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Designing Deployment Policies to Maximize the Co-benefits of China's Clean Energy Transition

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DESIGNING DEPLOYMENT POLICIES TO MAXIMIZE THE CO-BENEFITS OF CHINA'S CLEAN ENERGY TRANSITION

Junnan Yang

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Abstract

China's rapid economic growth over the past few decades has been fueled by the coal-dominated energy system. The increasing consumption of coal and other fossil fuels has resulted in a dramatic increase in China's greenhouse gas (GHG) emissions and worsening ambient air quality. The Chinese government has designed and implemented various deployment policies to support the transition toward significantly less coal and other fossil fuel consumption. My dissertation focuses on the climate, air quality, and industrial growth co-benefits of various deployment policies in China. It includes three analytical chapters.

Chapter 2 analyzes the climate, air quality and human health benefits of various solar PV deployment scenarios in China in 2030. I find that deploying distributed PV in the east with inter-provincial transmission maximizes potential CO_2 reductions and air quality-related health benefits. 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.

Chapter 3 analyzes the climate, air quality and human health implications of replacing small heating stoves with gas and electric heating in China. I examine the implications of using gas (conventional gas or coal-based synthetic natural gas (SNG)) and electricity (either resistance heaters or air-source heat pumps) for heating. I find deploying heat pumps as a substitute for small solid fuel stoves for heating has the greatest long-term potential of

significant air quality and climate co-benefits as China further decarbonizes its power sector.

Chapter 4 analyzes the role of deployment policies in promoting industrial growth in China's wind, solar PV and Lithium-ion battery industries. I argue that deployment policies are effective to support industrial growth when the end uses of the clean energy technology are relatively few and concentrated. For battery storage technology, I find that there are multiple use cases of storage systems in the power sector, which makes direct subsidization for battery storage systems less effective in promoting the Li-ion battery industry compared to China's wind and solar industries.

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Chapter 1: Introduction

China's rapid economic growth over the past few decades has been fueled by the coal-dominated energy system. China contributed 23% of global energy consumption and 34% of global energy consumption growth in 2017. Coal still dominates China's energy consumption, with a decrease from 70% in 2010 to 60% in 2017 [1]. Coal-fired power plants are the largest coal consumer and the share of coal in China's power generation was over 65% in 2017 [2], although the average utilization of coal-fired power plants has decreased in recent years. In China's relatively ambitious near-term energy targets in their 13th Five-year Plan, coal still accounts for 58% of the total energy consumption projected for 2020 [3].

The increasing consumption of coal and other fossil fuels has resulted in a dramatic increase in China's greenhouse gas (GHG) emissions and worsening ambient air quality. China became the world's largest emitter of GHGs in 2007 [4] and contributed 28% of global CO_2 emissions in 2017 [5]. Although more than 30% lower than in 2013, the annual mean $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) concentrations in China's capital city Beijing and the surrounding Tianjin and Hebei Provinces were above 60 $\mu g/m^3$ in 2017 [6], which is far beyond the World Health Organization's Air Quality Guideline (10 $\mu g/m^3$) for annual mean $PM_{2.5}$ concentrations [7]. Under pressure from recent severe air pollution and fulfilling China's pledge at the Paris Climate Conference to peak CO_2 emissions and produce 20% of primary energy from non-fossil sources by 2030 [8], a large-scale energy transition toward significantly less coal and other fossil fuel consumption is necessary for tackling both GHG mitigation and regional air pollution

simultaneously in China. To achieve a large-scale and low-carbon energy transition in China, it is critical that the Chinese government strengthen its commitment to policies that increase the share of renewable and clean energy sources in its energy mix, as well as foster the development of a diversified portfolio of clean energy technologies.

For over a decade the Chinese government has designed and implemented various "deployment policies" to support its clean energy transition. Deployment policies accelerate the diffusion of advanced energy technologies in the energy system by creating and/or boosting the market demand for those technologies. They can take different forms such as fiscal incentives, public finance and regulatory policies [9]. Fiscal incentives include tax credits, grants, or other types of financial rewards for owners and/or investors of clean energy projects. Public finance help scale up the market for clean energy technologies with a series of financial instruments such as low-interest loans, loan guarantees and public investment programs through government funds. Regulatory policies can be divided into quantity-, quality- and price-driven policies. Quantity-driven policies set targets for clean energy deployment (e.g. China's strategic five-year planning for renewable energy development) or mandatory procurement quotas (e.g. the Renewable Portfolio Standards in various states of the US). Quality-driven policies sets standards that favor the adoption of energy-saving and/or low-emission technologies, such as the Corporate Average Fuel Efficiency (CAFE) Standard for energy-saving automobiles in the US and China's energy-efficiency and energy-intensity targets, which will boost the demand for technologies that improve energy efficiencies in the power, industry and residential sectors. Price-driven policies, such as feed-in tariffs, provide subsidized electricity tariffs for renewable and clean energy electricity generation. China's clean

energy deployment policies have attempted to reduce fossil fuel consumption and support use of renewable energy technologies such as wind and solar photovoltaic (PV) electricity generation. Deployment policies have proven highly effective in scaling up China's clean energy deployment in a short period of time. For example, China's continuous growth in wind and solar PV deployment relies largely on demand-side incentives such as favorable feed-in tariffs for wind and solar electricity generation. Since the Chinese government established national feed-in-tariffs for solar PV power generation in 2013, the total installed capacity of solar PV has increased 18.5 times from 7 GW in 2012 to 130 GW of 2017 [10]. However, because the ultimate objective of deployment policies is to address China's pressing air pollution and climate mitigation challenges, the effectiveness of deployment policies should be examined based on the actual GHG mitigation, air quality and health co-benefits they achieve in both the near- and long-term.

