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Climate, air quality and human health benefits of various solar photovoltaic deployment scenarios in China in 2030

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Abstract

Solar photovoltaic (PV) electricity generation can greatly reduce both air pollutant and greenhouse gas emissions compared to fossil fuel electricity generation. The Chinese government plans to greatly scale up solar PV installation between now and 2030. However, different PV development pathways will influence the range of air quality and climate benefits. Benefits depend on how much electricity generated from PV is integrated into power grids and the type of power plant displaced. Using a coal-intensive power sector projection as the base case, we estimate the climate, air quality, and related human health benefits of various 2030 PV deployment scenarios. We use the 2030 government goal of 400 GW installed capacity but vary the location of PV installation and the extent of inter-provincial PV electricity transmission. We find that deploying distributed PV in the east with inter-provincial transmission maximizes potential CO_2 reductions and air quality-related health benefits (4.2% and 1.2% decrease in national total CO_2 emissions and air pollution-related premature deaths compared to the base case, respectively). Deployment in the east with inter-provincial transmission results in the largest benefits because it maximizes displacement of the dirtiest coal-fired power plants and minimizes PV curtailment, which is more likely to occur without inter-provincial transmission. We further find that the maximum co-benefits achieved with deploying PV in the east and enabling inter-provincial transmission are robust under various maximum PV penetration levels in both provincial and regional grids. We find large potential benefits of policies that encourage distributed PV deployment and facilitate inter-provincial PV electricity transmission in China.

1. Introduction

Solar photovoltaic (PV) electricity generation is a promising technology for tackling both greenhouse gas (GHG) mitigation and regional air pollution in China. In 2013, electricity generation in China contributed 53% of total CO_2 emissions [1], and was responsible for 86 500 annual premature deaths related to $PM_{2.5}$ exposure (~10% of the total premature deaths related to $PM_{2.5}$ exposure) [2]. Under pressure from recent severe air pollution and fulfilling China's pledge at the Paris Climate Conference to produce 20% of primary energy from non-fossil sources in 2030 [3], the Chinese government has prioritized the development of renewable energy, such as wind and solar electricity generation. As a result, China has experienced dramatic growth in PV installation and now has the largest installed PV capacity in the world (130 GW at the end of 2017) according to China's National Energy Administration (NEA) [4]. China's 2020 solar PV development target has increased several times from 50 GW in 2012 [5] to 110 GW in 2016 (which China has already surpassed) [6], reflecting rapidly increasing installation. In a recent report by the China National Renewable Energy Center, Chinese solar PV installed capacity is projected to reach 400 GW in 2030 [7], an increase of more than three times from current levels and a level they may exceed.

The projected 2030 installed electricity generation capacity in China is projected to be between 2500 and 2800 GW of which PV capacity, meeting current targets, could represent 14%–16% [8]. If current targets are exceeded, the percentage could increase.

To achieve the installed capacity target, various solar PV development strategies are being considered. Discussions primarily focus on deployment location and ways to utilize PV electricity. Current deployment strategies prioritize utility-scale PV installations that are overwhelmingly located in China's northwestern provinces where solar radiation is most abundant. In addition to the advantage in solar resources, utility-scale PV also has lower installation costs than distributed PV because of larger system size than distributed PV and enjoys economies of scale in installation. According to the Roadmap for China's Photovoltaic Industry Development published by China's Ministry of Industry and Information Technology in 2016, the average installation cost of utility-scale PV plants in China was 7.3 RMB/W (∼$1.1/W) in 2016 [9]. Average installation costs of distributed PV systems, on the other hand, were in the range of 9–10 RMB/W (∼$1.3–1.4/W) in 2016, according to a survey of various installers and market participants [10]. However, several concerns arise with developing utility-scale PV, such as inadequate open space for utility-scale PV plants in the east and limited interconnection capacity to connect utility scale PV plants in the northwest to demand centers in the east. To address these concerns, the government has started to encourage more deployment of distributed PV in its eastern provinces where more commercial and industrial buildings exist making rooftops more abundant. China's 12th Five-Year Plan (2010–2015) included both 10 GW utility-scale and 10 GW distributed PV installed by 2015 [5]. In reality, while the total installed capacity of utility-scale PV (37 GW) nearly quadrupled the 2015 target, installed capacity of distributed PV (6.06 GW) was about half the 2015 target [11]. This trend continued in 2016, with 30 GW utility-scale and only 4 GW distributed PV installed [12].

