary energy and GDP")
		GDP per capita	Growth rate of GDP (MER) per capita	Exogenous assumption	● Exactly SDG indicator 8.1.1 ("annual growth rate of real GDP per capita") ● Based on projections by the World Bank and IMF, and consistent with the China's Vision 2035[51] (GDP per capita at the level of medium developed countries, that is 22571 USD/capita)
		Energy investment	Investments in power supply, energy storage, hydrogen	Endogenous output	● New energy generation, hydrogen and energy storage industries represent industrial upgrading and new economic growth points, an aspect of SDG target 8.2 ("Achieve higher levels of economic productivity through diversification, technological upgrading and innovation")
		Passenger and freight volumes	Passenger and freight turnover	Exogenous assumption	● Exactly SDG indicator 9.1.2 ("passenger and freight volumes, by mode of transport") ● The aggregate turnover is given exogenously, and the traffic pattern, fuel choice, and energy efficiency upgrades are obtained by endogenous optimization of the model
		Industrial structure	Primary, secondary and tertiary sectors' added value as a share of GDP	Exogenous assumption	● A proxy indicator for SDG indicator 9.2.1 ("manufacturing value added as a proportion of GDP") ● The share of the secondary sector will be 38%, 35%, 30% and 20% in 2020, 2030, 2050 and 2100, respectively[52]

SDG	Target	Indicator	Definition	Type	Correspondence with SDG targets or indicators and other notes
		CO_2 emissions from industry	Direct CO_2 emissions from industry	Endogenous output	● A proxy indicator for SDG indicator 9.4.1 (“CO_2 emission per unit of value added”)
		CCS in industry	CO_2 emissions captured by CCS in the industry sector	Endogenous output	● A proxy indicator for SDG target 9.4 (“clean and environmentally sound technologies and industrial processes”)
		Reducing inequality within country	Gini coefficient of GDP per capita among provinces	Exogenous assumption	● A proxy indicator for SDG 10 (“Reduce inequality within and among countries”) ● Following the existing methodology[35,53], the national pathway is downscaled to the provincial level and the inter-provincial GDP per capita gap is reduced ● Gini coefficient among provinces decreasing and is 0.176 in 2030 and 0.137 in 2050
		Decent housing for all	urban/rural residential and Commercial building floor area by building envelope type	endogenous output for building envelope	● Related to living quality, proxy indicators of living quality for SDG target 11.1 (“adequate, safe and affordable housing”) ● Related to public space, proxy indicators SDG target 11.7 (“safe, inclusive and accessible, green and public spaces”) ● Exogenous assumption for floor area per capita according to socio-economic parameters
		$PM_{2.5}$ concentration	Population-weighted annual-average ambient $PM_{2.5}$ concentration	Endogenous output, and additional constraint of *CN60-SDG*	● Exactly SDG indicator 11.6.2 (“Annual mean levels of fine particulate matter”) ● Use of maximum feasible reduction (MFR) measures to control air pollution in the *CN60-SDG* (supplementary Data 1-3)
		Demand management level	Promote supply-demand interactions and sectoral coupling technologies	Constraint of *CN60-SDG*	● Implementing demand management to help grid balancing and renewable energy abandonment is an aspect of SDG target 12.1 (sustainable consumption and production patterns”) ● Add demand management measures like household storage feed-in, V2G, and load time-shifting
		Fossil fuel energy footprint	Coal, oil and natural gas in primary energy supply	Endogenous output	● Exactly SDG target 12.2 (“sustainable management and efficient use of natural resources”)
		Reduce food waste	food waste per capita	Constraint of *CN60-SDG*	● Exactly SDG target 12.3 (“halve per capita global food waste at the retail and consumer levels”) ● Assume a halving of food waste[54] by 2030 in line with the SDGs
		Renewable energy capacity	Geothermal, ocean, biomass, wind and solar power capacity	Endogenous output	● Exactly SDG indicator 12.a.1 (“installed renewable energy-generating capacity”)
		GHG emissions	GHG emissions	Endogenous output	● Exactly SDG indicator 13.2.2 (“total greenhouse gas emissions”) ● This study includes only CO_2, CH_4, N_2O, excluding F-gases
		Cumulative CO_2 emissions	Cumulative fossil fuel and industrial processes CO_2 emissions during 2020-2100	Constraint of *CN60* and *CN60-SDG*	● A proxy indicator for SDG indicator 13.2.2 (“total greenhouse gas emissions”) ● The range of carbon budgets (230 $GtCO_2$) is synthesized from the results of local and international allocation models[55-57]

