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To cite this article: Haozhe Yang *et al* 2024 *Environ. Res.: Energy* **1** 025001

IOP Publishing Environ. Res.: Energy 1 (2024) 025001 https://doi.org/10.1088/2753-3751/ad3bb8

ENVIRONMENTAL RESEARCH
ENERGY

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RECEIVED
14 September 2023

REVISED
1 March 2024

ACCEPTED FOR PUBLICATION
8 April 2024

PUBLISHED
22 April 2024

PAPER

Regional disparities in health and employment outcomes of China's transition to a low-carbon electricity system

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Keywords: electricity, China, coal, renewable energy, health, jobs, air pollution

Supplementary material for this article is available online

Abstract

Understanding the costs and the spatial distribution of health and employment outcomes of low-carbon electricity pathways is critical to enable an equitable transition. We integrate an electricity system planning model (GridPath), a health impact model (InMAP), and a multiregional input–output model to quantify China's provincial-level impacts of electricity system decarbonization on costs, health outcomes, employment, and labor compensation. We find that even without specific CO_2 constraints, declining renewable energy and storage costs enable a 26% decline in CO_2 emissions in 2040 compared to 2020 under the Reference scenario. Compared to the Reference scenario, pursuing 2 °C and 1.5 °C compatible carbon emission targets (85% and 99% decrease in 2040 CO_2 emissions relative to 2020 levels, respectively) reduces air pollution-related premature deaths from electricity generation over 2020–2040 by 51% and 63%, but substantially increases annual average costs per unit of electricity demand in 2040 (21% and 39%, respectively). While the 2 °C pathway leads to a 3% increase in electricity sector-related net labor compensation, the 1.5 °C pathway results in a 19% increase in labor compensation driven by greater renewable energy deployment. Although disparities in health impacts across provinces narrow as fossil fuels phase out, disparities in labor compensation widen with wealthier East Coast provinces gaining the most in labor compensation because of materials and equipment manufacturing, and offshore wind deployment.

1. Introduction

China's electricity sector emitted 4.8 gigatonnes (Gt) of carbon dioxide (CO_2) in 2020, contributing over 40% of China's annual energy-related CO_2 emissions and 13% of global fossil CO_2 emissions [1]. Air pollution from China's predominantly fossil fuel-based power plants also caused 100 000–170 000 premature deaths in 2018 [2, 3]. Decarbonizing China's electricity system is thus critical not only to limit global average temperature increase to 1.5 °C or 2 °C by the end of this century, but also to mitigate health damages caused by air pollution released by power plants. For example, Tong *et al* show mitigating CO_2 emissions in the electricity sector in line with the 1.5 °C climate target avoids about 1.1 million premature deaths caused by air pollution in China over 2010–2050 [3].

At the same time, because China's electricity sector is a major employer, a transition to low-carbon electricity will have a large impact on employment, and labor compensation in the power generation sector [4]. Employment in the electricity sector includes two components—direct jobs hired by the electricity sector and indirect jobs created in the upstream sectors of the electricity sector. The labor compensation measures wages from both the direct and indirect jobs. In 2017, nearly 3 million people were directly employed in the electricity generation sector, and another 3 million were employed in coal mining and gas extraction, two sectors that provide inputs to fossil-fueled electricity production [5]. Phasing out fossil fuels will eliminate some jobs, while investments in new wind, solar, storage, and other infrastructure will create new ones. Previous studies have shown gains in employment from a low-carbon transition in China. To achieve 80% renewable generation, Abhyankar *et al* estimated a 1.9 million increase in job-years cumulative over 2020–2035 [6]. Zhang *et al* estimate a net increase of 1.4 million jobs per year by 2030 and 5.8 million jobs per year by 2050 in the electricity sector for decarbonization pathways compatible with China's carbon neutrality goal by 2060 [7]. Similarly, Pai *et al* projected a 10% increase in energy sector jobs in 2050, compared to 2020, under a climate target below 2 °C [8], and Zhou *et al* predicted an increase of 1.5 million jobs in 2050 compared to 2020 under a 1.5 °C climate target [9].

Health and employment are the two main effects that communities experience in an energy transition and that are not captured by changes in system costs. Often, the distribution of these effects is not equitable across regions and communities. A low-carbon transition will no doubt lead to overall health benefits driven by reduced air pollution from fossil fuel power plants, but the distribution of these benefits will depend on where and when these power plants reduce their generation or completely retire. The distribution of employment effects is less clear as provinces will experience job losses in fossil fuel mining and power generation while gaining employment through clean energy investments, the scale of which will depend on the renewable energy potential and associated manufacturing industries across provinces. Previous studies have highlighted the inequitable distribution of benefits and losses across regions and communities in low-carbon energy transitions [10, 11].

However, few studies have examined the trade-off between the health and employment effects of low-carbon energy transitions across China's regions and provinces [12]. Moreover, while previous studies, highlighted above, have separately quantified the health and employment effects of decarbonization at the national level, they have not examined the distribution of these effects across China's regions and provinces, which is critical to plan a low-carbon transition that is also equitable. Furthermore, spillover effects, where renewable energy installations in one province create jobs in other provinces through interregional trade, have not been considered when measuring employment effects [7, 9]. As China decarbonizes its electricity sector, differences in economic and labor market conditions, fossil fuel and renewable energy resources, and population distribution across regions will likely cause disparate health and employment effects across China's communities. For example, the East Coast region covers a tenth of China's total area, but had 40% of China's population and contributed to 52% of its national gross domestic product (GDP) in 2021. In contrast, the West region occupies over 70% of the total area, but in 2021, was home to only 27% of China's population and contributed 21% of the national GDP [5]. Whereas several of the lower-income provinces in the West region are rich in wind and solar resources, the higher-income provinces in the East Coast region rely heavily on fossil fuel power plants, exposing their communities to local air pollution and its associated health impacts [13, 14].

In this study, we deploy a multi-model framework to develop a current-policy (Reference scenario) and low-carbon transition pathways for China's power system from 2020 to 2040 and compare the cumulative system costs, carbon emissions, and health and labor impacts of those pathways. First, we develop an electricity system planning model [15] (GridPath-China) to identify cost-optimal generation, storage, and transmission investments under various technical, economic, and carbon emission constraints. Second, using the temporally and spatially-explicit power plant generation outputs from the GridPath-China model, we use a reduced-form air pollution transport model (InMap—An Intervention Model for Air Pollution) for China [16] to estimate the distribution of ambient concentration of air pollutants, specifically fine particulate matter ($PM_{2.5}$), and the resulting premature mortality within the population. Third, we incorporate the electricity infrastructure investments and operations projections from the GridPath-China model into a multiregional input–output (MRIO) model to quantify the change in direct and indirect employment and labor compensation induced by the decarbonization of China's electricity system.

We compare three main scenarios: a current-policy (Reference) scenario with no cap on carbon emissions and two low-carbon scenarios with carbon emission caps that are consistent with pathways that limit global temperature rise to 2 °C and 1.5 °C by 2100 [17]. In all scenarios, the generation capacity of coal after 2020 is limited to less than 1100 GW based on the policy to avoid the over-capacity of coal power generation [18]. To disentangle the effects of decarbonization on supply-side investments, pollution, and employment, we assume the same electricity demand across the three main scenarios even though the low-carbon scenarios will likely see a higher demand because of greater electrification of end uses. Investment and operation decisions in all scenarios are made to minimize total system costs over 2020–2040. Using these results, we assess the changes in the distribution of health and labor effects across China's four main economic regions [19]—East Coast, Central, West, and Northeast—and provinces resulting from the pursuit of low-carbon targets. To examine the robustness of our results, we also perform sensitivity tests on electricity demand growth and technology cost projections.

2. Method

2.1. Scenarios

The 'Reference' scenario is a least-cost investment system operations pathway. The Reference scenario has no constraint on CO_2 emissions from China's power system and the electricity demand trend assumes current policies. In the low-carbon scenarios, CO_2 emissions are compatible with the 2 °C and 1.5 °C climate targets, and electricity demand is the same as the Reference scenario. The 2 °C scenario is defined as the scenario where the CO_2 emissions in China's power system and the electricity demand follow the trajectory to limit the global average temperature increase by 2 °C. The 1.5 °C scenario is defined as the scenario where the CO_2 emissions in China's power system and the electricity demand follow the trajectory to limit the global average temperature increase by 1.5 °C.