China's current PV utilization strategy emphasizes local consumption, which means PV electricity is used within the province where it is generated. Utilization within broader regions is restricted by insufficient transmission capacity and limited incentives to promote power exchange and transmission [13–15]. The rapid development of utility-scale PV in the northwest and the focus on local consumption have led to significant grid integration constraints. In two of the five northwestern provinces, Gansu and Xinjiang, PV penetration rates in 2015 were 8% and 5.4%; however more than 30% of the electricity generated from PV there was curtailed in 2015 and 2016 [11, 16]. Previous studies have demonstrated that inadequate transmission capacity in China limits the ability of provinces to export excess wind and solar generation, and results in wind and solar-generated electricity being curtailed in Northwestern and Northeastern China where wind and solar resources are abundant [15, 17]. Continuing the current utility-scale deployment and utilization strategies in the future, if a major upgrade of the current power grid does not occur, would likely lead to more curtailment of PV electricity generation in western China due to lack of demand.

There are several studies evaluating the environmental benefits of solar PV in both China [18–20] and other parts of the world [21–24]. However, there is limited analysis to date on the air quality and carbon emission impacts of various future solar PV deployment and utilization strategies. Variations in PV electricity generation and utilization by location, and variations in the air pollutant emissions from the power plants being displaced, lead to differences in air quality and climate co-benefits of PV deployment.

For the first time, we conduct an integrated assessment that quantifies and compares the climate, air quality, and related human health benefits of various solar PV deployment and utilization scenarios for 2030 China. We use a 2030 coal-intensive power sector projection developed by the International Institute for Applied System Analysis (IIASA) as the base case [25]. The base case assumes implementation of China's 12th Five-year Plan (FYP) through 2015 with no additional new air pollution or climate mitigation policies [25]. The FYP is the Chinese government's overall strategy to address economic, social and environmental challenges. The 12th FYP includes energy intensity standards, as well as NO_x and SO_2 emission reduction targets, but does not have any specific renewable energy requirements [26]. Thus our 2030 base case is relatively conservative since both China's updated 13th FYP (2016–2020) [27] and China's Nationally Determined Contributions to the Paris Agreement [3] have led to additional policies supporting renewable energy development and a cap on total coal consumption. Starting from this base case, we construct four scenarios all implementing the current government goal of 400 GW PV installed capacity in 2030 (table 1). In the first scenario (*Skewed_Provincial*), we apply the 2015 6:1 utility-scale to distributed PV installed capacity ratio to China's 2030 PV deployment and only allow PV electricity to be used within the province where it is generated. In the following two scenarios, we change either the deployment to reach equal installation of utility-scale and distributed PV in 2030 (*Balanced_Provincial*) or the utilization strategy to enable inter-provincial PV electricity transmission within China's regional power grids (*Skewed_Regional*, see figure S1 for China's regional power grids). We include both changes in the deployment and utilization strategies in the last scenario (*Balanced_Regional*), which has equal installation of utility-scale and distributed PV as well as inter-provincial electricity transmission for PV electricity in 2030.

Table 1. Description of PV deployment and utilization scenarios (all scenarios assume achievement of the government goal of 400 GW national PV installed capacity in 2030).

Scenario	Deployment	Utilization
Skewed_Provincial	*Skewed*: 2015 utility-scale vs. distributed ratio (6:1) maintained	*Provincial*: PV electricity used within the generating province
Balanced_Provincial	*Balanced*: Equal installation of utility-scale and distributed PV	*Provincial*: PV electricity used within the generating province
Skewed_Regional	*Skewed*: 2015 utility-scale vs. distributed ratio (6:1) maintained	*Regional*: Inter-provincial PV electricity transmission allowed within regional grid
Balanced_Regional	*Balanced*: Equal installation of utility-scale and distributed PV	*Regional*: Inter-provincial PV electricity transmission allowed within regional grid

We compare CO_2 reductions, $PM_{2.5}$ mitigation and related human health benefits of the four scenarios resulting from displacing coal-fired power plants relative to the base case in 2030. We use the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) [28] that fully considers the impacts of regional transport and detailed chemistry of air pollutants to simulate the changes in $PM_{2.5}$ concentrations due to air pollutant emission reductions. The air pollution-related health impacts are calculated based on the integrated exposure response functions developed by the Global Burden of Disease study [29].