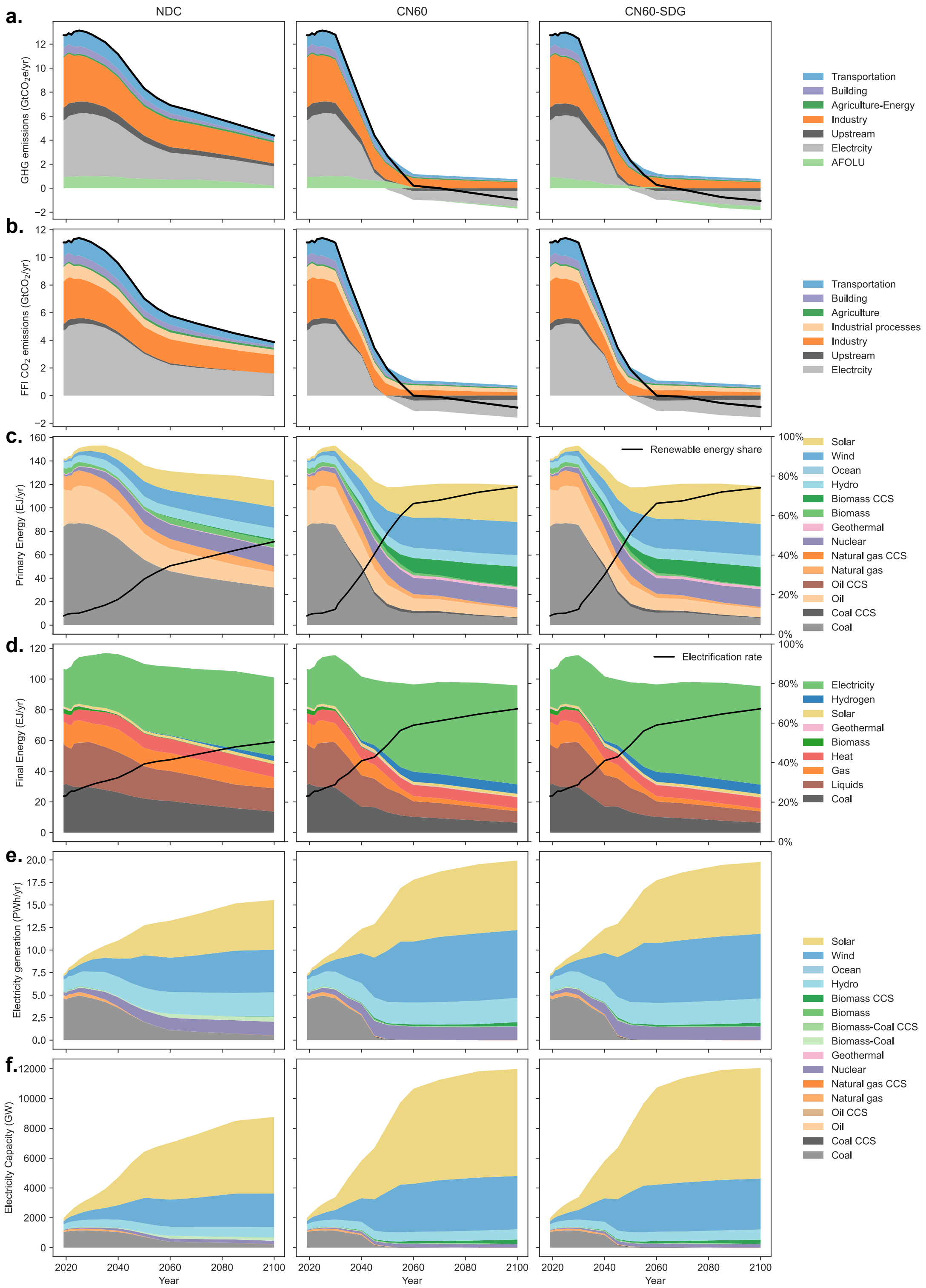
SDG	Target	Indicator	Definition	Type	Correspondence with SDG targets or indicators and other notes
		Long-term climate strategy	Net-zero of fossil fuel and industrial processes CO_2 emissions by 2060	Constraint of *CN60* and *CN60-SDG*	● A proxy indicator for SDG indicator 13.2.2 ("total greenhouse gas emissions") ● China's carbon neutrality target[58] is not explicitly scoped, and in this study we interpret it as net-zero fossil fuel and industrial processes CO_2 emissions
		NDC target	Energy-related CO_2 emissions peak by 2030	Constraint of all scenarios	● A proxy indicator for SDG indicator 13.2.2 ("total greenhouse gas emissions") ● Follow updated NDC government documents[59]
		Forest area	Forest area	Endogenous output	● A proxy indicator for SDG indicator 15.1.1 ("Forest area as a proportion of total land area")
		Afforestation and reforestation	Land area afforested and reforested	Endogenous output	● A sub-aspect of SDG target 15.2 ("increase afforestation and reforestation")
		Biodiversity hotspots	Avoiding conversion of biodiversity hotspots from 2030 onwards	Constraint of *CN60-SDG*	● Biodiversity hotspots area conservation is a sub-aspect of SDG target 15.4 ("conservation of mountain ecosystems, including their biodiversity") and are closely relevant for SDG target 15.5 ("reduce the degradation of natural habitats") ● We use UNEP-WCMC Carbon and Biodiversity Report[60] to identify highly biodiverse areas. And we consider the area as highly biodiverse where three or more biodiversity priority schemes overlap (Conservation International's Hotspots, WWF Global 200 terrestrial and freshwater eco-regions, Birdlife International Endemic Bird Areas, WWF/IUCN Centres of Plant Diversity and Amphibian Diversity Areas)
		Protected area	total surface of protected areas to 17% by 2030	Constraint of *CN60-SDG*	● Protected land area is a sub-aspect of SDG indicator 15.1.2 ("Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas")