The annual carbon emission budgets for the three scenarios were compiled from the median projections of 8 Integrated Assessment Models (IAMs) in the CD-LINKS (Linking Climate and Development Policies—Leveraging International Networks and Knowledge Sharing) Database (tables S1–S3) [20, 21]. These IAMs include AIM/CGE 2.1, COPPE-COFFEE 1.0, DNE21+ V.14, GEM-E3 V1, IMAGE 3.0.1, MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 1.7–3.0, and WITCH-GLOBIOM 4.4. In the CD-LINKS database, the NPi, NPi2020_1000 and NPi2020_400 scenarios correspond to the Reference scenario, 2 °C scenario, and 1.5 °C scenario in our study. The NPi scenario includes currently implemented climate policies and assumes the policies continue after the duration of the policy. The NPi2020_1000 assumes a carbon budget of 1000 Gt CO_2 for the period 2011–2100, corresponding to staying below 2 °C at >66% probability through the 21st century. The NPi2020_400 assumes a carbon budget of 400 Gt CO_2 for the period 2011–2100, corresponding to staying below 1.5 °C at >66% probability through the 21st century.

In our main scenarios, we assumed that electricity demand is the same across the Reference, 2 °C, and 1.5 °C scenarios. All scenarios used the median values for electricity demand under the NPi scenario (Reference scenario) across the IAMs. The electricity demand projections from CD-LINKS for all years were multiplied by a constant factor so that the calibrated 2020 electricity demand from IAMs equals the actual 2020 demand (7.6 PWh).

To assess the impact of different demand trajectories under the 2 °C, and 1.5 °C scenarios, we performed sensitivity analyses by designing a demand growth scenario (table S4). In the demand growth scenario, the electricity demand under the 2 °C and 1.5 °C scenarios is the median of the selected IAMs in the NPi2020_1000 and NPi2020_400, respectively.

2.2. Electricity model

We used the GridPath model, an open-source power system model, to optimize the total investment and operation costs of electricity infrastructure (coal, natural gas, nuclear, hydropower, solar, wind, storage and transmission) in China from 2020 to 2040 [15, 22, 23]. We chose 2040 as our end-year because it is near enough to limit uncertainty in technology cost trajectories and far enough to develop meaningful pathways for policy-making. In our GridPath-China model, the 31 provinces in China are classified into 32 load zones, where Inner Mongolia is split into an Eastern Inner Mongolia load zone and a Western Inner Mongolia load zone. We modeled three investment periods—2020 (2020–2025), 2030 (2025–2035) and 2040 (2035–2045). Within each investment period, we modeled one day per month with 24 h to represent each of the 12 months. This representative day has the average hourly load for the month. To ensure reliability during peak load hours, we assumed a planning-reserve margin of 15% of the peak load. Total coal capacity after 2020 is constrained to less than 1100 GW in all scenarios based on National Development and Reform Commission's policy to avoid the over-capacity of coal generation [18]. Carbon capture and storage (CCS) is not allowed in our model. The minimum generation level assumed is 100% of rated capacity for nuclear power plants, 40% for coal power plants and gas turbines, and 45% for combined cycle gas turbines. The hourly ramp rate of the rated capacity is 30% for coal power plants and 60% for gas power plants. An 8% discount factor is used to calculate the net present value of system costs, similar to assumptions in other studies [24].

We collected the latitudes and longitudes for existing coal power plants and their heat rates from Global Energy Monitor, which are critical for the air quality model [25]. Existing generation capacities for all technologies, projected generation capacities for hydropower and nuclear, monthly average capacity factors of hydropower, and provincial-level fuel costs were compiled from the SWITCH-China model [26]. We collected the existing and planned hydropower and pumped hydro capacities larger than 1 GW from Global Energy Monitor [27]. We collected data for existing transmission lines from State Grid [28] and Southern Grid [29]. The derating factors of coal and nuclear capacities are collected from the 2020 Electric Power Yearbook [30]. Hourly load, and projected generation capacity factors for solar, onshore, and offshore wind were collected from Abhyankar *et al* [6]. China-specific costs (2020) of renewable energy are from the International Renewable Energy Agency [31], and costs of battery storage technologies and fossil-fuel technologies were collected from Zhuo *et al* [32] (tables S5 and S6). We then applied normalized cost projection curves from 2020 to 2040, derived from the NREL 2021 Annual Technology Baseline (ATB) database [33] (table S7), to the China-specific technology costs. The projected cost for transmission lines was collected from Grid Project Construction Cost Analysis in the 12th Five-year Period [34].

Scenarios shown in the main text assumed the 'moderate' cost projection scenario from NREL's ATB. In addition, we performed sensitivity analyses assuming two different cost projections (table S8). The low and high-cost scenarios assume the 'advanced' and 'conservative' cost projection trends from the NREL ATB database.

3. Employment and labor compensation

3.1. Direct employment and labor compensation

For each investment period, the direct jobs refer to the employment created by the operation and maintenance (O&M) of the power plants.,

The number of direct jobs for energy technology m (DJ_r^m) was calculated as the product of the total installed capacity for energy technology m in region r (C_r^m) and the employment factor per unit installed capacity (F_m),

$$DJ_r^m = C_r^m \cdot F_m. \tag{1}$$

The direct labor compensation was calculated as the product of direct jobs (DJ_r^m) and wages (w_r^m) for energy technology m and region r,

$$DL_r^m = DJ_r^m \cdot w_r^m. \tag{2}$$

3.2. Indirect employment and labor compensation

The MRIO model was used to calculate changes in indirect employment and associated labor compensation due to decarbonization of the electricity sector.

The basic formula for the MRIO model shows relationship between the total monetary output **X** and the final demand Y,

$$X = (I - A)^{-1} Y \tag{3}$$

where $(I-A)^{-1}$ is the Leontief Inverse Matrix, which captures both direct and indirect inputs to satisfy one unit of final demand in monetary value; **I** is the identity matrix; **A** is the matrix showing the coefficient for intermediate input.

The number of jobs directly hired by region r, industry i ($job_{r,i}$) divided by the monetary output in region r, industry i ($x_{r,i}$) derived the job intensity (job/$) in region r, industry i ($ej_{r,i}$),

$$ej_{r,i} = \frac{job_{r,i}}{x_{r,i}}. \tag{4}$$

The matrix for indirect jobs (IJ) measures the indirect job driven by the final demand,

$$IJ = \mathrm{diag}(ej)(I - A)^{-1} Y \tag{5}$$

where ej is the vector of job intensity ($ej_{r,i}$).

The wage per job in region r, industry i ($wage_{r,i}$) divided by the output in region r industry i was the wage intensity in region r, industry i ($ew_{r,i}$),

$$ew_{r,i} = \frac{wage_{r,i} \cdot job_{r,i}}{x_{r,i}}. \tag{6}$$

The matrix for indirect labor compensation (IL) measures the indirect labor compensation driven by the final demand,

$$IL = \text{diag}\,(ew)\,(I - A)^{-1}Y \tag{7}$$

where ew is the vector of wage intensity ($ew_{r,i}$).

We used the synthetic industry approach [35] to represent the energy technologies (wind, solar, hydropower, coal, natural gas, nuclear, storage and grid) that are not identified as an industry in the input-output table. In the synthetic industry approach, we created a proxy vector of demand for the energy technology m (Y^m), which is a package of goods and services from region s, industry j ($y^m_{s,j}$).

For each investment period, IJ^m and IL^m are vectors showing the number of jobs and labor compensation created by the final demand of the energy technology m,

$$IJ^m = \text{diag}\,(ej)\,(I - A^*)^{-1}Y^m \tag{8}$$

$$IL^m = \text{diag}\,(ew)\,(I - A^*)^{-1}Y^m \tag{9}$$

where A^* is the intermediate input matrix, where the elements are zeros in the columns and rows representing the electricity sector.

The synthetic industries for energy technology are split into two categories: total investment and operation. The total investment quantifies the indirect jobs created by the investment in new capacity, and the operation quantifies the indirect jobs created by the operation of the existing and new capacity.