2. Materials and methods

2.1. Scenario design and PV electricity generation

Our four PV deployment scenarios have 400 GW national total PV installed capacity in 2030, as planned for 2030 solar PV deployment in the *China Renewable Energy Roadmap 2050* [7]. In the *Skewed* scenarios, we assumed that distributed PV is 1/6 and utility scale is 5/6 of the national 2030 400 GW PV target. Thus a total of 66.7 GW of distributed PV and 333.3 GW of utility-scale PV are projected for 2030. In the Balanced scenarios, both distributed and utility-scale each 200 GW in 2030. For the distribution within each province and across China we assume a proportional increase from 2015 installed capacity for both distributed and utility-scale PV to achieve a total of 400 GW PV in 2030 (figure 1). Capacity factors for both types of PV for each province are calculated using satellite-derived surface irradiance data and the PVLIB-Python model (see section 2 of the online supplementary information for details of calculating the capacity factors, available at stacks.iop.org/ERL/13/064002/mmedia) [30]. We assume utility-scale PV plants are equipped with one-axis tracking PV arrays facing south, while distributed PV systems have panels with fixed angles determined by latitude to maximize incident radiation. This is justified because most distributed PV in China is installed on flat industrial rooftops where optimal angle of installation is feasible. We apply capacity factors and variations in monthly average solar radiation to calculate annual and monthly electricity generation from utility-scale and distributed PV in each province. To address the grid-integration constraints due to intermittency of solar PV and guarantee reliable operation of the grid, we allow a maximum of 30% solar PV electricity generation in each province in the scenarios without inter-provincial transmission. We define PV electricity generation below the 30% cap as grid-integrated PV electricity; any PV electricity that exceeds the 30% cap is curtailed. The 30% penetration cap is derived from studies indicating that this level of renewable electricity generation is feasible without incurring grid instability in the absence of significant balancing measures [31, 32]. In the *Regional* scenarios (which include inter-provincial transmission), we assume this 30% cap applies to each regional grid rather than to each province. Enabling inter-provincial electricity transmission smooths the variability of daytime PV power output and thus allows more PV generation by expanding power balancing areas. We do not permit additional exchange between the various regional electricity grids beyond the power exchange assumed in the base case scenario because inter-regional transmission capacity is quite small compared with the power demand within each regional grid in China [25]. We also conduct sensitivity analyses of the impacts on air quality and health benefits of PV under various PV grid-integration assumptions (e.g. from 5%–100% penetration).

2.2. CO_2 and air pollutant emission reductions

We use a provincial-level coal-intensive emission scenario from the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants project (ECLIPSE_v5a_CLE) developed by the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model at IIASA as the base case for 2030 [25]. We assume PV electricity is only used to displace coal-fired power plants in China and calculate decreases in electricity production from coal-fired power plants in each PV deployment scenario. This is justified by the Chinese government's commitment to reducing air pollutant emissions and increasing power generation efficiencies of coal-fired power plants. In fact, China's current equal-share electricity dispatch system guarantees each thermal power plant a specific number of operating hours per year. This limits the incentive for a coal plant to adjust its output to facilitate more variable renewable energy integration and can lead to curtailment of renewable energy when demand is low despite the fact that the renewable