Supplementary Table 3 The population weighted $PM_{2.5}$ concentrations modeled by previous studies under different climate and air pollution control settings. CMT – climate change mitigation target; AIR – air pollution control settings; Net zero – dedicated China's carbon neutrality scenario; CLE - current legislation reduction strategy (Currently released and upcoming policies); WBD2 – well below 2-degree; MFR - maximum feasible reduction strategy (Best available end-of-pipe pollution control technologies). Unit: μg/m^3.

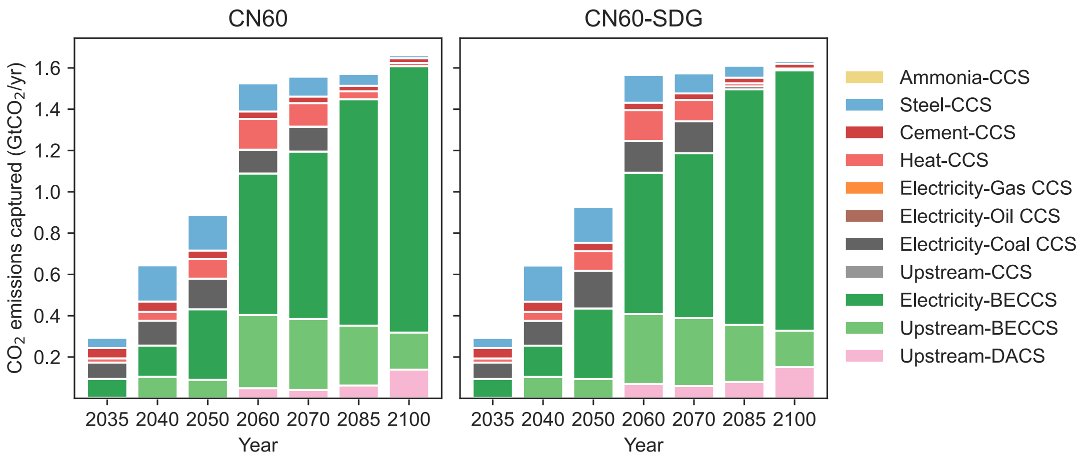
study	scenario	CMT	AIR	2030	2035	2050	2060
This study	NDC	NDC	CLE	36.06	35.16	34.48	
	CN60	Net zero	CLE	33.50	31.02	25.16	
	CN60-SDG	Net zero	MFR	26.23	19.33	10.85	
Cheng et al, 2023[9]	Baseline		CLE	33.4			30.1
	Clean air		MFR	26.0			22.1
	On-time peak-clean air	NDC	MFR	24.7			17.6
	Early peak-net zero-clean air	Net zero	MFR	22.1			7.6
Xu et al, 2023[11]	SSP1-2.6	RCP2.6	CLE	24.39	21.26		
	SSP2-4.5	RCP4.5	CLE	31.15	28.81		
	SSP3-7.0	RCP7.0	CLE	42.54	43.21		
Shi et al, 2021[61]	CAEP-CAP	Net zero	MFR	27	23		11
Zhang et al, 2021[62]	NDC-CLE	NDC	CLE	24.54	24.00	21.60	19.31
	NDC-MFR	NDC	MFR	23.78	22.05	16.39	12.64
	RE-CLE	Net zero	CLE		20.32		9.03
	RE-MFR	Net zero	MFR	20.67	18.70	9.44	6.10
Cheng et al, 2021[10]	Current-goals	NDC	CLE	27.6			20.2
	Ambitious-pollution-NDC goals	NDC	MFR	27.2			14.6
	Ambitious-pollution-2°C-goals	RCP2.6	MFR	22.3			9.5
	Ambitious-pollution-Neutral-goals	Net zero	MFR	21.3			7.9
	Ambitious-pollution-1.5°C-goals	RCP1.9	MFR	20.0			6.7
Liu et al, 2021[63]	No2.1:2050 CLE		CLE			12.95	
	No3.1:2050 MTFR		MFR			6.66	
Xing et al, 2020[64]	NDC-CLE	NDC	CLE				
	NDC-MFR	NDC	MFR		21.7		
	CBE-MFR	WBD2	MFR		18.4		
Li et al, 2019[34]	NDCCUM-CLE	NDC	CLE	39.5		37.45	
	NDCCUM-MFR	NDC	MFR	32.96		18.88	
	WBD2-CLE	WBD2	CLE	36.9		30.9	
	WBD2-MFR	WBD2	MFR	30.38		16.31	

