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Accelerating China's power sector decarbonization can save lives: integrating public health goals into power sector planning decisions

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Abstract

China, the world's largest greenhouse gas emitter in 2022, aims to achieve carbon neutrality by 2060. The power sector will play a major role in this decarbonization process due to its current reliance on coal. Prior studies have quantified air quality co-benefits from decarbonization or investigated pathways to eliminate greenhouse gas emissions from the power sector. However, few have jointly assessed the potential impacts of accelerating decarbonization on electric power systems and public health. Additionally, most analyses have treated air quality improvements as co-benefits of decarbonization, rather than a target during decarbonization. Here, we explore future energy technology pathways in China under accelerated decarbonization scenarios with a power system planning model that integrates carbon, pollutant, and health impacts. We integrate the health effects of power plant emissions into the power system decision-making process, quantifying the public health impacts of decarbonization under each scenario. We find that compared with a reference decarbonization pathway, a stricter cap (20% lower emissions than the reference pathway in each period) on carbon emissions would yield significant co-benefits to public health, leading to a 22% reduction in power sector health impacts. Although extra capital investment is required to achieve this low emission target, the value of climate and health benefits would exceed the additional costs, leading to $824 billion net benefits from 2021 to 2050. Another accelerated decarbonization pathway that achieves zero emissions five years earlier than the reference case would result in lower net benefits due to higher capital costs during earlier decarbonization periods. Treating air pollution impacts as a target in decarbonization can further mitigate both CO_2 emissions and negative health effects. Alternative low-cost solutions also show that small variations in system costs can result in significantly different future energy portfolios, suggesting that diverse decarbonization pathways are viable.

1. Introduction

China, the world's second-largest economy, emitted 30% of global greenhouse gases in 2020 [1, 2]. To constrain global warming to below 2 °C, China has announced a carbon neutrality goal by 2060, with CO_2 emissions peaking by 2030 [3]. Due to reliance on coal, the power sector, which contributes 40% of total CO_2 emissions in China, will be a major component of the country's decarbonization efforts [4, 5]. In addition to CO_2, combustion of fossil fuels emits other air pollutants that negatively impact public health, including sulfur dioxide (SO_2), nitrogen oxides (NO_2), and fine particles ($PM_{2.5}$). Recent studies estimate that over 10% of the premature deaths caused by air pollution in China are associated with power plant emissions [6–8]. As decarbonization reduces fossil fuel use for electricity generation, it will also bring about co-benefits to air quality and public health.

Several studies have used power system models to investigate decarbonization pathways in China. Burandt *et al* showed that reaching peak emissions in 2030 is not sufficient to meet the global CO_2 budget proposed under the Paris Agreement [9]. He *et al* showed that rapidly decreasing renewable energy costs will enable accelerated decarbonization of the power sector in China [10]. However, Zhuo *et al* found that higher electricity costs will be needed to achieve zero emissions [11]. The role of various low-carbon technologies has also been evaluated in deep decarbonization of the power grid in China, including deployment strategies for battery storage, financial and technological challenges of carbon capture and storage (CCS), and economic costs assessment of offshore wind [12–14].

Researchers have also studied the health co-benefits of decarbonizing energy-related sectors in China. By investigating impacts of end-use sectors on power generation, Peng *et al* and Liang *et al* identified public health benefits associated with fleet electrification and regional differences in air pollution mitigation [15, 16]. As the electricity grid decarbonizes, Peng *et al* demonstrated that large co-benefits would arise from the deployment of alternative-energy-vehicles, potentially avoiding over 330 000 mortalities per year [17]. In meeting the 2 °C target, climate change mitigation policies can lead to substantial air quality improvements, particularly in China and India [18, 19].

However, few studies consider detailed power system planning and operational constraints when estimating the health impacts of decarbonizing the power grid in China. Additionally, although the health co-benefits of a cleaner power grid can exceed the costs to implement it, most analyses treat improved air quality as an "ancillary benefit" instead of a core consideration in decarbonizing the power system [20]. The Chinese government has emphasized synergistic control strategies for climate and air pollution. The National Development and Reform Commission in China is requiring environmental impact analyses for project investments and many Chinese provinces have been implementing co-control strategies for air and climate pollutants [21, 22]. Experts in China have formed a working group (Carbon Neutrality and Clean Synergistic Control Strategies Working Group) to explicitly study synergistic control of greenhouse gas and air pollutants [23].

To enable data driven decision support through quantitative estimates of health impacts associated with power sector decarbonization, we design three scenarios (a reference decarbonization and two accelerated decarbonization scenarios) with and without consideration of the health damages associated with power plant emissions, apply a capacity expansion model that includes key constraints in power system operations to project future energy resource use in China, and use an air quality model to quantify public health impacts of decarbonization under each scenario. The analysis shows the benefits of accelerating decarbonization and considering health impacts in the decarbonization of China's power system, and compares different approaches to accelerate this transition. In doing so, we offer three main contributions. First, we combine a state-of-art power system model and a reduced-complexity air quality model to quantify the potential public health consequences of various decarbonization pathways. Both models are open-source but rarely applied to the power sector in China. We provide such a framework to advance integration of energy systems and public health, offering high transparency at reasonable computational costs. Second, we consider the mitigation of adverse health impacts as an explicit target of decarbonizing the power system by internalizing health impacts associated with air pollution into capacity expansion decisions. Third, we describe an approach to explore diverse low-cost decarbonization pathways. Aligned with current political emphases on both decarbonization and clean air in China, this work directly quantifies the tradeoffs between system costs and benefits in climate and public health during the decarbonization process, while presenting a transparent and open-source method for decision support related to decarbonization policy design.