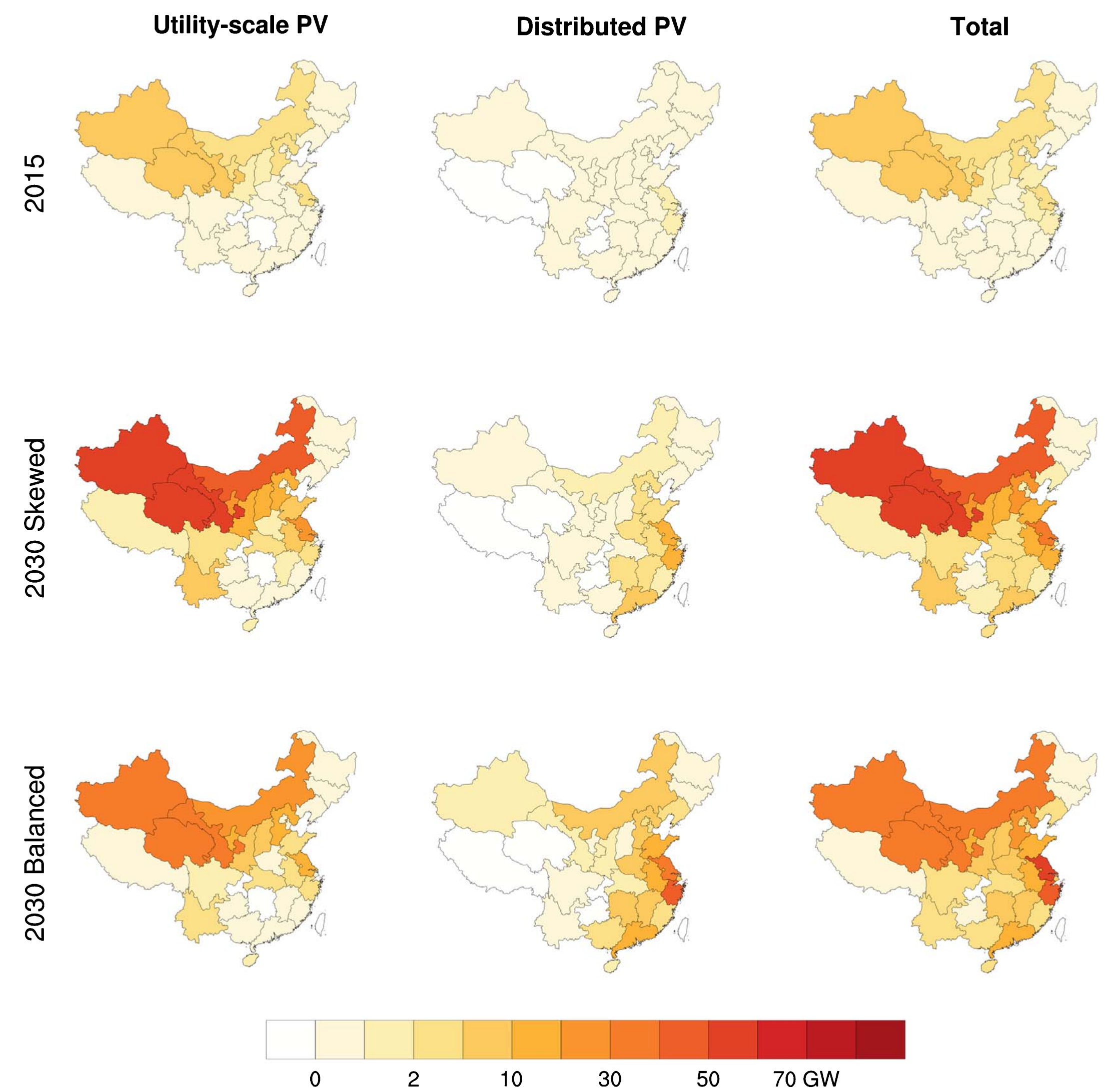

Figure 1. PV installed capacity (GW) by province for (*a*) 2015; (*b*) 2030 Skewed deployment (1:6 ratio of utility to distributed PV); and (*c*) 2030 Balanced deployment (1:1 ratio of utility to distributed PV).

electricity is cheaper to generate [15]. To address the curtailment issue for renewables and reduce emissions from coal plants, China began a pilot program of 'energy efficient dispatch', which gives priority to non-dispatchable renewables and hydropower when determining the dispatch order [33]. Under this new rule sub-critical coal-fired power plants and oil-fired plants are the last power plants to dispatch. In addition, the share of coal in China's power generation was over 65% in 2016 and the share of natural gas was only 3% [34]. Natural gas power plants are all newly built and play a critical role in smoothing intermittent wind and solar generation. Therefore, in our study we assume PV generation will only replace coal-fired power plant considering both the environmental impacts of coal-fired power plants and the objective to prioritize renewable energy integration. For *Provincial* scenarios, we assume that in each province PV electricity first displaces subcritical coal-fired power plants with the lowest generation efficiency and the highest emission factors. In *Regional* scenarios, we determine the order of subcritical coal power plant displacement by the damaged-weighted $PM_{2.5}$ precursor emissions based on the health impacts of SO_2 and NO_x emissions from the power sector (see section 3 of the online supplementary information for more details on the order of coal-fired power plant displacements) [35]. The most polluting subcritical coal plants are also the least efficient ones (i.e. emit the most CO_2 per unit electricity generated). Replacing these high-polluting and inefficient coal-fired power plants is consistent with China's commitment to reduce air pollutant emissions and increase power generation efficiencies of coal plants. Emission reductions of each pollutant for each scenario are calculated as the sum of displaced electricity generation of coal-fired power plants multiplied by the emission factor of the pollutant.

2.3. Air quality simulation

Since the ECLIPSE_v5a_CLE scenario only includes provincial annual emissions, we map the air pollutant emissions in ECLIPSE_v5a_CLE and four PV scenarios onto gridded (0.25 degree by 0.25 degree) monthly emission profiles following the spatial and

Table 2. Projected 2030 potential and grid-integrated PV electricity generation, carbon mitigation, and air pollutant reductions in each of the four scenarios.

Scenario	Potential generation (TWh)	Grid-integrated generation (TWh)	CO_2 reduction (Mt)	SO_2 reduction (Kt)	NO_x reduction (Kt)
Skewed_Provincial	660	487	460	270	275
Balanced_Provincial	585	535	508	333	306
Skewed_Regional	660	560	550	416	281
Balanced_Regional	585	585	570	453	285

temporal allocation patterns from the Multi-resolution Emission Inventory for China (MEIC) for the year 2012 (*SI Detailed methods on spatial and temporal allocations of emissions in the base case and PV scenarios*) [36]. For regions outside China, we map country-specific annual emissions in ECLIPSE_v5a_CLE onto grids (0.5 degree by 0.5 degree) with monthly emissions following the spatial and temporal allocation patterns of the Hemispheric Transport of Air Pollutants (HTAP) 2010 emission inventory [37]. Biogenic emissions were derived online according to the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [38] and open biomass burning emissions were obtained from the Global Fire Emission Database, version 4 (GFEDv4) [39].