Supplementary Table 4 Fraction of capacity that can contribute to the peak load. Each power system technology is assigned a coefficient from 0 to 1 to represent the proportion of credible output capacity to total capacity at every timepoint. This can be used to reflect the volatility of different power sources.

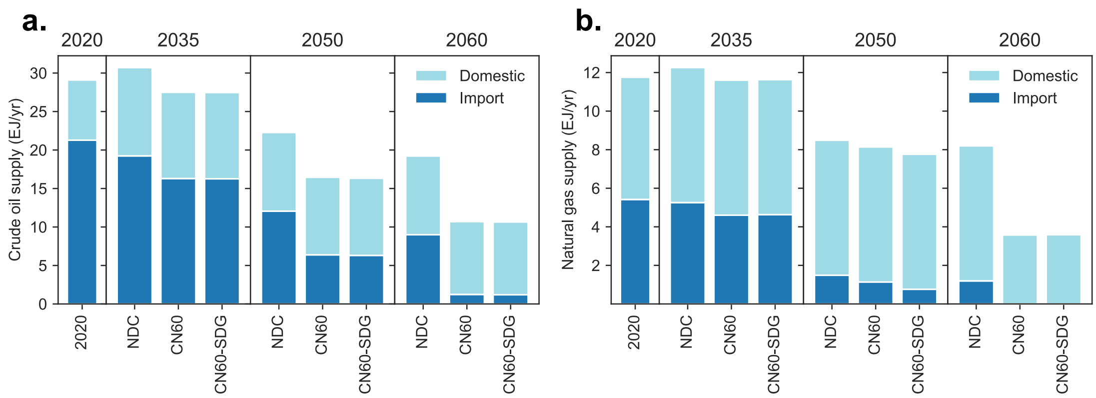
Technology	**Fraction**
CHP	0.95
Thermal power plant	0.97
Nuclear power	0.97
Geothermal	0.95
Hydropower	0.50
Ocean	0.15
Solar-CSP	1.00
Solar-PV	0.15
Wind	0.15
Storage	1.00