In region r, the total indirect jobs created by the energy technology m (IJ^m_r) was calculated as the summation of jobs created in region r, industry i, which are driven by investments or operations of technology m in region s, industry j ($IJ^m_{r,i,s,j}$),

$$IJ^m_r = \sum_i \sum_s \sum_j IJ^m_{r,i,s,j}. \tag{10}$$

Similarly, in region r, the indirect labor compensation created by the energy technology m (IL^m_r) was calculated as the summation of labor compensation in region r, industry i created by the investments or operations of energy technology m in region s, industry j ($IL^m_{r,i,s,j}$),

$$IL^m_r = \sum_i \sum_s \sum_j IL^m_{r,i,s,j}. \tag{11}$$

We used the 2017 MRIO table [36]. The final demand in the synthetic industry (i.e. investment and operation costs) was derived from the GridPath model. Data for the demand vector of the goods and services making up the synthetic industries were derived from Garrett-Peltier [35], NREL [37] and Chen [38] (supplementary data S1). Employment and wage data were collected from China Labor Statistical Yearbook [39] and the National Bureau of Statistics [5].

3.3. Total employment and labor compensation

For each energy technology, the total job-years in region r (TJ_r) was calculated as,

$$TJ_r = \sum_t \left(DJ_{r,t} \cdot p_t + IJ^{operation}_{r,t} \cdot p_t + IJ^{investment}_{r,t} \right) \tag{12}$$

where $DJ_{r,t}$ represents the direct jobs in region r over the investment period t, $IJ^{operation}_{r,t}$ represents the indirect jobs created by the operation of capacities in region r over time period t, $IJ^{investment}_{r,t}$ represents the indirect jobs created by the investment of new capacities in region r during period t, and p_t is the years represented by the investment period t in the electricity system planning model. $DJ_{r,t}$ and $IJ^{operation}_{r,t}$ are created in each year over the period t, and hence are multiplied by p_t to estimate total jobs. $IJ^{investment}_{r,t}$ are jobs created through total investments in new capacity during an investment period and thus are not multiplied by p_t.

For each energy technology, the total labor compensation in region r (L_r) was calculated as,

$$L_r = \sum_t \left(DL_{r,t} \cdot p_t + IL^{operation}_{r,t} \cdot p_t + IL^{investment}_{r,t} \right) \tag{13}$$

where $DL_{r,t}$ represents the direct labor compensation in region r over the investment period t, $IL^{operation}_{r,t}$ represents the indirect labor compensation created by the operation of capacities in region r over the investment period t, $IL_{r,t}^{investment}$ represents the indirect labor compensation created by the investment of new capacities in region r during period t.

The data for the employment factor was compiled from prior studies [8, 40]. The average wages of the fossil fuel, nuclear, hydropower, solar, wind, and storage sectors were collected from US Bureau of Labor Statistics [41]. The average wage in China's electricity sector is scaled based on the average wage of the electricity sector in China and the US (tables S9 and S10) [5].

Employment intensities under the Reference scenario in 2040 for each technology are shown in table S11. A comparison of the total employment in our research and other studies is shown in tables S12 and S13, while we assume that the productivity (job/dollar derived from the MRIO and job/MW from O&M) remains constant over 2020–2040.

3.4. Air quality and health benefits

We used InMAP (Intervention Model for Air Pollution), a reduced-form air pollution model, to simulate the $PM_{2.5}$ under the different scenarios [42]. InMAP China has been shown to capture the effect of emissions changes on predicted $PM_{2.5}$ concentrations when compared with a weather forecasting model with a state-of-the-science chemical transport model (i.e. WRF-CMAQ) [16]. We compiled SO_2, NO_x, and $PM_{2.5}$ emissions (table S14) for the electricity sector using the activity (generation) data generated by GridPath, the location of power plants, and emission factors derived from published emission standards (i.e., ultra-low emission standard) [43]. Emission factors are a product of regulated emission intensity (ug m^{-3}) and the emitted volume (m^3 kg^{-1} fuel). Emissions for other sectors and meteorological data were derived from InMAP China [16]. To quantify the impact of electricity generation in China, we first run InMap with emissions from power plants, and then run InMap without the emissions from the power plants. The Cox Proportional Hazards model [44] was used to estimate premature deaths due to $PM_{2.5}$ pollution, and avoided premature deaths are estimated as the difference in premature deaths associated with the simulation with power plant emissions and the one without the power plant emissions.

In each grid cell used by InMap, we first calculated the hazard ratio (HR) when the concentration of $PM_{2.5}$ (μg m^{-3}) is C,

$$HR = e^{\beta C} \tag{14}$$

where β is the parameter in the exposure-response function.

The attributable fraction (AF) measures the premature deaths attributed to $PM_{2.5}$,

$$AF = \frac{HR - 1}{HR}. \tag{15}$$

The mortality attributed to $PM_{2.5}$ (M) was calculated as,

$$M = AF \cdot A \cdot P \tag{16}$$

where A is the age-standardized all-cause mortality rate of the population in China; P is the population.

In each year y, the value of statistical life (V_y) was calculated as,

$$V_y = V_{base} + \left(I_y - I_{base}\right) \cdot MV \tag{17}$$

V_{base} is the baseline value of statistical life in 2020 value ($1.0 million); I_y is the disposable income per capita in year y; I_{base} is the baseline value of the disposable income per capita ($0.006 million); MV is the marginal value of statistical life per capita disposable income (99.8).

The value of premature mortality (VM) was the product of the value of statistical life (V) and the number of premature deaths (M),

$$VM = V \cdot M. \tag{18}$$

The value of the parameter β is based on a long-term cohort study in China, which is age-standardized [45]. The all-cause mortality rate was compiled from Institute for Health Metrics and Evaluation [46]. Population density was compiled from the Center for International Earth Science Information Network [47], and was assumed to follow the population growth trajectory in CD-LINKS. The value of statistical life varies between different studies, which is related to the economic and social status of the surveyed samples. People in countries with higher incomes tend to have a higher value of statistical life. For example, the value of statistical life is higher in the US than China. The US Environmental Protection Agency uses $7.4 million [48], while the US Department of Transportation uses $12.5 million [49]. The value of a statistical life in the base year and the marginal value of a statistical life per disposable income per capita were collected from Tang *et al*, which used local data from China [50]. The trend of disposable income was derived from CD-LINKS. We compare our estimates to those from other studies in table S15.

3.5. Cost of carbon emissions

We used the social cost of carbon (CS_t) to calculate the total cost of carbon (TC_t) associated with the greenhouse gas emissions (GHG_t) in year t as

$$TC_t = GHG_t \cdot CS_t. \tag{19}$$

We used the trajectory of the social cost of carbon under a 3% discount rate, published by the White House [51]. We include only CO_2 emissions in the greenhouse gas emission estimates. The net present value for the total cost of carbon is discounted at a 3% social discount rate.

4. Results

4.1. New capacity investments and energy generation

Under the Reference and both low-carbon scenarios, renewable energy (hydro, wind, and solar) capacity and generation increase their share. Under the Reference scenario, although the total fossil fuel installed capacity in 2040 (∼1700 GW) increases compared to that in 2020 (∼1400 GW), the share of fossil fuels in the total installed capacity decreases from 57% to 32% (figure 1(A)). More importantly, energy generation from fossil fuels decreases by 20% in 2040 compared to 2020, comprising only 35% of total generation (figure 1(B)). Driven by a rapid decline in renewable energy costs, specifically for wind and solar photovoltaic technologies (tables S1–S4), renewable energy capacity in the Reference scenario grows four-fold to 3500 GW, contributing over 50% of the energy generation in 2040.

Under the 2 °C scenario, our results show that in 2040, fossil fuel capacity is reduced by 40% to 1300 GW and its electricity generation decreases by over three quarters to only 8% of the total. The decrease in fossil fuel generation is compensated for by greater renewable energy capacity (∼5200 GW) and generation (87% of the total).

Under the more tightly carbon-constrained 1.5 °C scenario, the total installed capacity increases by 50% in 2040 compared to the Reference scenario. This increase is driven by lower capacity factors of renewable energy compared to fossil fuel power plants, which require more capacity to generate the same amount of electricity. The share of fossil fuel capacity plummets by two-thirds compared to the Reference scenario, whereas renewable energy capacity, predominantly wind and solar, doubles to ∼6400 GW. Balancing the variability in electricity generation from this large increase in wind and solar capacities also requires a significant scale-up of battery storage capacity, an eight-fold or ∼730 GW (4900 GWh of energy capacity) increase compared to the Reference scenario. The total transmission capacity also increases mainly to access geographically diverse renewable resources (figures S1–S3).