We simulate air quality for January, April, July, and October in each scenario using the WRF-Chem v3.6. The model resolution is 27 km by 27 km, with the domain covering China and parts of other Asian countries (9°N–58°N, 60°E–156°E). The model has 31 vertical layers from the surface (32 m) to 100 hPa. We use the RADM2 gas-phase chemistry scheme and MADE-SORGAM aerosol scheme. Meteorology is from the 2014 National Centers for Environmental Prediction (NCEP) Final Analyses data every 6 hours with results from a 2014 simulation of the global chemical transport model, MOZART-4, used for chemical initial and boundary conditions [40]. Other model configurations are included in table S1.

2.4. Analysis of health impacts associated with air pollution

We calculate changes in premature mortality of four respiratory and cardiovascular diseases that are associated with long-term ambient $PM_{2.5}$ exposure: chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD) and ischemic stroke. Changes in the number of premature deaths of each disease in each 27 km by 27 km WRF-Chem grid box are calculated based on the Global Burden of Disease study [29] (see section 4 of the online supplementary information for details of calculations of health impacts associated with air pollution changes).

3. Results

3.1. Projected installed capacity and electricity generation

We first calculate the potential electricity generation from installed PV panels, i.e. without the 30% penetration cap at either the provincial or regional grid level. If we apply the 2015 6:1 utility-scale to distributed PV installed capacity ratio to 2030 (*Skewed* scenarios), China's projected solar PV deployment would concentrate in the northwest (figure 1) and produce 660 TWh PV electricity (table 2). This is 13% higher than the 585 TWh produced in the scenarios where utility-scale and distributed PV have equal installed capacity (*Balanced* scenarios, figure 1). More electricity is generated from PV in the *Skewed* scenarios largely because more abundant solar radiation exists in the northwest (where the majority of utility-scale PV plants are located) than in the east (where most distributed PV is located). In addition, capacity factors obtained with one-axis tracking systems applied in utility-scale PV plants are also higher than those obtained with fixed arrays used in distributed PV systems (table S2). However, without additional transmission, utilization of this electricity cannot occur.

After imposing the 30% grid integration constraints, the *Balanced_Regional* scenario produces the most grid-integrated electricity (585 TWh, table 2) while the *Skewed_Provincial* scenario produces the least (487 TWh) among the four scenarios, equivalent to 6% and 4.8% of the total projected power generation in 2030. This is because 26% of the projected electricity generated from PV panels is curtailed in *Skewed_Provincial*, especially in the northwestern provinces where electricity demand is low while solar PV generation is high. For example in Xinjiang and Qinghai Province, the share of electricity generation that comes from PV is projected to exceed 70% of 2030 demand in *Skewed_Provincial* (figure S2). This indicates significant grid integration challenges for the northwestern provinces in 2030 if utility-scale PV is continuously deployed without transmission to other provinces. In contrast, all generated PV electricity can be grid-integrated without curtailment in *Balanced_Provincial*. Thus although the northwest has the highest PV electricity generation potential, the relatively low local power demand projected in the base case for the region limits utilization of solar PV unless sufficient storage or grid upgrades and transmission are available. Shifting deployment to the east and expanding inter-provincial transmission would help reduce integration constraints.

3.2. Carbon mitigation

Compared to the base case, CO_2 emission reductions range from 460 million tons to 570 million tons in the four PV deployment scenarios (table 2). *Balanced_Regional* and *Skewed_Provincial* have the largest and smallest reductions, equivalent to 4.2% and 3.7% decrease in national total carbon emission in 2030, respectively. The differences among the scenarios depend on the amount of grid-integrated PV electricity and the type of coal plant being displaced. We do not consider here the variations in carbon mitigation that would result from different end-use electrification possibilities. In all cases we prioritize displacement of the least efficient coal plants. In both *Provincial* scenarios, however, in addition to the sub-critical plants some relatively clean and efficient supercritical/ultra-supercritical coal plants are replaced because no subcritical plants remain. Whereas in the *Regional* scenarios, solar PV only replaces sub-critical coal plants because the pool of sub-critical plants is larger.

We find that in all four scenarios, solar PV supplies between 3.5% and 4% of China's projected total primary energy demand in 2030. This indicates that solar PV will play a significant role in China's goal of having 20% of its primary energy from non-fossil sources [3]. Increasing deployment of distributed PV in the east, as well as enabling transmission of PV electricity between provinces will augment the carbon mitigation benefits of solar PV.

3.3. Air pollutant emission reductions

Across our four scenarios, air pollutant emission reductions range from 1.2% to 2% for SO_2, 1.5%–1.7% for NO_x, 1%–1.3% for primary $PM_{2.5}$ and PM_{10} nationally. The smaller percent reductions of air pollutants than CO_2 are because the power sector only accounts for 16%, 15%, 8% and 7% of the projected SO_2, NO_x, primary $PM_{2.5}$ and PM_{10} emissions respectively, while contributing 48% of the total CO_2 emissions in the 2030 base case. This occurs because of the use of effective end-of-pipe control devices for air pollutants but no carbon mitigation technology employed in the power sector.