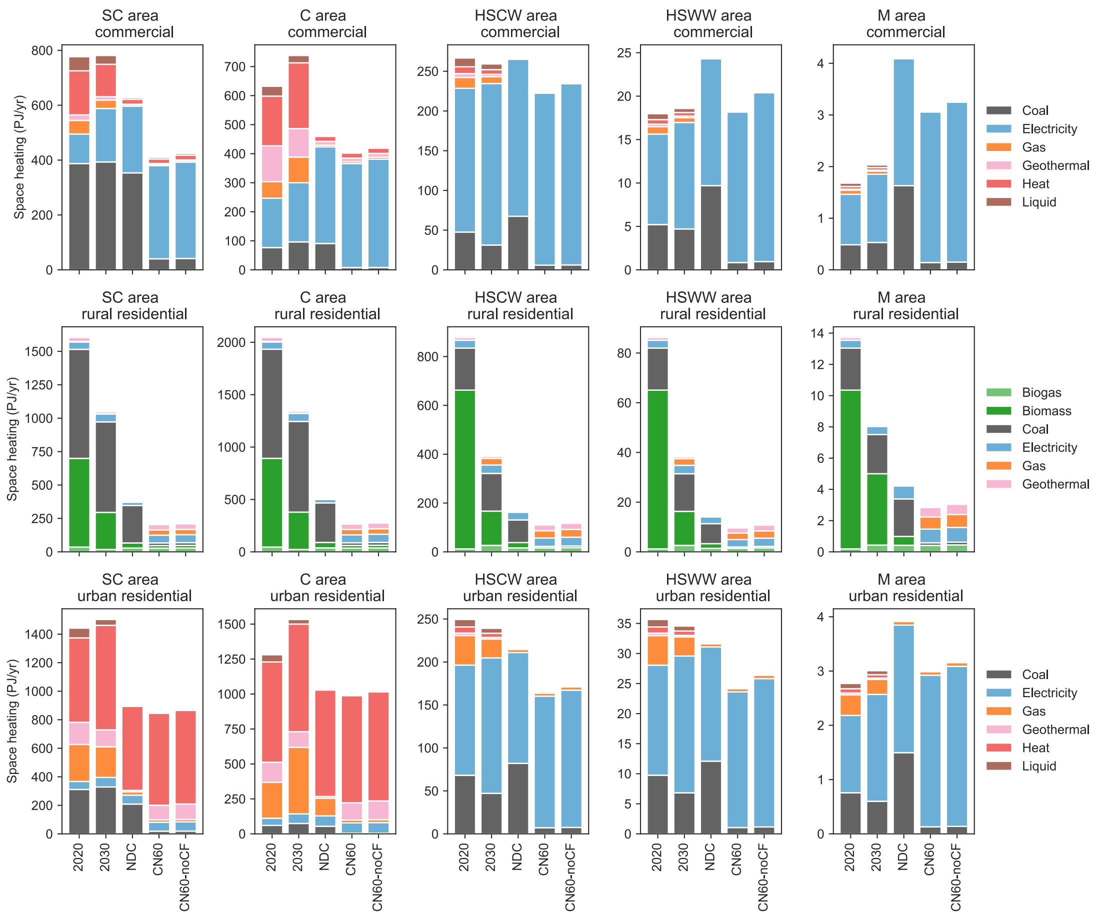
Supplementary Fig. 1 The net-zero transition pathway in China. a GHG emissions pathway. GHGs comprise CO_2, CH_4 and N_2O emissions/sinks from the fossil fuel, industrial processes and AFOLU sector. The black line represents net CO_2 emissions. **b** Fossil fuel and industrial processes (FFI) CO_2 emissions pathway. **c** Primary energy mix and renewable energy share. **d** Final energy mix and electrification rate. **e** Electricity generation by technology. **f** Electricity capacity by technology.