At the regional level, fossil fuel capacity declines follow historical patterns of fossil fuel power plant distribution in 2020, whereas increases in renewable energy capacities are driven by resource availability. Under the Reference scenario, fossil fuel capacities are predominantly concentrated in the East Coast and West regions in 2040 (figures 1(C) and (F)), similar to the pattern in 2020 (figures S4 and S5). As expected, these regions experience largest reductions in fossil fuel capacities (figures 1(D)–(F)) under the low-carbon scenarios.

Renewable energy installations, under the Reference scenario, are mainly concentrated in the West Region (1300 GW, 37% of total renewable energy capacity) because of an abundance in solar and wind resources, as well as in the East Coast region (1500 GW, 43% of total renewable energy capacity) driven by offshore wind resources (figures 1(H)–(J)). Under the 2 °C scenario, the increase (1700 GW) in renewable energy capacity is also concentrated in the East Coast and West regions. Under the more stringent 1.5 °C scenario, renewable energy capacity doubles compared to the Reference scenario—1300 GW in the West region, 1000 GW in the East Coast region, and 270 GW in the Northeast region.

A lack of a carbon target in the Reference scenario results in a relatively modest 26% reduction in annual CO_2 emissions in 2040 compared to 2020. However, under the low-carbon scenarios, annual CO_2 emissions in 2040 decrease by 85% (2 °C scenario) and 99% (1.5 °C scenario) relative to 2020 because of the imposition of carbon caps across the planning period.

The regional pattern of renewable energy deployment is similar across electricity demand and technology cost sensitivity scenarios (figures S6–S8). High costs of renewable energy and storage decrease renewable energy capacity and increase fossil fuel capacity under the Reference scenario, but achieve a similar mix in the 2 °C and 1.5 °C scenarios across all cost scenarios because of the need to meet low-carbon targets. Without

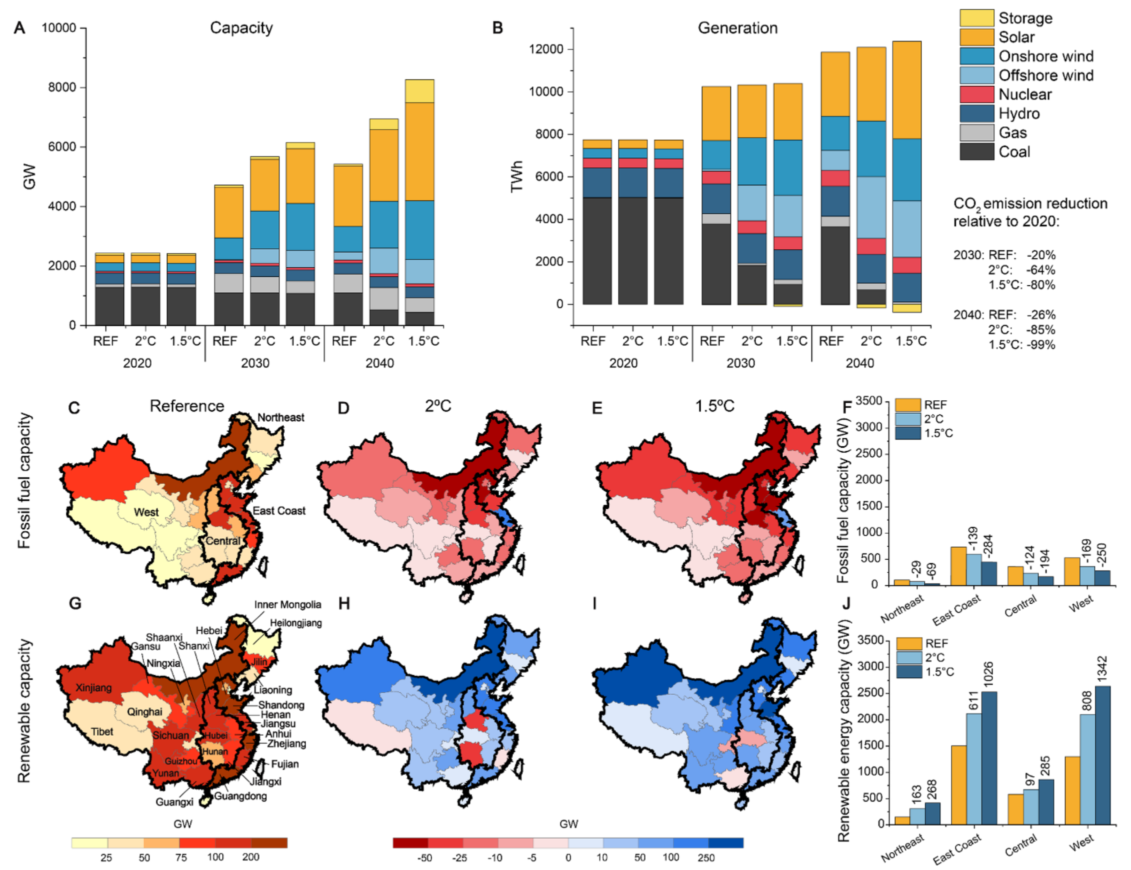

Figure 1. (A) Capacity mix and (B) generation mix of technologies from 2020 to 2040 under the Reference scenario (REF), 2 °C and 1.5 °C scenarios. In 2040, capacities of fossil fuels (coal and natural gas) under the Reference scenario (C) and change in capacities of fossil fuels (D) under the 2 °C scenario and (E) under the 1.5 °C scenario compared to the Reference scenario. In 2040, (F) capacities of fossil fuels under the Reference, 2 °C and 1.5 °C scenarios by region. In 2040, (G) capacities of renewable energy (hydropower, solar and wind) under the Reference scenario, and change in capacities of renewable energy (H) under the 2 °C scenario and (I) under the 1.5 °C scenario compared to the Reference scenario. In 2040, (J) capacities of renewables under the Reference, 2 °C and 1.5 °C scenarios by region. The Reference scenario assumes no carbon emission cap, and the 2 °C and 1.5 °C scenarios are compatible with the 2 °C and 1.5 °C targets proposed by the Paris Agreement.

any constraint on coal generation capacity (figure S6(G)), the share of coal capacity remains at about 50% of the total installed capacity over 2020–2040 under the Reference scenario.

4.2. National-level outcomes of China's energy transition pathways

We estimate cumulative system costs, which include investment, fuel, and operations costs, and carbon emissions from 2020 to 2040 to assess the economic and climate impacts from each scenario. To compare employment and health outcomes across scenarios, we estimate job-years and labor compensation, and premature deaths due to air pollution caused by electricity generation, respectively, across the study period. We present both total cumulative system costs (net present value discounted at a private discount rate of 8% [24]) and annual average costs per unit of electricity generation. We also compare the net present value of total wages, monetized value of avoided premature mortality, and climate damages using a social cost of carbon, all discounted at a social discount rate of 3%.

Cumulative total system costs, including both investment and operations costs, increase slightly across 2020–2040 under the 2 °C scenario and significantly under the 1.5 °C scenario, when compared to the Reference scenario. Under the Reference scenario, the total discounted system cost over 2020–2040 is $6.1 trillion, whereas average costs per unit of electricity demand decrease from $58 per MWh in 2020 to $52 per MWh in 2040 (figures 2(A) and (B)). Under the 2 °C and 1.5 °C scenarios, total discounted system costs over 2020–2040 increase by 8% and 16%, respectively, and annual average costs per unit of electricity demand in 2040 increase by 21% and 39%, respectively, compared to the Reference scenario. This increase in system cost will ultimately lead to higher rates for consumers. Our study is limited to estimating only direct electricity system costs and does not include other costs to the overall economy imposed by higher electricity prices, which could subdue electricity demand and GDP growth.