2. Method

2.1. Power system modeling

To project China's energy portfolio, we use the GridPath power system modeling platform to simulate the country's power grid and determine the generation and transmission capacity needed to meet future demand, while minimizing system costs [24, 25]. Capacity expansion models, like GridPath, are widely used by research institutes and utilities in China to analyze economic and technological implications in a decarbonized power system [26–28]. Compared with other similar models (e.g. SWITCH-China and PLEXOS), GridPath has the advantages of being open-source, actively maintained, highly flexible, and computationally efficient. In the model used, each province is treated as a load zone connected to others by transmission lines. To manage the model's high computational costs, we cluster power plants by load zone, retirement date, fuel type, and heat rate. Technologies considered in this system are coal with and without CCS, natural gas with and without CCS, nuclear, hydropower, offshore and onshore wind, solar photovoltaic (PV), battery

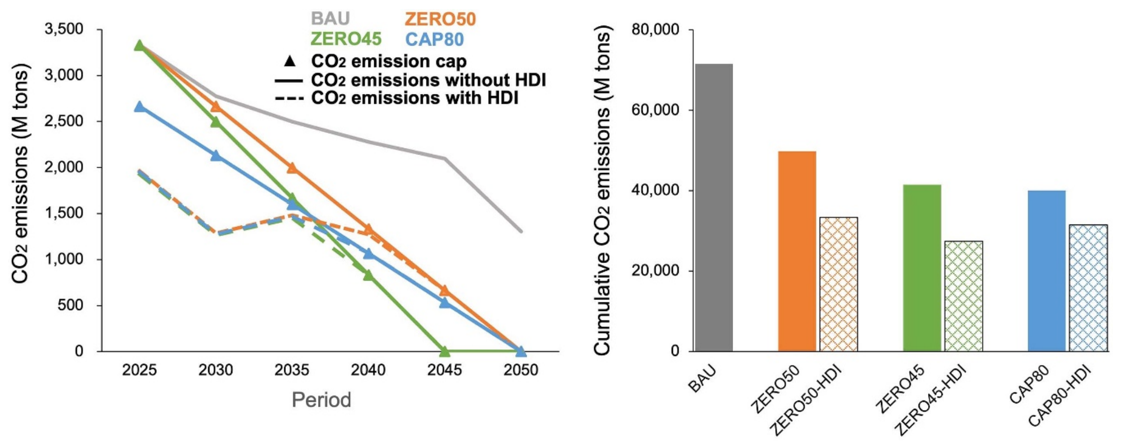

Figure 1. Annual CO_2 emission limits and trajectories (left) and cumulative CO_2 emissions from 2021 to 2050 (right) for the power sector in China under each scenario considered. BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50. Trajectories with health damages internalized into capacity expansion decision-making (HDI) are also shown.

storage, and pumped-hydro storage. Over 1000 power plant clusters are used to simulate the power system in China. We use two representative days (weekday and weekend day) to represent each month and 6 hours (1 hour for every 4 hours) to represent each day. Here, we project the generation and transmission capacity of the power grid in China from 2021 to 2050 and examine 5 year periods (e.g. period 2025 represents the years 2021–2025). We obtain capital costs for most technologies from He *et al* and Bloomberg New Energy Finance [10, 29]. Costs of CCS technology are from Zhou *et al* [11] (table S1). Regional fuel costs are from SWITCH-China [10]. Renewable energy profiles are from He *et al* [10] and Abhyankar *et al* [30]. Transmission line characteristics are also from SWITCH-China [10]. Future electricity demand is the median value of several China energy system decarbonization pathway studies. These forecasts include estimated load growth from electrification of transportation and heating, increasing electricity demand from 8900 in the 2025 period to 13 200 TWh in the 2050 period [5, 31–35] (table S2). Detailed descriptions of China's power system and the model used to represent it are provided in the supplementary information.

2.2. Decarbonization scenarios

We design a business-as-usual (BAU) scenario and three decarbonization scenarios. The BAU scenario does not consider any constraints on CO_2 emissions from power plants and its 2025 CO_2 emissions serve as a baseline for all scenarios considered. For decarbonization, we first consider a scenario that achieves zero emissions in 2050 and assume that the emission decrease from periods 2025 to 2050 is linear (ZERO50). A zero-emission power sector target in 2050 is set to reflect potential policies in-line with China's stated commitment to reach carbon neutrality by 2060 across all economic sectors. Prior research suggests that the power sector in China will need to attain net zero carbon emissions by 2050 in order to meet the carbon neutrality goal [11, 36]. We then consider two approaches to accelerate the power sector's decarbonization. The ZERO45 scenario achieves zero emissions in the power sector five years earlier than 2050. The CAP80 scenario applies a cap that constrains carbon emissions in each period to 20% below those projected under the ZERO50 scenario. Figure 1 shows CO_2 emission limits set for the power sector in China under each of the three decarbonization scenarios considered.

2.3. Public health impacts

We estimate the marginal health damages of SO_2, NO_x, and $PM_{2.5}$ emissions from fossil-fuel (coal and gas) power plants at the province level and quantify the health impacts of power sector emissions in China. The health damages are based on mortalities caused by exposure to $PM_{2.5}$ (formed from SO_2 and NO_x emissions or $PM_{2.5}$ directly released from power plants), which accounts for the majority of the negative health impacts associated with power sector emissions [37–39]. We use a reduced-form air quality model, InMAP-China, to estimate the emissions' marginal damages [40]. InMAP has been used frequently used to quantify the health impacts associated with the power sector in the United States [41–43], and it has also been shown to accurately capture the spatial distribution of pollutant when simulating annual average $PM_{2.5}$ concentrations over China [40]. Air quality simulations are conducted at 36 km horizontal resolution. We estimate annual premature deaths associated with $PM_{2.5}$ exposure by applying a mortality hazard ratio for long-term exposure to $PM_{2.5}$ derived from a large cohort study of Chinese population [44]. Population and base mortality in 2017 estimates from the Global Burden of Disease Study are used [45] and the population distribution is taken from the gridded population of the world [46]. These demographic data are included in InMAP-China. A set of InMAP-China simulations are conducted—a simulation with emission estimates from Wu *et al* [40] and simulations with 50% reductions to power plant SO_2, NO_x or $PM_{2.5}$ emissions within each province—to represent the large decrease in electricity generation from fossil fuels expected. The decrease in predicted mortality (ΔM) caused by an emission reduction (ΔE) is used with a selected value of the statistic life (VSL) estimate to calculate marginal health damage costs as:

$$\text{Health Damages}_{\text{p,z}}\,(\$/\text{ton}) = \text{VSL} \cdot \Delta M_{\text{p,z}}/\Delta E_{\text{p,z}}$$

where VSL is the value of a statistical life in China ($1.3 million 2022USD [47]), p is the pollutant considered, and z is the load zone selected. In Luo *et al*, we found greater values of VSL can further reduce mortalities, but different VSLs estimated for different regions in China do not significantly change the distribution of damages [48]. Therefore, only one VSL is used in this study. We repeat the process for three air pollutants and 30 provinces to estimate spatially-varying marginal health damage costs across China. Marginal costs are also quantified based on 100% emission reductions to power-sector emissions as a sensitivity analysis, but yield very similar results to those obtained with 50% emission reductions and do not change the model's capacity expansion results.

Marginal health damage costs of emissions and projected emission changes are used to compare the health impacts of each scenario and assess the costs and benefits of each decarbonization pathway. Although marginal damage estimates of each province include the total damages across China caused by emissions from that province, in our analysis we assume that the province itself will incur most of the health damages. Prior research shows that the population within 50 km of a point source receive over half of total $PM_{2.5}$ damages associated with its emissions [49]. For each decarbonization scenario, we additionally investigate the effects of internalizing health damages on projected capacity expansion and public health impacts by treating marginal damage costs as a component of variable operation costs in the power sector simulations. The ZERO50-HDI, ZERO45-HDI, and CAP80-HDI scenarios consider the same CO_2 emission constraints previously described, while also internalizing health damages caused by power plant emissions into their optimization.

2.4. Exploring uncertainty through alternative low-cost solutions

Deterministic capacity expansion models, including GridPath, project future installed capacity by minimizing system costs. Therefore, only one optimal solution is generated by GridPath. Modeling to generate alternatives is an emerging approach to assess uncertainties in capacity expansion modeling and many algorithms have been developed to explore potential near-optimal solutions [50–55]. However, most of these studies focused on energy systems in the United States or Europe. To quantify uncertainties in power sector capacity expansion in China in the context of decarbonization, we allow for small increases in system costs above the least-cost result from ZERO50. To do this, we first run GridPath to minimize system costs and obtain the least-cost solution (NPV_0). We then add a slack value (S) to the least cost and add a constraint in the model to ensure that system costs do not exceed $NPV_0 + S$. Next, we run a reformulated version of GridPath in which we minimize or maximize the capacity of a specific technology, subject to system cost constraints (i.e. ensuring that the solution's cost does not exceed $NPV_0 + S$). As GridPath is a linear optimization model, when planning for future installed capacity, values between the range of the minimum and the maximum installed capacity are also alternative low-cost solutions whose system costs do not exceed $NPV0 + S$. We analyze slack values of 0.1%, 1%, and 3% of NPV_0 and investigate the model's responses when minimizing or maximizing the capacity of different technologies in 2050.

3. Results

3.1. Power system decarbonization in China

Figure 2 shows projected electricity generation and installed capacity by source in 2045 and 2050 under each scenario considered. Most future installed capacity is from renewable energy, with solar PV power accounting for the largest fraction in 2050 due to its relatively low capital costs and high availability across China. Offshore wind power is more expensive than other renewable technologies and its capacity remains limited in the projections, mainly concentrated in Jiangsu and Zhejiang where electricity demand is very high. Due to high renewable energy penetration, over 1000 GW of batteries are added to the system by 2050 even when no cap on CO_2 emissions is applied, demonstrating the cost-effectiveness of renewable energy and energy storage. Carbon capture and storage (CCS) is added to the system under all decarbonization projections. However, due to high natural gas prices in China, most CCS would be coupled with coal-fired power plants, while a small amount of natural gas CCS would be added to provide system flexibility.

Although considerable renewable energy capacity is added to the power system under the BAU scenario, cumulative power sector CO_2 emissions projected from periods 2025 to 2050 under this scenario are 43% higher than those under the scenario that linearly reduces emissions to zero by 2050 (ZERO50) (see figure 1). The ZERO50 pathway only increases the system costs (operational + capital costs