Deploying more distributed PV with inter-provincial transmission (*Balanced_Regional*) results in the largest reductions in primary $PM_{2.5}$ and SO_2 emissions, however deploying more distributed PV in the east without inter-provincial transmission (*Balanced_Provincial*) results in the largest NO_x reductions (table 2, see figures S3 and S4 for gridded SO_2 and NO_x emission reductions). This occurs because in the base case there is less curtailment of PV and more high-emitting coal-fired power plants in the east than in the northwest. Therefore, air pollutant reductions are always greater in the *Balanced* scenarios than in the corresponding *Skewed* scenarios.

3.4. PV deployment scenarios' effect on $PM_{2.5}$ concentrations

We simulate the monthly mean $PM_{2.5}$ concentrations for January, April, July and October 2030 in the base case. The annual mean $PM_{2.5}$ concentration is calculated as the average of these four months. $PM_{2.5}$ concentrations are generally higher in the North, Central and East China than in the West, with annual mean concentrations in the base case in 2030 higher than 60 $\mu g\, m^{-3}$ in several provinces (figure S6). We find variations in the spatial distribution of reductions of population-weighted $PM_{2.5}$ concentrations in the four PV scenarios compared to the base case (figures 2(*e*)–(*h*)). Modest reductions (around 0.3 $\mu g\, m^{-3}$) occur in annual mean population-weighted $PM_{2.5}$ concentrations across China in *Skewed_Provincial* (figure 2(*e*)). Compared to *Skewed_Provincial*, larger reductions in $PM_{2.5}$ (0.5–0.6 $\mu g\, m^{-3}$) occur in the eastern and southern provinces, while reductions decrease (0.4–0.6 $\mu g\, m^{-3}$) in the northwestern provinces in *Balanced_Provincial* (figure S7(*a*)). This is consistent with the differences in emission reductions between the two scenarios. Compared to the *Skewed_Provincial* scenario, the two *Regional* scenarios have greater $PM_{2.5}$ reductions in the provinces containing the dirtiest coal power plants but smaller reductions in other provinces (figures S7(*b*) and (*c*)). For example, annual average reductions in Shaanxi, Ningxia, and Shandong now reach 1–1.5 $\mu g\, m^{-3}$. Although figures 2(*c*) and (*d*) show that in some provinces there will be no displacement of coal plants in 2030 in the *Regional* scenarios, we still find small reductions of $PM_{2.5}$ in those provinces (figures 2(*g*) and (*h*)), due to decreased transport of primary $PM_{2.5}$ and its precursors from nearby provinces that experience emission reductions.

The seasonal variation of $PM_{2.5}$ mitigation shows that there are more significant reductions in April and October in the north, and in July in the south, especially along the Yangtze River and in the Pearl River Delta (PRD, see figure S8). Variations in PV electricity generation are determined by variations in incoming solar radiation, cloud cover and aerosol optical depth [30]. PV generation in most northern provinces is higher in April and October than in July and in southern provinces is highest in July (figure S9).

3.5. Avoided air pollution-related premature deaths

The total projected premature mortalities due to $PM_{2.5}$ in the 2030 base case are 880 000 (440 000–1 300 000, with the range representing the 95% confidence interval of relative risk due to exposure to $PM_{2.5}$ in the Global Burden of Disease study [29]). We define the avoided premature mortalities associated with a decrease in ambient $PM_{2.5}$ as the health benefit of PV development in each scenario. Figures 2(*i*)–(*l*) provide the provincial distribution and total decrease in premature mortalities for each scenario. Deploying equal capacities of distributed and utility-scale PV with inter-provincial transmission (*Balanced_Regional* scenario) leads to the greatest health benefit with 10 000 (5000–14 000) avoided premature mortalities. Deploying more utility-scale PV in the northwest without inter-provincial