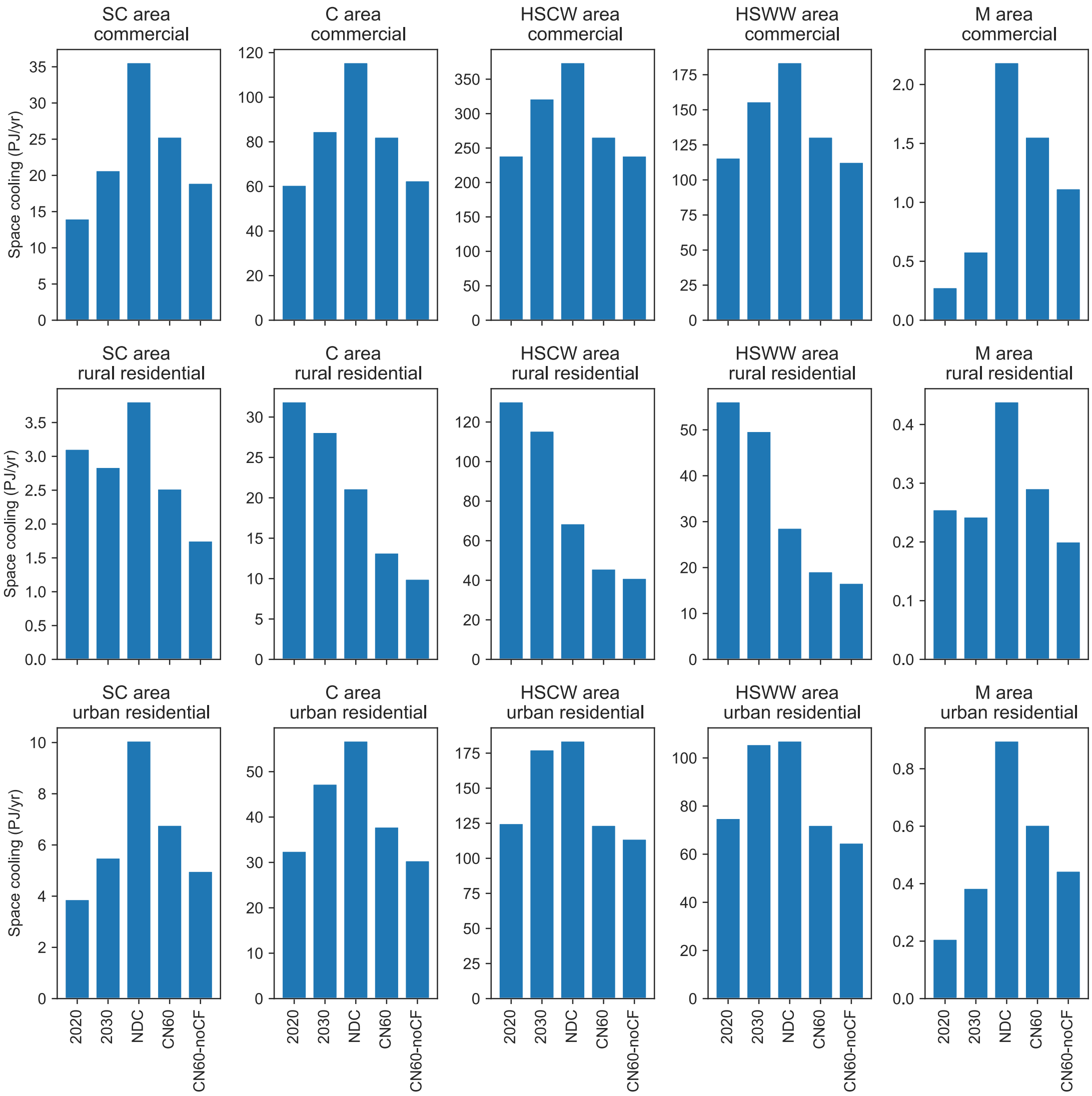
Supplementary Fig. 2 CO_2 captured by carbon capture and storage (CCS). BECCS - Bioenergy with Carbon Capture and Storage; DACS - Direct Air Capture and Storage. Upstream-BECCS includes biomass to H_2 with CCS and bioliquid refining with CCS.



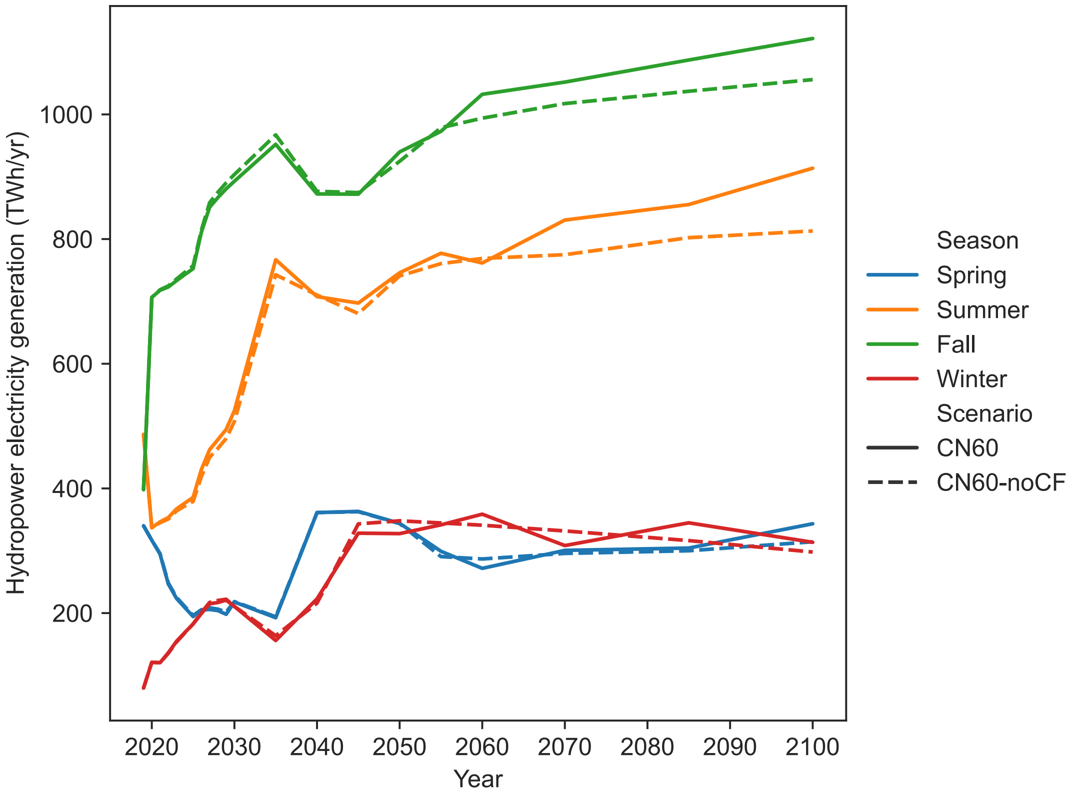
Supplementary Fig. 3 Oil and gas energy independence in China. A Crude oil. **B** Natural gas.