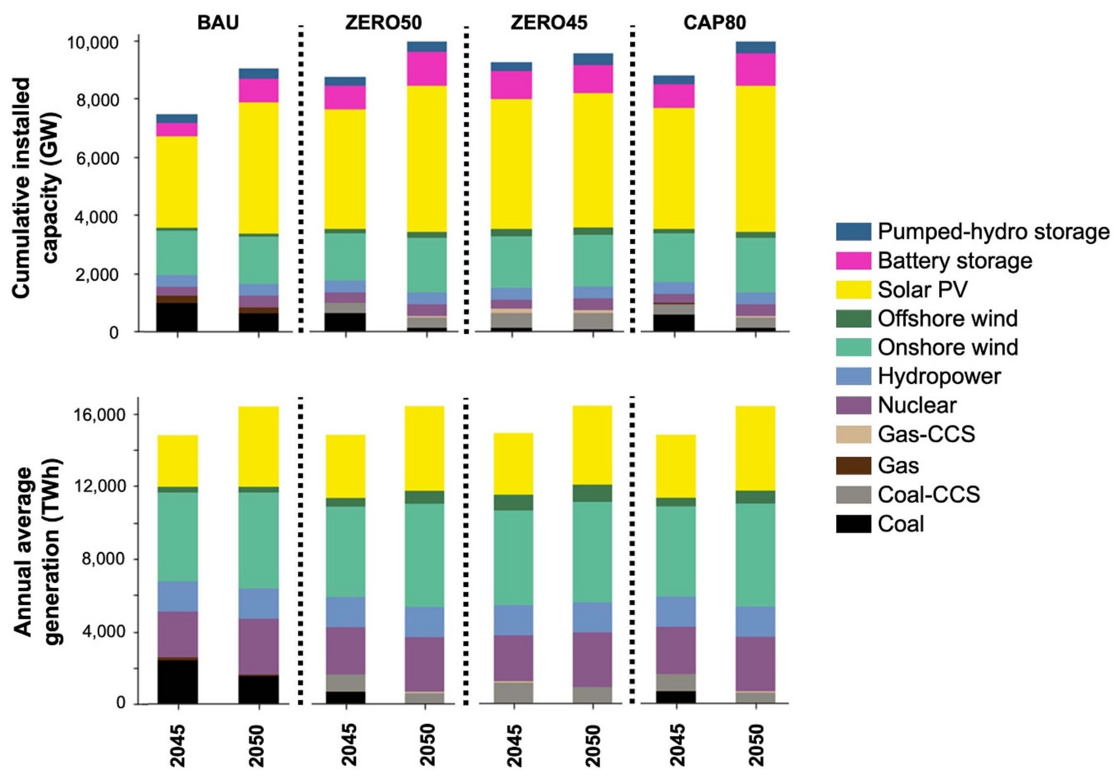

Figure 2. Projected capacity (top) and generation mix (bottom) in 2045 and 2050 without considering health damages. BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50.

accumulated from periods 2025 to 2050) by 2.4% relative to BAU, resulting in an average $6 per ton CO_2 emissions abatement cost that is significantly lower than estimates of the social cost of carbon (SCC, $27/ton for China [56]). Under accelerated decarbonization, the CAP80 scenario results in an energy mix that is very similar to that under the ZERO50 scenario, while the ZERO45 scenario has a significantly higher generation capacity in 2045 to achieve its earlier zero emission goal. The CAP80 scenario requires a 1.7% increase in system costs, but would reduce total carbon emissions by additional 20% at an abatement cost of $9 per ton of CO_2 relative to the ZERO50 case. Due to decreasing costs of new power plants, achieving zero CO_2 emissions by 2045 would be more expensive. Given that cumulative emissions under the ZERO45 case are lower than those under the ZERO50 case, CO_2 emission mitigation costs under the ZERO45 scenario are higher at $16 per ton, albeit still considerably lower than the SCC.

Due to regional differences in available resources, projected energy portfolios vary across load zones. As shown in figure 3(a), central and north China would experience the largest negative health impacts of power plant emissions under the BAU scenario, as many newer coal-fired power plants in these regions will not be retired in the near term without a carbon emission limit, and population density here is also high. Under decarbonization, total health damages from periods 2025 to 2050 would decrease by 17%–27% relative to the BAU scenario, with the CAP80 scenario yielding the greatest reduction (figure 4). Projected health co-benefits of power system decarbonization are substantial, ranging from $180–290 billion across 30 years (figure 5). However, they are lower than the projected climate benefits, as air pollution levels drop significantly in the future.

Compared to the BAU scenario, most regions across China are projected to benefit from decarbonization of the power system. However, there are regional differences in the public health impacts of decarbonization, with the Sichuan (SC), Chongqing (CQ), Hubei (HUB), Beijing (BJ), and Tianjin (TJ) provinces experiencing higher total health damages relative to BAU (figures 3(b)–(d)). Due to limited renewable and nuclear energy potential, coal-fired generation with CCS is added in these regions to meet electricity demand under the decarbonization projections, therefore increasing emissions of non-CO_2 air pollutants. The new coal-fired plants with CCS lead to an increase in national health damages associated with power sector emissions from 2040 to 2045 under the ZERO50 and CAP80 scenarios (figure 4). Although regions like Beijing currently rely on electricity imports, GridPath finds that it would be less costly to build CCS capacity than to expand the transmission network in order to meet future demand increases.

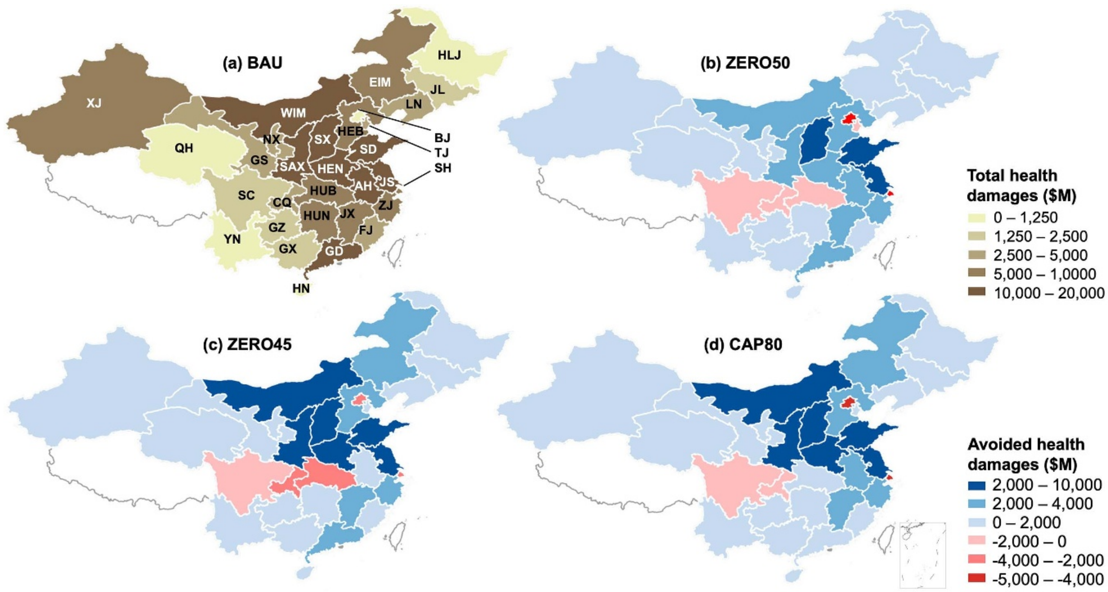

Figure 3. Total monetized health damages under the BAU scenario (a) and avoided health damages under decarbonization scenarios from periods 2025 to 2050 ((b) ZERO50; (c) ZERO45; (d) CAP80). Names of load zones considered in the model are labeled in (a) and their full names are provided in figure S2. BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50.