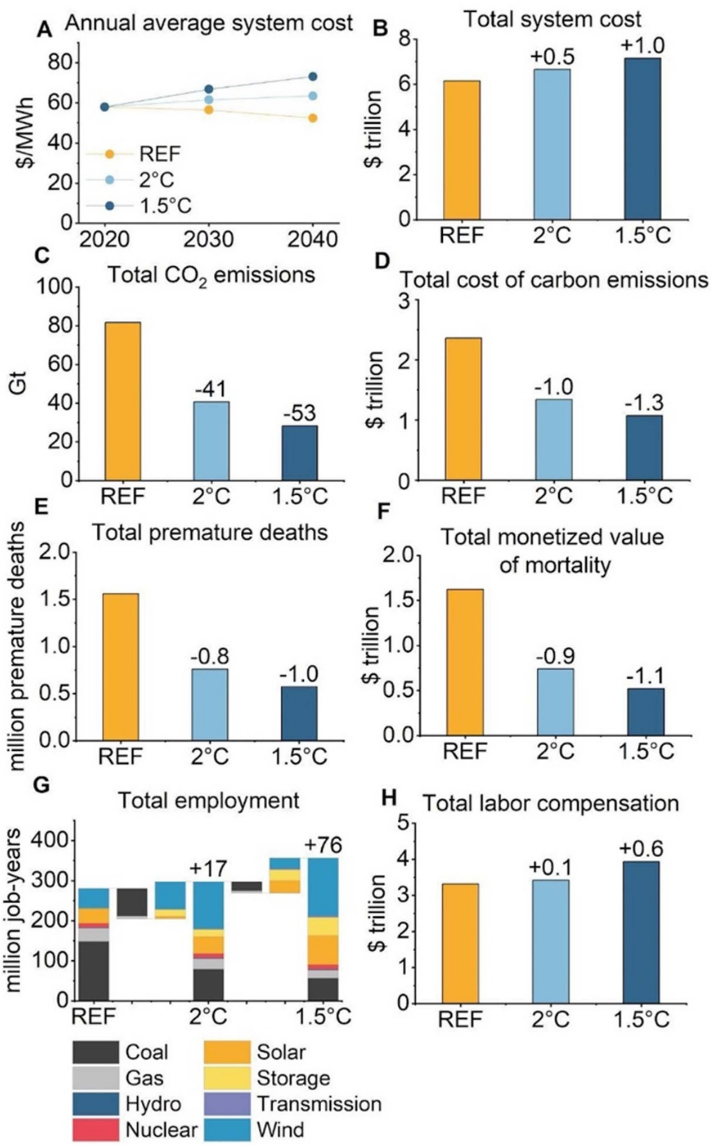

Figure 2. Total impacts from 2020 to 2040 of China's electricity sector under the Reference scenario pathway (REF) and low-carbon scenario pathways compatible with 2 °C and 1.5 °C. (A) Annual average system costs per unit of electricity demand ($/MWh), (B) net present value of cumulative system cost ($ trillion), (C) cumulative CO_2 emissions (Gt), (D) total cost of carbon emissions ($ trillion). (E) Cumulative premature deaths caused by $PM_{2.5}$ pollution from the electricity sector, (F) cumulative monetized value of premature deaths caused by the electricity sector ($ trillion), (G) cumulative employment (job-years) created by each technology/sector including differences in employment between scenarios, (H) cumulative labor compensation ($ trillion). Cost and value estimates are in 2020 USD. The net present value of system costs is calculated assuming a private discount rate of 8%. Net present value of labor compensation, monetized value of premature deaths, and cost of carbon emissions calculated assuming a social discount rate of 3%.

Employment and labor compensation patterns across scenarios are similar to those of the total system costs. Under the 2 °C scenario, 17 million more cumulative electricity sector-related job-years (both direct and indirect jobs) are created from 2020 to 2040 compared to the 280 million job-years created under the Reference scenario (figure 2(G)). The loss of employment due to lower fossil fuel investments and generation is 76 million job-years, whereas the expansion of renewables, storage systems, and electricity grids adds 93 million job-years. Similarly, labor compensation also increases by 3% or $0.1 trillion compared to a total of $3.3 trillion under the Reference scenario (figure 2(H)). Under the 1.5 °C scenario, job gains from greater investment in renewables compensate for job losses from phasing out fossil fuel generation, leading to a net cumulative employment increase (76 million job-years, or 27%) compared to the Reference scenario. Phasing out fossil fuels leads to a reduction of 104 million job-years compared to the Reference scenario, while new jobs created by renewables, storage systems and electricity grids reach 179 million job-years. This net increase in employment raises total labor compensation by 19% or $0.6 trillion. In sensitivity tests, scenarios with higher costs for generation and storage technologies incur higher employment and labor compensation compared to the base low-carbon scenarios (figures S9 and S10). These estimates do not include jobs that are likely to be created for energy efficiency and end-use electrification retrofits, or job losses that may be incurred in fossil fuel transportation and other sectors (e.g. heating) due to greater electrification of end uses.

Air pollution and carbon emissions from fossil fuel generation cause substantial health and climate damages but these damages decrease with increasing levels of decarbonization. From 2020 to 2040, air pollution under the Reference scenario causes 1.6 million premature deaths and result in \$1.6 trillion in health damages, while CO_2 emissions reach 82 Gt and result in climate damages of \$2.4 trillion (figures 2(C)–(F)). Meeting the carbon emissions cap compatible with the 2 °C target avoids 0.8 million (51%) of the premature deaths associated with power plant emissions and 41 Gt (41%) of cumulative CO_2 emissions under the Reference scenario, across 2020–2040 (figures 2(C) and (E)). This reduction in premature deaths and carbon emissions under the 2 °C scenario corresponds to a decrease of \$0.9 trillion in health damages and \$1.0 trillion in climate damages (figure 2(F)). Compared to the Reference scenario, the 1.5 °C scenario avoids 1.0 million air pollution-related premature deaths (63%) and \$1.1 trillion in monetized health damages, while also avoiding 53 Gt of CO_2 emissions or \$1.3 trillion in climate costs (figures 2(C)–(F)).

4.3. Labor compensation gains and losses across regions and provinces

Among the four economic regions, the East Coast region experiences the largest total employment and labor compensation under the Reference scenario. The region accounts for approximately half the total cumulative employment and total labor compensation over 2020–2040 (figures 3(A), (B) and S11). More importantly, per capita employment and labor compensation in the East Coast region are about 20%–50% greater than the other regions (figures S12 and S13).

Under the 2 °C scenario, labor compensation in the Northeast, West, and Central China regions decreases because labor compensation losses from phasing out of fossil fuels are not fully compensated by increases in labor compensation driven by the build-up in renewable energy capacity (figure 3(B)). The GDP per capita in most provinces (19 out of 21) across these three regions is at or below the national average.

However, under a more stringent carbon target in the 1.5 °C scenario, these three regions experience a modest rise in net employment and labor compensation, compared to the Reference scenario Employment and labor compensation driven by new renewable capacity are assumed to be proportional to the investments in renewable energy. A more stringent carbon target requires greater investments in renewable energy, which results in greater employment and labor compensation gains compared to losses due to fossil fuel infrastructure phaseouts. This effect is most pronounced in the West region, which has abundant renewable resources (figure 3(E)), where the number of jobs and labor compensation decreases by 0.5% and 10% under the 2 °C scenario, respectively, but increases by 9% and 4% in the 1.5 °C scenario compared to the Reference scenario. This increase is mainly driven by renewable energy installations in Inner Mongolia, which contribute about 20% of the growth in jobs and 40% of the growth in labor compensation in the region.

For the East Coast region, net employment and labor compensation increase in both low-carbon scenarios, thus increasing the gap in employment between regions (figure 3(B), job and wage per capita shown in figures S12 and S13). Two reasons account for this increase. First, the East Coast region has mature manufacturing industries, and thus more indirect jobs are created in the manufacturing sector (figure 3(F)). Second, by harnessing the high-quality offshore wind resources in the region, the East Coast region installs ∼2100 GW of renewable energy capacity in the 2 °C scenario and ∼2400 GW in the 1.5 °C scenario by 2040, which accounts for ∼40% of the total installed renewable energy capacity in each scenario. Under the 2 °C scenario, the East Coast region experiences an increase of 18% in employment and 8% in labor compensation. This rise is greater under the 1.5 °C scenario, with job increases of 34% and labor compensation increases of 28% (figure 3(B)).