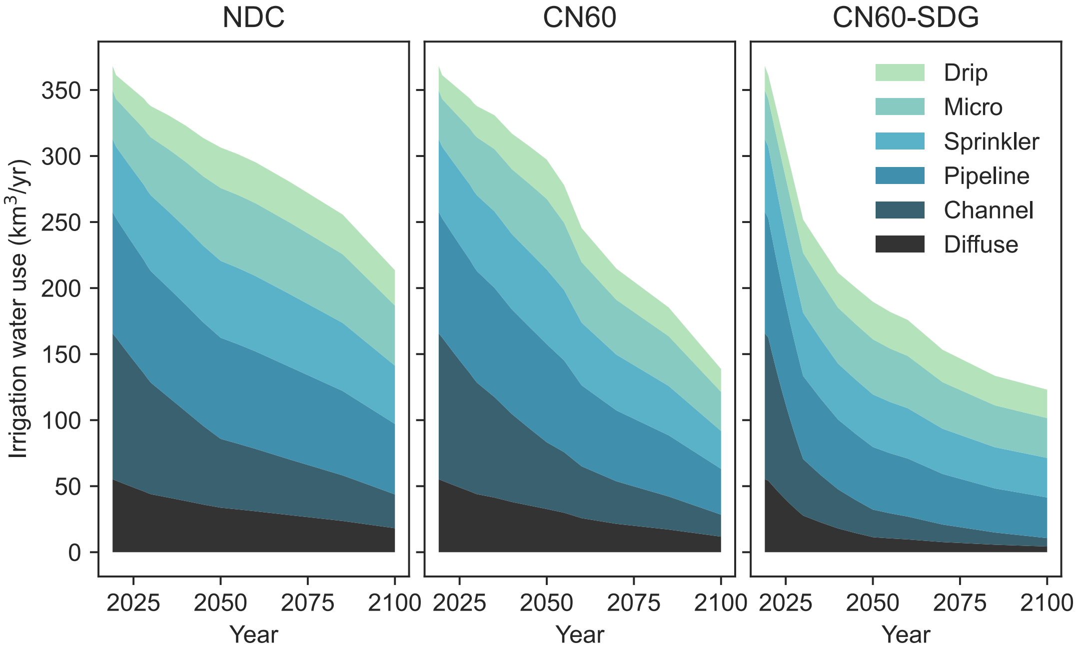
Supplementary Fig. 4 Space heating energy demand in building sector by climate zone in China. The *2020* and *2030* bars represent the situation in 2020 and 2030 under the *NDC* scenario. The *NDC*, *CN60* and *CN60-noCF* bars represent the situation in 2060 under the three scenarios. *CN60-noCF* is a scenario that freezes temperatures at 2020 levels (without considering climate feedback), otherwise consistent with the *CN60* scenario. Abbreviations for climate zones can be found in Extended Data Table 2.