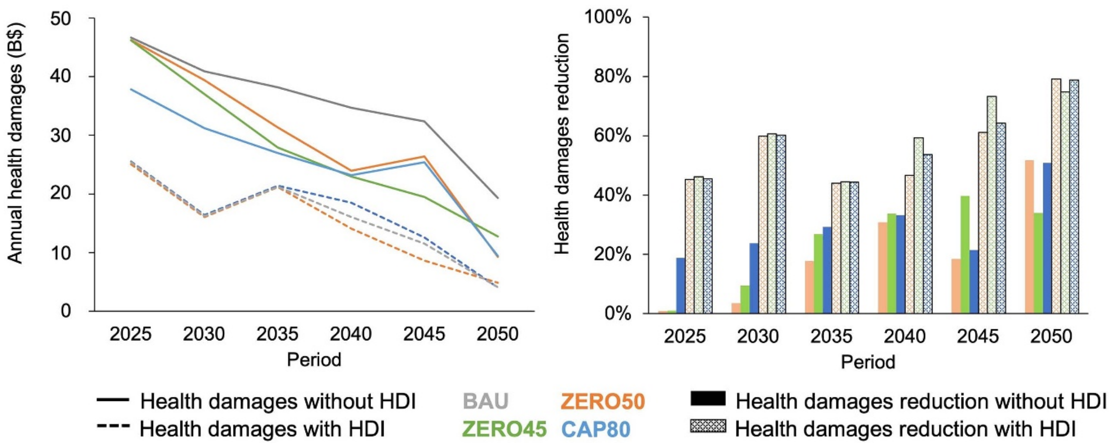

Figure 4. Average annual monetized health damages associated with power sector emissions in each five-year period from periods 2025 to 2050 under the scenarios considered (left) and reductions in health damages under each scenario, relative to the BAU scenario (right). BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50; HDI: health damages internalized in the power system capacity expansion decision making.

3.2. Integration of health impacts into power sector projections

In the decarbonization scenarios that consider health impacts in the capacity expansion process, the projections co-minimize health damages and system costs. Internalizing health damages into investment and operation decisions results in greater capacity from offshore wind and gas-fired generation with CCS due to their lower health impacts (figure 6). Internalization of health impacts also lowers CO_2 emissions. CO_2 emitted by the power sector in China from periods 2025 to 2050 is reduced by an additional 21%–34% with health damages internalization, relative to decarbonization without consideration of health impacts (figure 1). However, when internalizing health damages, accelerating decarbonization (CAP80-HDI and ZERO45-HDI) does not significantly reduce total CO_2 emissions beyond those on the trajectory towards zero CO_2 emissions by 2050 (ZERO50-HDI), as projected CO_2 emissions under the scenarios remain below the scenarios' emission limits and are similar for all decarbonization scenarios considered (figure 1).

Beyond the substantial health co-benefits achieved by decarbonizing the power sector in China, 39%–46% of the remaining health damages associated with power plant emissions can be mitigated by internalizing health damage costs into expansion

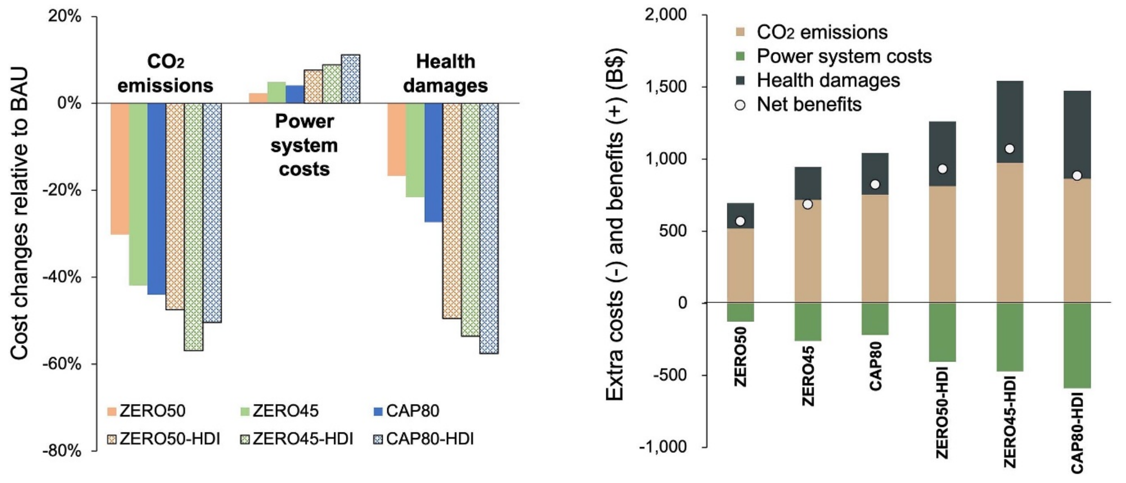

Figure 5. Total changes in CO_2 emission costs, power system costs, and health damages (left) and net benefits of decarbonization (right) relative to the BAU scenario from periods 2025 to 2050. BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50; HDI: health damages internalized in the power system capacity expansion decision making process.