Although the 1.5 °C low carbon scenario improves labor market outcomes in the majority of China's provinces compared to the Reference scenario, several provinces are still expected to experience employment losses due to their reliance on fossil fuel generation and mining, and a lack of high-quality renewable resources (figures 3(C) and (D)). Shanxi province in the Central region, the largest supplier of coal (∼30%) in China [52], loses nearly 10 million job-years (−36%) and \$98 billion of labor compensation (−35%) under the 1.5 °C scenario. Shaanxi province, the third largest coal supplier in China (∼15%), also loses jobs and labor compensation under both low-carbon scenarios. Similarly, Shandong province in the East Coast region relies heavily on fossil fuels and the growth in renewable energy capacity under the low-carbon scenarios fails to negate the compensation losses in the fossil fuel industries. Other provinces, including Ningxia, Gansu, and Hubei, also lose jobs under both low-carbon scenarios. We found that the renewable resources in Ningxia and Gansu, though abundant, are mainly used to meet demand within the province. Inner Mongolia and Xinjiang are the major net exporters of electricity in the Northwest. As electricity demand and exports are both low in Gansu and Ningxia (figure S14), the low-carbon transition does not

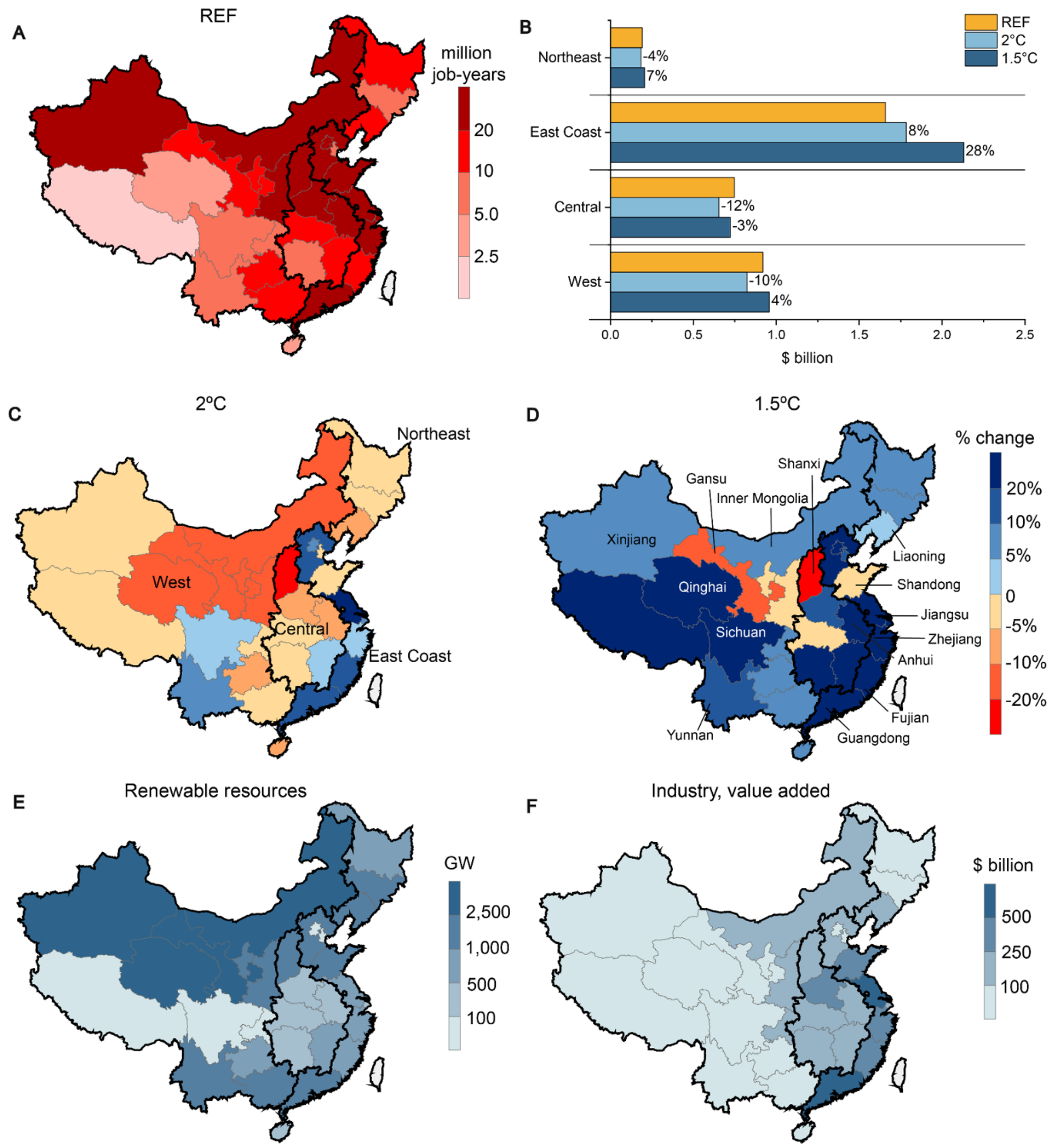

Figure 3. (A) Cumulative electricity sector-related labor compensation across 2020–2040 under the Reference scenario (REF). (B) Cumulative labor compensation ($ billion) under the Reference, 2 °C and 1.5 °C scenarios in the four economic regions (numbers indicate the relative change from the Reference scenario). Change in cumulative labor compensation (%) under the (C) 2 °C scenario and (D) 1.5 °C scenario, relative to the Reference scenario. (E) Renewable energy resources (GW) by province. (F) Industrial value added in 2022 ($ billion) in China [5].

lead to a loss in employment and labor compensation. These results show that the labor market implications of decarbonizing the electricity sector can vary greatly across regions.

4.4. Health benefits from electricity sector decarbonization across regions and provinces

To assess the health effects of decarbonization pathways, we estimate exposure to air pollution, specifically $PM_{2.5}$, from coal and gas-fired power plants and its impacts on premature mortality at a spatial resolution of 36 km. We present results aggregated at the province level in the main text (figure 4).

As China's electricity sector decarbonizes from 2020 to 2040 in the Reference scenario, annual health impacts due to air pollution caused by the electricity sector decrease across regions but historical inter-regional inequities persist. Annual premature mortality in 2040 drops by 50%–60% compared to 2020 across all regions, with the East Coast and Central regions being the largest beneficiaries (figure S15). Because of their continued reliance on fossil fuel generation under the Reference scenario and their higher population density, the East Coast and Central regions experience the largest cumulative premature deaths due to air pollution from electricity generation across our planning horizon—0.7 million (45% of the total

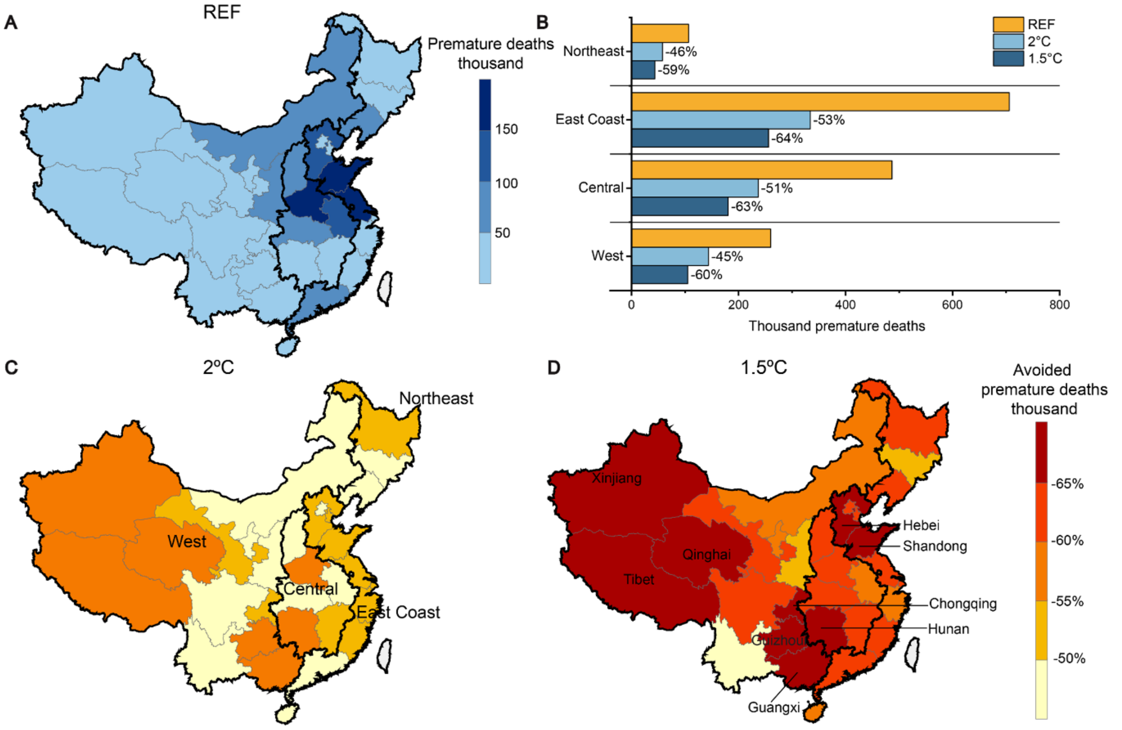

Figure 4. (A) Cumulative premature deaths caused by air pollution from the electricity sector across 2020–2040 under the Reference scenario (REF). (B) Cumulative premature deaths during 2020–2040 under the reference, 2 °C, and 1.5 °C scenarios in the four economic regions (numbers indicate the change from the Reference scenario). Avoided premature deaths under (C) the 2 °C scenario and (D) the 1.5 °C scenario, relative to the Reference scenario.

premature deaths) and 0.5 million (31% of the total premature deaths), respectively (figures 4(A) and (B)). Cumulative premature deaths per capita are also highest in these regions (figure S16).