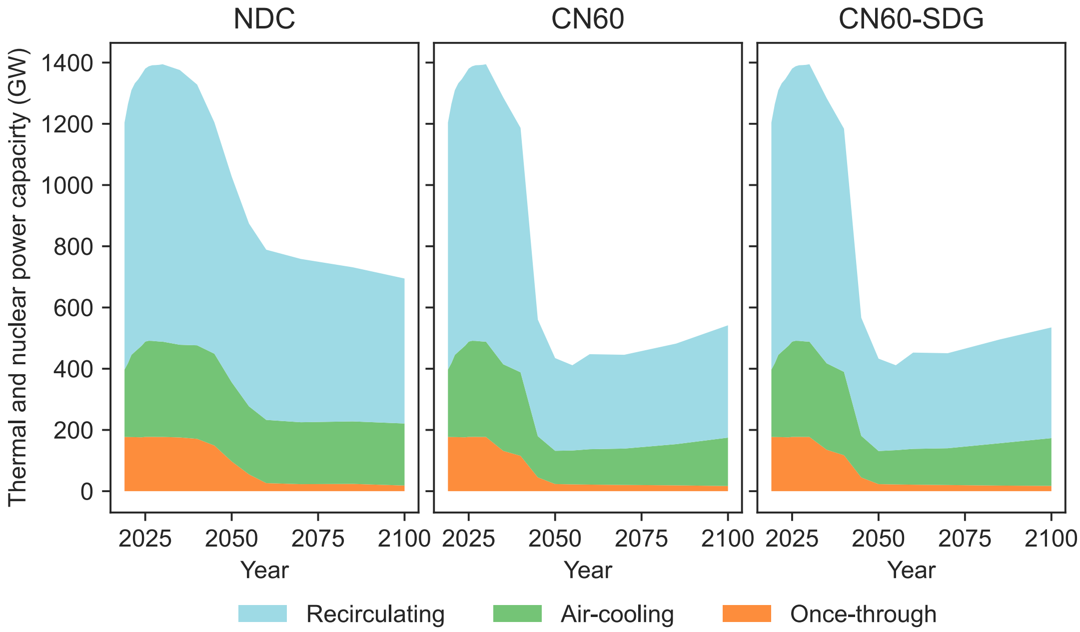
Supplementary Fig. 5 Space cooling energy demand in building sector by climate zone in China. The *2020* and *2030* bars represent the situation in 2020 and 2030 under the *NDC* scenario. The *NDC*, *CN60* and *CN60-noCF* bars represent the situation in 2060 under the three scenarios. *CN60-noCF* is a scenario that freezes temperatures at 2020 levels (without considering climate feedback), otherwise consistent with the *CN60* scenario. Abbreviations for climate zones can be found in Extended Data Table 2.



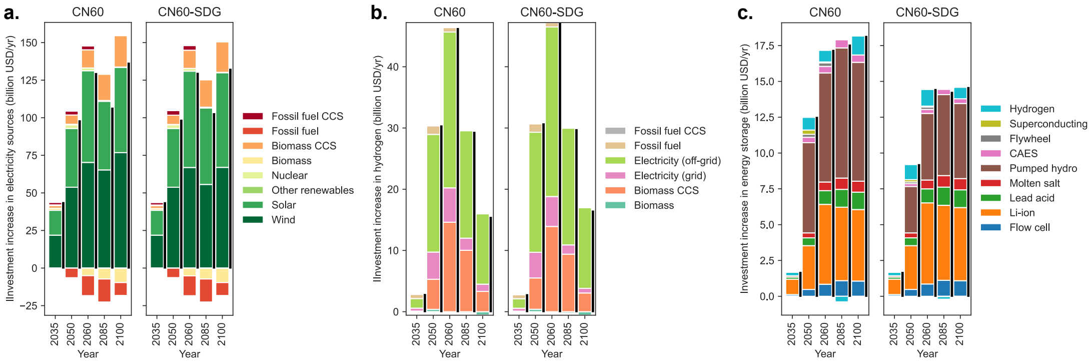
Supplementary Fig. 6 Hydropower electricity generation by season in China. *CN60-noCF* is a scenario that freezes temperatures at 2020 levels (without considering climate feedback), otherwise consistent with the *CN60* scenario.



Supplementary Fig. 7 Irrigation water use by irrigation technology in China.



Supplementary Fig. 8 Installed capacity of thermal and nuclear power by cooling type in China.



Supplementary Fig. 9 Annual investment increase relative to the *NDC* scenario in China. a Electricity production**, b** Hydrogen production, **c** Storage facilities. The vertical black bar next to an existing vertically stacked bar chart represents net values.

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