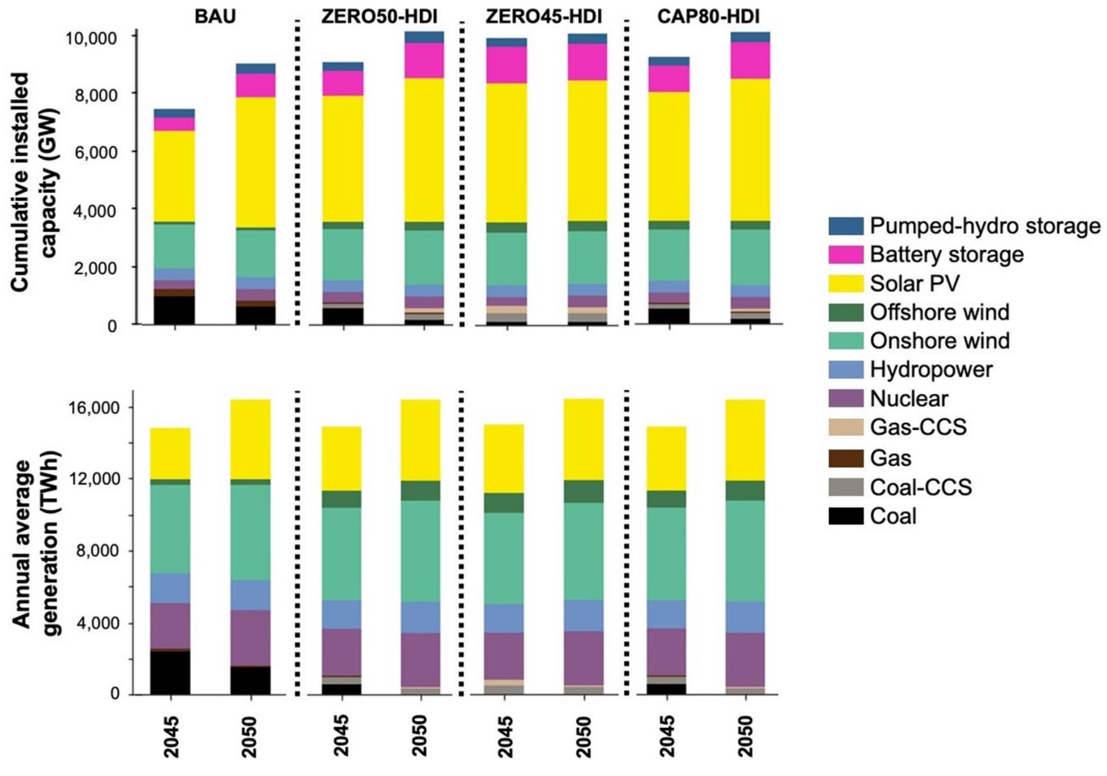

Figure 6. Projected capacity (top) and generation mix (bottom) in 2045 and 2050 considering health damages. BAU: no CO_2 emission cap applied; ZERO50: zero CO_2 emissions achieved by 2050; ZERO45: zero CO_2 emissions achieved by 2045; CAP80: CO_2 emission limits are 80% of those under ZERO50; HDI: health damages internalized in the power system capacity expansion decision making.

and operation decisions. This internalization is projected to increase total system costs by only 6%–7% (figure 5). Considering both health and climate benefits in investments and operational decisions leads to larger overall net benefits (figure 5).

In addition to the magnitude of public health benefits, health damages internalization also changes in the distribution of public health impacts and electricity generation. When internalizing health impacts, the outcomes of accelerated decarbonization scenarios are similar (see figure S2). Figure 7 compares the energy portfolio of electricity generation and health damages associated with power plant emission under the ZERO50 and ZERO50-HDI scenarios in 2030, when a large amount of coal-fired generation remains.

Public health damages in central-south China, where both load and population are high, decrease