Under the low carbon scenarios, regions with the largest health burden under the Reference scenario also account for the largest shares of health benefits attained by the reduction in air pollution from electricity generation (figure 4(B)). Under the 2 °C and 1.5 °C scenarios, the East Coast and Central regions together experience the largest share (∼75%) of the total reduction in cumulative premature deaths across 2020–2040 (figure 4(B)). Under the 2 °C scenario, 0.37 million cumulative premature deaths (47% of total reduction) are reduced in the East Coast region, followed by 0.25 million (32% of total reduction) in the Central region. Premature deaths are further reduced under the 1.5 °C scenario, with 0.45 million (46% of total reduction) in the East Coast region and 0.31 million (31% of total reduction), relative to the Reference scenario. At the province level, Shandong and Jiangsu in the East Coast region and Henan in the Central region experience the largest cumulative premature mortalities caused by air pollution from fossil fuel generation over 2020–2040 in the Reference scenario, but also experience large gains in avoided premature mortalities in the low-carbon scenarios (figures 4(C), (D) and S17). The relative reduction in premature deaths in the low-carbon scenarios is also large in West and Northeast regions, but the absolute reduction is much lower, because these regions have historically been less impacted by air pollution from electricity generation.

4.5. Potential trade-offs between employment effects and health benefits

Compared to the Reference scenario, all provinces gain health benefits due to the phase-down of fossil fuel power plants under the low-carbon scenarios. However, we found that provinces, especially those with low GDP per capita, are more likely to experience a trade-off between health benefits and labor compensation losses because these provinces lose jobs related to the coal industry (figure 5(A)). On average, high-income provinces experience benefits in both health and labor compensation under the low-carbon scenarios, while upper- and lower-middle-income groups lose labor compensation under the 2 °C scenario and gain labor compensation under the 1.5 °C scenario. Average labor compensation in the low-income provinces decreases under the 1.5 °C scenario, mainly driven by the coal-producing Shanxi province.

At the provincial level, while all provinces experience health benefits, the employment and labor compensation outcomes have mixed results. Nearly all high-income provinces experience gains in both health benefits and labor compensation. Beijing, Shanghai, Jiangsu, Guangdong, Fujian and Zhejiang, experience an increase in labor compensation and a decrease in premature deaths under both the 2 °C and

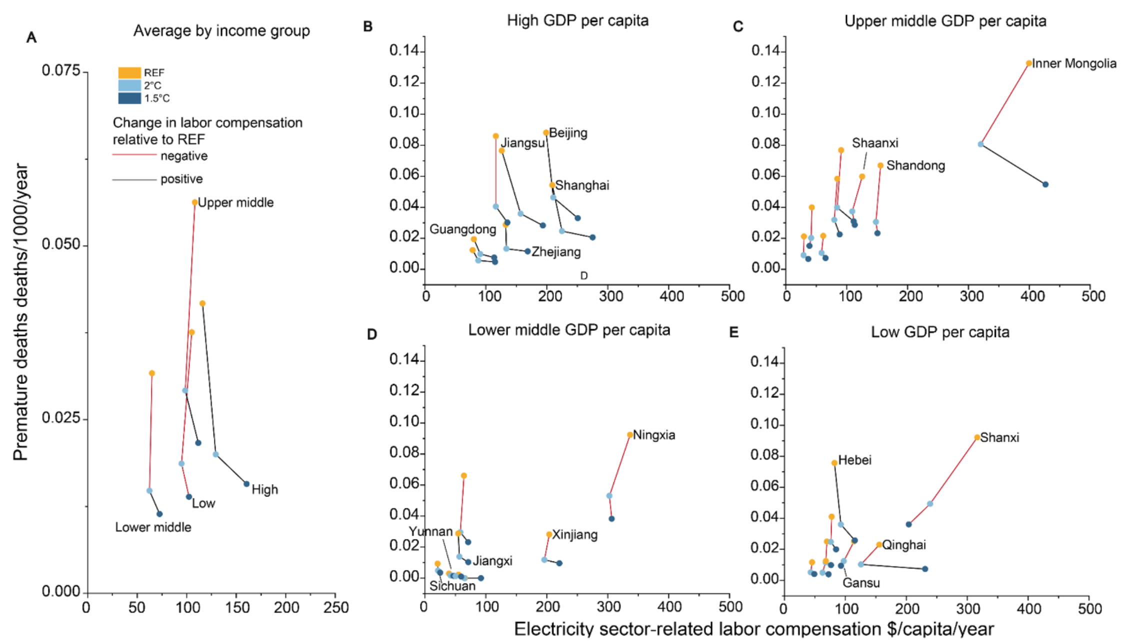

Figure 5. (A) Average premature deaths (deaths per 1000 per year) and electric sector-related labor compensation ($/capita/year) under the reference, 2 °C and 1.5 °C scenarios by income group. Premature deaths and labor compensation under the reference, 2 °C and 1.5 °C scenarios in (B) high-income, (C) upper-middle-income, (D) lower-middle-income and (E) low-income provinces. The income level is classified based on the four quantiles of the provincial GDP per capita in year 2020. The red lines represent a decrease in labor compensation compared to the Reference scenario.

1.5 °C scenarios relative to the Reference scenario (figure 5(B)). In contrast, only a few provinces in the lower-middle-income and low-income groups—Jiangxi, Hebei, Yunnan and Sichuan—experience an increase in labor compensation and a decrease in premature deaths under both the 2 °C and 1.5 °C scenarios. Nine out of the 16 lower-middle and low-income provinces experience labor compensation loss while avoiding premature deaths in health outcomes in the 2 °C scenario compared to the Reference scenario. Six provinces experience a decrease in labor compensation while avoiding premature deaths under both 2 °C and 1.5 °C scenarios—Shanxi, Ningxia, Gansu, Shaanxi, Hubei, and Shandong. Five out of these six provinces are major coal producers and the first three are from the low-income and lower-middle-income groups. These three provinces account for almost one-third of China's coal production and 10% of coal generation capacity. Phasing out coal power plant capacity and energy generation reduces premature deaths, but also results in unemployment and reduced labor compensation in these provinces. Decreases in labor compensation, especially in provinces with lower GDP per capita highlight the need to create new employment opportunities in coal-producing provinces, which will be critical for equitable development as coal infrastructure retires and coal-dependent jobs are lost.

To understand the temporal trends in employment impacts, we examined how the regional disparities in employment and avoided premature deaths evolve with a finer 5 year investment period (figure S18). Compared to the Reference scenario, in the low-carbon scenarios, while health benefits accrue across all regions in each investment period, the East region begins experiencing larger gains in employment right from 2025 compared to the other regions. Furthermore, the 2 °C scenario creates fewer jobs in the three regions—West, Central, and Northeast—from 2035 onwards compared to reference. However, in the 1.5 °C scenario, health benefits and employment gains occur in all investment periods across all provinces, except for a dip in employment in 2035 in the West and Central regions.