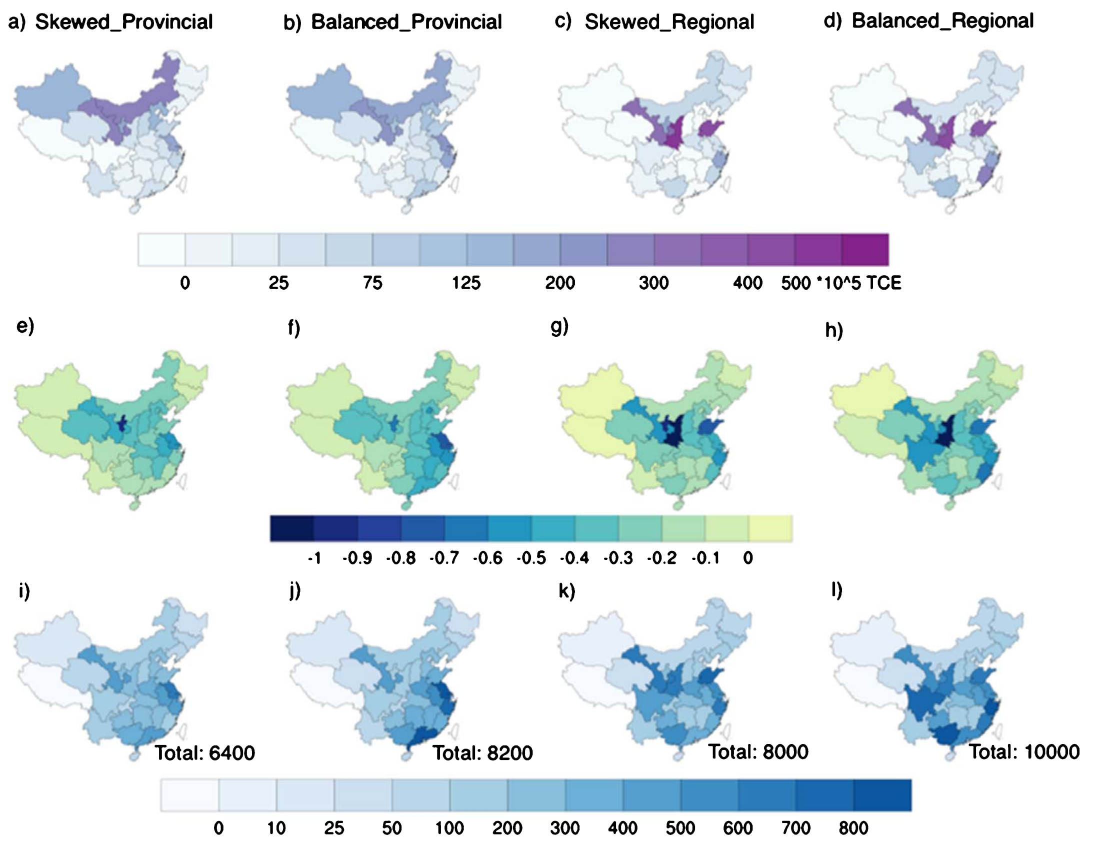

Figure 2. Carbon mitigation and air pollution reduction benefits of various PV deployment scenarios: (*a*)–(*d*): projected reduction in coal consumption resulting from solar PV deployment by province and national totals (unit: 10^5 ton coal equivalent (TCE)); (*e*)–(*h*): differences in annual mean population-weighted $PM_{2.5}$ in the four scenarios compared to the base case (unit: $\mu g\ m^{-3}$); (*i*)–(*l*): annual avoided premature mortalities associated with $PM_{2.5}$ reductions compared with the 2030 base case in each province for the four scenarios (numbers in the lower right corner of each plot indicate total avoided premature mortalities, unit: number of avoided premature mortalities).

transmission (*Skewed_Provincial* scenario) has the least health benefits with only 6400 (2800–9500) avoided deaths. The largest health benefit, combined with the largest CO_2 reduction is achieved in the *Balanced_Regional* scenario indicating that developing distributed PV in the east and enabling inter-provincial PV electricity transmission would achieve the largest air quality and climate co-benefits of the 2030 PV deployment scenarios considered here.

4. Discussion and conclusions

There are substantial variations in the climate, air quality and human health co-benefits of various PV deployment scenarios relative to the coal-intensive base case in 2030 China. We find that deploying more distributed PV in the east while enabling inter-provincial PV electricity transmission within China's regional grids achieves significantly greater co-benefits (56% more avoided premature deaths and 24% more CO_2 reduction) than deploying more utility-scale PV in the northwest without inter-provincial transmission. This is because we assume that provincial or regional power grids cannot accommodate more than 30% of electricity production coming from intermittent solar PV generation. Concentrating on utility-scale PV projects in the northwest, which is China's current PV development pattern, will result in significant PV curtailment in 2030 under these assumptions. In fact, the Chinese government has recognized the significance of PV curtailment and has started implementing a suite of policies to address the curtailment issue. For example, in 2016, China's National Energy Administration (NEA) set the minimum generation hours for utility-scale PV generation for provinces where PV curtailment occurred (between 1300–1500 h) [41]. Any province that does not meet the minimum generation hours will not receive a quota for utility-scale PV installation the following year. This mechanism serves as an incentive for various stakeholders (PV developers, provincial governments, and grid operators) to reduce the curtailment level. Our study demonstrates not only the increased air quality and climate co-benefits of installing distributed PV in the east, but also the fact that the air quality and climate co-benefits would likely be reduced due to PV curtailment in the northwest. Thus it is in the interest of the Chinese government to improve transmission in order to reduce PV curtailment in the future.