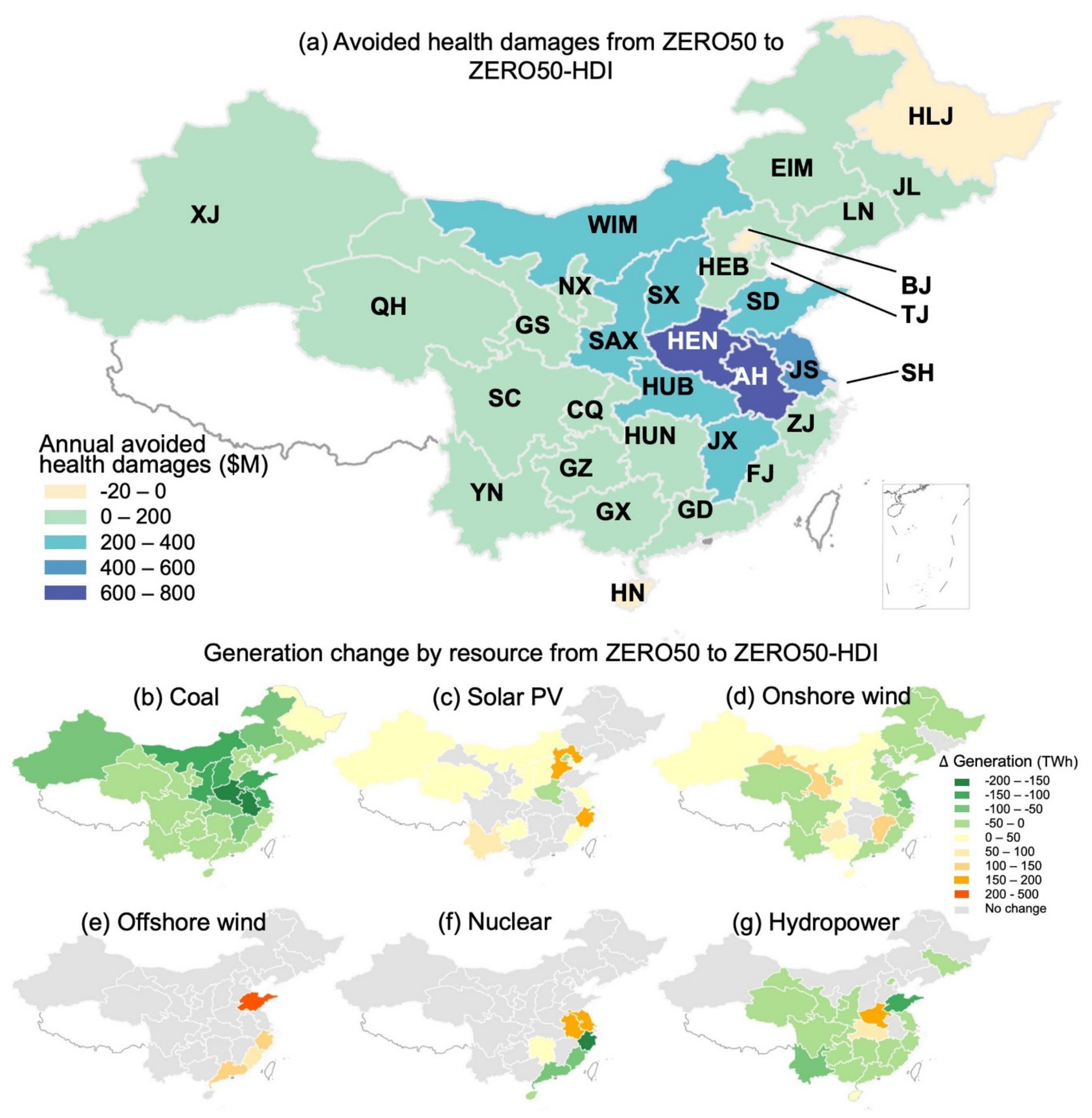

Figure 7. Projected annual avoided public health damages (a) and annual electricity generation change by resource (b)–(g) in the 2030 period after internalizing health damages into capacity expansion decision-making under ZERO50 scenarios. Names of load zones considered in the model are labeled in (a) and their full names are provided in figure S2. ZERO50: zero CO_2 emissions achieved by 2050; HDI: health damages internalized in the power system capacity expansion decision making.

significantly with internalization due to high health costs of fossil fuel generation (figure 7(a)). After internalizing health damages, only Shandong (SD) and Guangdong (GD) have health damages exceeding $1600M in 2030, as a large portion of their electricity remains from coal. Although coal-fired generation is greater in Xinjiang (XJ) and Inner Mongolia (WIM and EIM), lower population density there leads to relatively low health damages. Considering health damages reduces coal generation in nearly all provinces except for Heilongjiang (HLJ) (15% increase) due to its comparatively lower health damage costs (figure 7(b)).

Total electricity generation in each province in 2030 does not appreciably change with the internalization of health damages, as coal generation is replaced with other energy sources depending on location. With health damages internalization, greater generation comes from onshore wind in the northwest (Xinjing (XJ), Gansu (GS), and West Inner Mongolia (WIM)) and greater generation from offshore wind in eastern coastal regions (e.g. Guangdong (GD), Fujian (FJ), Zhejiang (ZJ), and Shandong (SD)). A regional transition in hydroelectric and nuclear generation also occurs. When internalizing health damages, hydroelectric and nuclear generation shift to inland provinces with limited solar and wind resources, such as Hubei (HUB) and Anhui (AH), while coastal regions have increased generation from solar or offshore wind power.

3.3. Alternative low-cost solutions

We generate 21 near cost-optimal divergent pathways (termed 'extreme pathways') in this analysis by maximizing or minimizing the capacity of selected technologies (minimize and maximize wind, solar PV,

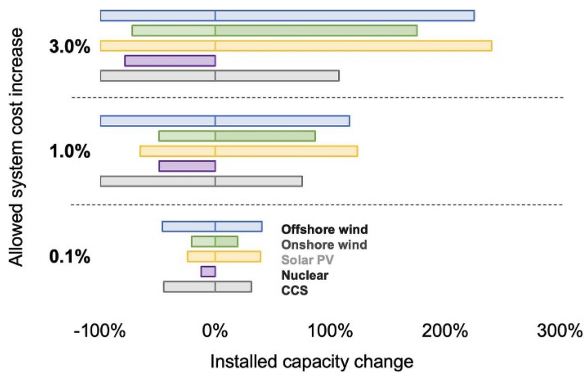

Figure 8. Range of possible changes in projected installed capacity of different technologies in 2050, relative to the least cost scenario (i.e. ZERO50), when allowing an increase in system costs relative to the least cost projection. The range shown by each bar represents projections when maximizing and minimizing capacity of each targeted technology under allowed system cost increase. CCS includes both coal and gas-CCS.

and CCS respectively, and minimize nuclear, all conducted with three slack values) in 2050 while allowing a small increase in system costs. Figure 8 shows the wide range of possible installed capacities in 2050 when system costs are allowed to increase slightly and figure S3 shows detailed capacity fuel mix under each extreme pathway. Even with a 0.1% increase in system costs, installed capacity can vary by −46%–41%, depending on the technology, compared with the least cost projection (i.e. ZERO50). This can explain why accelerating decarbonization is not projected to increase system costs significantly. Although the capacity expansion model identifies the decarbonization pathway with the least cost, many near-optimal low-cost pathways exist with diverse energy portfolios.