5. Discussion

China has pledged to reach peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060. In its Nationally Determined Contribution (NDC), China also committed to installing at least 1200 GW of wind and solar capacity by 2030, more than doubling its 2020 capacity [53]. Our results show that even without imposing a carbon emissions target, under the cost-optimal Reference scenario, total wind and solar capacity in 2030 is more than double the NDC commitment and annual carbon emissions in 2030 decrease by 20% compared to 2020. More importantly, achieving a carbon emissions goal compatible with the 2 °C warming target (85% lower in 2040 compared to 2020) has slightly higher total system costs than the Reference scenario. Further, the 2 °C pathway results in an increase in the number of job-years and labor compensation, and large benefits in terms of avoided health and climate damages. Achieving an even more ambitious low-carbon pathway compatible with a 1.5 °C target (99% lower in 2040 compared to 2020) costs significantly more, but also results in larger increases in labor compensation, health benefits, and avoided climate damages.

Our results for wind and solar installed capacities are similar to studies that assumed recent cost projections for these technologies [26], but they are greater than others that imposed limitations on the growth of manufacturing capacities [32]. Compared to the employment effects in our study, the estimate from Zhang *et al* [7] is 40% lower than ours due to the omission of the indirect employment impacts from a life-cycle perspective (table S10), and the estimate from Zhou *et al* [9] is 60% lower than ours due to the omission of the private sector employment (table S11). Similarly, our estimates of premature deaths in 2020 under the Reference scenario are lower than those of other studies because of higher shares of clean energy in 2020 and our assumption that the emission standards have perfect compliance (table S17) [3].

5.1. Low-carbon pathways bring significant health benefits beyond already implemented low sulfur regulations

Although China has made large strides in limiting the sulfur emissions from its coal power plants through the enforcement of ultra-low sulfur standards [43], further phasing out fossil fuel generation in line with 2 °C and 1.5 °C targets can lead to significant health benefits—0.8 million and 1.0 million avoided deaths, respectively, over 2020–2040. Under both the low-carbon scenarios, about 80% of the reduction in cumulative premature deaths occurs in provinces of the East Coast and Central regions, which have historically disproportionately borne the pollution burden from fossil fuel generation.

Our study only considers the direct air pollutant emission from power plants and has not calculated the air pollutant emissions from a life-cycle perspective from the transportation and industrial sectors. This omission may underestimate the health benefits because the life-cycle particulate matter emissions from wind and PV are substantially lower than coal and natural gas generation [54]. Further, we only quantified the impacts of $PM_{2.5}$ on premature mortality. Accounting for additional health end-points (e.g. impacts on chronic respiratory disease) and other air pollutants released by power plants (e.g. NO_x and ambient ozone) would increase the health benefits attributable to the decarbonization of the electricity sector. Overall, we find that health benefits are likely to be higher in low-carbon scenarios, especially in the 1.5 °C scenario, which assumes greater electrification of end-uses.

5.2. Net gains and losses in employment driven by fossil fuel phaseout, renewable resource endowments, and manufacturing

Decarbonization of China's electricity system is expected to exert distinct impacts on employment across provinces. Although total employment and labor compensation at the national level increases under the 2 °C compatible carbon emissions target, most provinces in the West, Central and Northeast regions, which account for 80% of the jobs in the coal mining sector, experience a net loss in employment and labor compensation compared to the Reference scenario. In other words, the growth in renewable capacities in these regions is not enough to balance the loss in employment and labor compensation in the fossil fuel sector (figure S19). In contrast to the provinces in the West, Central, and Northeast regions, most of which have a low GDP per capita, East Coast provinces (e.g. Jiangsu, Guangdong, and Zhejiang) with high GDP per capita experience a net gain in employment and labor compensation. This gain is driven by the development of offshore wind in the region, spillover effects of employment through renewable energy development in other regions, and a relatively low loss of employment in the fossil fuel sector because of the region's small share of coal mining jobs (7% excluding Shandong).

Under the more stringent 1.5 °C compatible carbon emissions target, most provinces gain employment due to the expansion of renewable energy capacity. However, in Shanxi, Shandong, Hubei, Gansu, Ningxia and Shaanxi provinces, jobs and labor compensation decrease due to a phase-out of their large existing capacity of fossil fuel generation and mining or a relatively poor quality of renewable resources.

Creating employment opportunities in low-income provinces is important for a low-carbon energy transition to be equitable and inclusive. Our results show an increasing gap in employment impacts between the high-income East Coast region and other regions with more stringent decarbonization targets. Net gains in employment and labor compensation are greater in the East Coast region than all other regions, partly because the East Coast region absorbs ∼20%–30% of the jobs created by energy infrastructure development in other regions driven by spillover effects (figure S20). The West region, even with its greater development of solar and wind resources, creates only half of the resulting cumulative job increases locally because of its reliance on material and manufactured goods imports from the East Coast region (figure S20). In addition to its highly developed manufacturing industry, the East Coast region's development of large-scale offshore wind capacities, higher investment costs of which create more indirect jobs than onshore wind, exacerbates regional disparities in employment.

In the provinces that experience job losses and reduced labor compensation under the low-carbon scenarios, installing CCS could extend some level of coal generation while meeting emissions targets and thus avoid large employment losses (figure S20). We observe an increase in employment and labor compensation in most provinces to achieve low-carbon targets. Shanxi and Hubei provinces still experience a reduction in employment and labor compensation because CCS cannot reduce all carbon emissions to zero and some coal capacity is retired to meet carbon targets, but the relative decrease in employment is much more modest compared to the scenario without CCS. As coal and gas capacities with CCS continue to operate, provinces, especially in the West region, see fewer investments in renewable energy and thus a smaller increase in employment and labor compensation compared to the scenario without CCS. We do not estimate health benefits of CCS scenarios because of significant uncertainties in emissions of criteria pollutants from power plants with CCS but expect that overall health benefits of the low-carbon scenarios will be reduced because of greater coal capacity and energy generation with CCS systems.

5.3. Policy and program interventions needed to ensure an equitable low-carbon transition

Our results show that the low-carbon transition in China's electricity sector will likely yield uneven employment outcomes across low- and high-income provinces. In the absence of policy interventions, some low-income provinces, especially those that have historically relied on fossil fuel extraction such as Shaanxi, are likely to experience significant employment losses but relatively modest health benefits, deepening regional disparities in economic development. While new employment opportunities will mostly arise in regions with high-quality wind and solar energy resources, materials and manufacturing industries that support the low-carbon transition could be encouraged in lower-income regions and provinces which have especially relied heavily on coal mining. Toward this goal, in its 14th Five-Year Plan, China pledges to reduce the regional disparity by incentivizing the transfer of job opportunities from the wealthier East Coast region to the West, Central and Northeast regions [55]. China has already announced a few regional development plans—China Western Development Plan, Northeast Area Revitalization Plan and Rise of Central China Plan—that encourage the transfer of manufacturing industries from the East Coast region to the Central, West and Northeast regions, and further develop renewable energy resources in the West region. Such programs have contributed to narrowing the gap in employment opportunities; however, their actual effects deserve further research. Targeted social assistance, financial transfers, and revenue sharing for renewable development in low-income regions could facilitate a just transition. For example, first, the central government could strengthen the social safety net to ease the burden of the transition for affected coal workers. Currently, these programs are run at the provincial level. Nationalizing these programs would provide more stability for workers in the most vulnerable regions and sectors. Second, carbon tax and dividend payments could be used to collect necessary revenue to pay for assistance programs during the transition. Third, local and provincial governments in fossil fuel-dependent regions could create opportunities to address environmental damages from coal mining and ecosystem restorations, which in turn could provide stimulus to local economic revitalization. More studies, especially at the sub-provincial level and across multiple dimensions in addition to GDP disparities, will be needed to better understand and plan for the impacts of the low-carbon energy transition in China.

Data availability statements

GridPath model code is available at https://github.com/blue-marble/gridpath. The code for the paper is available at https://github.com/cetlab-ucsb/China-low-carbon. The data are available at https://zenodo.org/records/10873443.

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

Acknowledgments

We acknowledge the Chancellor's Fellowship from the University of California, Santa Barbara. Use was made of computational facilities purchased with funds from the National Science Foundation (CNS-1725797) and administered by the Center for Scientific Computing (CSC). The CSC is supported by the California NanoSystems Institute and the Materials Research Science and Engineering Center (MRSEC; NSF DMR 1720256) at UC Santa Barbara.

Author contributions

H Y, J L, and R D conceptualized the study. H Y, O D, A M, and R D developed the methodology and software. H Y, Q L, and R D conducted the formal analysis. H Y and Q L curated the data. H Y, Q L, G H, J L, J X J, F G M, O D, A M and R D wrote and edited the paper. R D supervised the project.

Conflict of interest

None.

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