We impose the 30% grid-integrated solar PV penetration cap in our main results because in the US regional grids can currently only handle around 30% of generated electricity from intermittent renewable power [31, 32]. Although other studies have found grid-integration constraints of renewables to be more significant in China than in the US due to a less flexible power generation mix and a lack of supportive policies [42], we expect that with gradual technical upgrades and policy reforms China could obtain similar renewable integration as the US by 2030. Potential technical upgrades include building grid-scale storage capacity (e.g. pumped hydro storage and batteries) [15, 42, 43], encouraging demand-side management [42], and improving prediction accuracy of wind and solar power output [15]. Policies that would improve grid integration of renewables include facilitating electricity transmission across provinces [15, 44, 45], changing regulations in order to increase the flexibility of coal and natural gas generation (e.g. decrease minimum output requirements) [33, 42], and prioritizing dispatch of renewables [33, 42]. We further show that our conclusions that increased co-benefits resulting from more distributed PV installations in the east and enabling inter-provincial transmission are robust under various assumptions of the level of grid integration of solar PV (*SI Sensitivity analysis of the implications of various levels of PV grid integration*). Therefore, our analysis offers important insight into specific deployment and utilization strategies to achieve China's solar PV target, with the aim of maximizing air quality and climate co-benefits.

While it is difficult to develop a detailed power system model for China because of insufficient publicly available power system data, we analyze the climate and air quality benefits from solar PV in a way that is consistent with China's ongoing power sector development plans. Recent power sector capacity planning in China prioritizes renewable energy development and explicitly accelerates the phase down of the least efficient and highest-emitting coal-fired power plants [46]. Hence our study represents the potential benefits of implementing current planning decisions. As a next step it would be valuable to test our emission reduction results using a more complex power system model that considers the implications of intermittent renewable electricity generation and various electricity dispatch systems.

5. Policy implications

We find that distributed PV deployment and inter-provincial transmission both increase co-benefits of PV development because they could alleviate grid-integration constraints in the northwest and achieve greater air quality-related health benefits via increasing the displacement of high-emitting coal-fired power plants first. However, both policies also have economic and institutional challenges. Although China has consistently proposed equal annual installation of utility-scale and distributed PV [5, 6], the installed capacity of distributed PV remains only one sixth that of utility-scale PV [12]. Higher installation costs compared to utility-scale PV projects [10], issues with rooftop property rights [47], as well as lack of flexible financing mechanisms and innovative business models [47, 48] are identified as barriers to large-scale distributed PV development in China. However, the lower than expected growth in electricity demand and limited long-range transmission capacity have exacerbated the curtailment of utility-scale PV projects in the northwest [16]. In addition, some utility-scale projects are suffering from subsidy payment delays of up to 18 months as the Chinese government struggles to collect sufficient funds from surcharges on retail electricity prices to cover the subsidies [47]. Thus investment in the PV sector is expected to shift towards distributed PV in the future. To facilitate the transition, the Chinese government must build a clear and stable policy framework for distributed PV development that addresses legal and financial barriers by ensuring availability of rooftop resources, creating financing platforms for distributed PV projects, and encouraging innovative business models.

Significant challenges exist in increasing the inter-provincial power exchange because of limited transmission capacity and resistance from electricity importing provinces [13]. Although the Chinese government explicitly promoted inter-provincial power exchange in the latest round of power sector reforms [46], the recent slowdown of growth in power demand and potential overcapacity of power generation have rendered provincial utilities more reluctant to import electricity from other provinces [16]. Thus in order to promote inter-provincial transmission and implement the green dispatch system, Chinese policies that facilitate electricity exchange, especially electricity generated from renewable energy sources across provinces and regions would be highly beneficial. In addition, the development of ultra-high voltage (UHV) long-distance transmission lines and inter-regional interconnections that link PV generation in the resource-rich northwest with demand centers in eastern and central China could further reduce curtailment and lead to greater climate and air quality benefits [49].

Finally, we note that developing solar PV alone is not sufficient for China to achieve its pledge to peak CO_2 emissions before 2030 or to substantially reduce air pollution. This is because although China has a bold solar PV development plan, the projected share of grid-integrated PV electricity in China's total electricity generation will likely still be relatively small in 2030 (projected to be ~6%). In addition, the cost-effectiveness of developing solar PV compared to other strategies for China's air pollution and climate change mitigation should also be addressed in future studies. Going beyond existing CO_2 mitigation and air pollution control measures (e.g. by further increasing the penetration of various non-fossil energy sources in the total energy supply, increasing efficiency of end-uses, and implementing more stringent pollution-control policies) is necessary to achieve China's pledge to peak CO_2 emissions before 2030 while addressing air pollution challenges [50]. A more comprehensive energy strategy that creates synergies among various sectors to tackle both climate and air pollution challenges in the future would be highly beneficial. One example of such a strategy would be to promote electrification in the residential and transportation sectors with increased electricity generation coming from renewable sources including increased PV generation [51–53].

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