Installed capacity of solar, offshore wind, and CCS can be reduced to zero if a 1%–3% system cost increase is allowed with the system still achieving zero emissions in 2050, indicating that there are a lot of technology mix options within certain system cost tolerance. Installed capacities of wind and solar are highly negatively correlated. When solar or wind capacity is reduced, additional wind or solar is needed to meet electricity demand due to their similar costs. In cases where wind or solar's capacity is maximized or minimized, variable renewables contribute 61%–75% of total annual electricity generation. Monthly levels do not exceed 78%. For example, due to the higher capacity factor of wind, less wind capacity is needed to replace solar capacity. Wind and solar power are not direct substitutes and in the cases in which renewable energy capacity is minimized, additional flexible capacity (e.g. CCS) is added and energy storage discharges more during peak hours to ensure sufficient generation at all hours (see figure S4). When CCS is not allowed, solar PV capacity cannot be minimized to zero even when system costs are allowed to increase by 3% (figure S5). CCS and nuclear are more strongly and negatively correlated with wind than solar capacity. Regions with CCS under the least cost projection usually have lower solar resource availability. Nuclear resources are mostly in coastal regions, where wind capacity factor is relatively high. The health damages associated with CCS are mitigated when CCS capacity is minimized. In the cases where CCS capacity is eliminated, much of the generation is replaced by offshore wind power (see figure S6). Although system costs increase by only 0.1%–3% when CCS capacity is reduced in the alternative solutions, net benefits relative to the ZERO50 scenario, including climate and public health impacts, range from 1% to 5%.

4. Discussion and conclusions

To investigate the potential impacts of policies affecting the power system in China, we explore a series of scenarios, including decarbonization by 2050, accelerated decarbonization, and accelerated decarbonization with internalization of health damages from power sector emissions. Given rapidly decreasing costs of renewable energy, we anticipate that the power system in China could achieve zero CO_2 emissions by 2050, with a 2% increase in overall system costs and a 43% reduction in cumulative CO_2 emissions, compared to a system without any CO_2 emission constraints. Due to greater climate and public health co-benefits, accelerating decarbonization will result in significant net benefits, which may vary by acceleration pathways. Attaining zero CO_2 emissions in the power sector by 2045 (ZERO45) results in lower cumulative CO_2 emissions compared with limiting emissions from periods 2025 to 2050 to a greater extent (CAP80), but leads to lower net-benefits due to earlier capital investments. By integrating health impacts into capacity expansion decision making, CO_2 emission and health damages can be further reduced by over 50%, lead to net benefits that are projected to far exceed those of decarbonization scenarios that do not consider health impacts of power sector emissions.

Although substantial benefits from decarbonizing the power grid are projected in China, we also observe potential negative health impacts from CCS. All decarbonization scenarios considered result in addition of CCS by 2050, concentrated in locations with limited renewable resources, which can lead to regional increases in health damages. Although internalizing health damages can reduce coal CCS and remove emissions from locations with high damage costs (e.g. Beijing and Shanghai), some regions (e.g. Sichuan) may still be negatively impacted. The health benefits arising from decarbonizing the power grid will not be evenly distributed due to the regional heterogeneity in electricity demand, population density, and meteorological conditions. Although north and central-south China will experience the largest health benefits, they would continue to have comparatively high damages. Internalizing health damages into operational and planning decisions can mitigate negative impacts in these regions. However, damages in regions with lower population density or high electricity demand remain relatively high. For example, Xinjiang and Inner Mongolia would still experience more negative impacts than most regions in 2030. The density of ethnic minority residents in these two regions is also higher. To prevent minority populations suffering disproportionately higher air pollution burdens, distributional health impacts should be considered in decarbonization.

In our modeling framework, we assume a linear relationship between health damages and emissions of SO_2, NO_x, and $PM_{2.5}$ at the provincial level. While not able to fully represent atmospheric chemistry and physics, these relationships capture the spatial distribution of health impacts of emissions. Many studies have quantified health damage costs from emissions in the United States using reduced-form air quality models, including health damages associated with the power sector [43, 57–60]. However, this analysis has rarely been performed in China. To aid in decision-making and policy design, our study uses this approach to demonstrate the value of integrating health impacts into power system operational and planning decisions, offering specific findings related to power sector decarbonization in China, as well as a framework using open access models that allows other researchers to consider tradeoffs in decarbonization.

Real-world capacity changes to the power grid are not solely determined by capacity expansion models. Although capacity additions and retirements are influenced by many factors, such as environmental impacts, job creation, and technology development, overall costs play a vital role in the decision-making process. By combining a capacity expansion model and an air quality model, we capture the potential impacts of various decarbonization strategies. Given the uncertainty inherent in power systems planning, the scenarios developed in this work should not be treated as predictions for the future. What is captured by this analysis is the potential impacts of various decarbonization strategies. For example, decarbonization will reduce coal generation, consequently reducing CO_2 emissions and negative public health impacts. Considering health damages in the capacity expansion decision making processes will not only reduce generation from fossil fuels, but may also shift coal generation to regions with lower population density. Although the magnitude of emission reductions or distributions of health impacts may vary under an uncertain future, this work shows overall trends in this transition. Large uncertainties associated with the capital cost projections propagate to power system projections. These uncertainties may affect the total capacity of renewable energy but will not significantly change coal generation, as most coal-fired power plants are existing or under construction in 2022. As most air pollutant emissions from the power sector are associated with coal combustion, identifying regions that would receive larger health damages can help design regulations to mitigate negative impacts. We also generate multiple suboptimal alternative decarbonization pathways and show that many cost-effective alternative solutions exist and can vary significantly in terms of future installed capacity. These results demonstrate that decarbonization can be achieved through multiple pathways, but benefit greatly from early action.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions statement

Qian Luo: Conceptualization, Methodology, Software, Formal Analysis, Writing- Original draft preparation. Jeremiah X Johnson: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing. Fernando Garcia-Menendez: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing. Jiang Lin: Resources, Methodology, Writing- Reviewing and Editing. Gang

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Conflict of interest

The authors declare no competing interests.

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