Although studies have demonstrated China's success in using various deployment policies to facilitate its clean energy transition, there is limited in-depth analysis to quantify and compare the air quality and greenhouse gas mitigation implications of deployment policies that are being implemented and/or under discussion. Previous studies have examined the air quality and climate co-benefits of both near-term and long-term deployment policies across different sectors in China [11-15]. For example, Peng et al. (2017) [11] examine various demand-side policies that promote pollution-control technologies in China's power (installing ultra-/supercritical power plants to replace subcritical coal plants), industry (strengthening the energy efficiency standards), residential (deploying liquefied petroleum gas-based heating and cooking stoves to replace coal-based stoves) and transportation (deploying low-emitting vehicles to replace high

emitters) sectors and find that policies that support energy efficiency improvement in the industry sector achieve the largest air quality and climate benefits. Qin et al. (2017) [12] explore various synthetic natural gas (SNG) deployment strategies in China's power, industry and residential sector and find that deploying SNG in the residential sector results in nearly 10- and 60-times greater reduction in air pollution-related health than deploying SNG in the industry and power sectors; deploying SNG in the residential sector also results in only 20 to 30% of the increase in CO_2 emissions compared with deploying in the industry or power sectors. However, studies that compare the co-benefits of deployment policies across different sectors provide limited information on the air quality and climate implications of different policy designs within each specific sector. Among a suite of demand-side incentives to achieve the same target within each sector, it is critical for the government to identify and select policies that bring the largest potential environmental benefits. For example, to reach the 400 GW projected PV installed capacity target in 2030 (equivalent to nearly 15% of China's total projected installed capacity in the power sector) [16], the Chinese government has implemented various feed-in-tariffs to encourage PV installations in various locations [17,18]. However, different PV deployment policies could result in different air quality and climate benefits because they differ in how much electricity would be generated from PV and the types of power plant being displaced. Similarly, to replace the inefficient solid fuel-based small heating stoves in northern China, the Chinese government designed a series of deployment policies (including upfront installation cost reductions and subsidized retail electricity rates for electrified heating) that support various gas and electric heating strategies [19-21]. However, studies that evaluate the air quality and carbon mitigation outcomes of employing different heating strategies to

replace small solid fuel heating stoves in northern China are still lacking. Therefore, a thorough and quantitative examination of the climate, air quality and related human health benefits of different deployment policies within each specific sector is necessary to help the Chinese government design and implement deployment policies that could achieve the largest environmental benefits.

In Chapters 2 and 3, I use air pollution model WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) and epidemiological concentration-response relationships to analyze the climate, air quality and human health implications of various deployment policy designs in two critical components of China's clean energy transition: (1) using utility-scale and distributed solar PV plants to displace coal-fired power plants in the power sector; and (2) using gas and electric heating to replace the inefficient small heating stoves in the residential sector.

Chapter 2 analyzes the climate, air quality and human health benefits of various solar PV deployment scenarios in China in 2030. Using a 2030 coal-intensive power sector projection as the base case, I estimate the climate, air quality, and related human health benefits of various 2030 PV deployment scenarios from displacing coal-fired power generation. I 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. I 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. I 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. I find large potential benefits of policies that encourage distributed PV deployment and facilitate inter-provincial PV electricity transmission in China.

Chapter 3 analyzes the climate, air quality and human health implications of replacing small heating stoves with gas and electric heating in China. Residential space heating using small solid-fuel based stoves is a significant source of severe winter air pollution in northern China. The Chinese government is responding with efforts to replace small stoves using solid fuel for heating with natural gas and electricity. In this chapter I examine the air quality, human health and climate implications of various strategies to replace these stoves with gas or electric heating in China's Beijing-Tianjin-Hebei region in 2012. I examine the implications of using gas (conventional gas or coal-based synthetic natural gas (SNG)) and electricity (either resistance heaters or air-source heat pumps) for heating. The additional electricity for heating is obtained from one of three sources: the 2012 BTH regional power grid, the 2012 North Power Grid, or a low-carbon power source consistent with China's 2030 carbon reduction targets. I find replacing all small heating stoves with gas or electric heating lead to similar levels of avoided $PM_{2.5}$-related premature mortalities (4.9%-5.4%) but substantial variations in CO_2 emissions. Using heat pumps with the low-carbon electricity source reduces CO_2 emissions from residential heating by 53% and reduces CO_2 emissions in the BTH region by 3.5%; using resistance heaters with either 2012 electricity sources or using SNG *increases* CO_2 emissions from residential

heating by 20%-65% and *increases* total CO_2 emissions in the BTH region by 1.1%-3.8%. I find deploying heat pumps as a substitute for small solid fuel stoves for heating has the greatest long-term potential of significant air quality and climate co-benefits as China further decarbonizes its power sector.

In addition to the environmental benefits, the Chinese government also aims to foster and promote the booming clean energy industry through implementing policies that create markets for the large-scale adoption of various clean energy technologies. For example, China's State Council listed both wind and solar PV industry as two "strategic emerging industries" in the 12th Five-year Plan in 2011 and included specific deployment targets for both wind and solar PV in 2020 [22]. In the following specific development plan for the solar PV industry, the Chinese government stated that the objectives of solar PV deployment policies were to "guarantee energy supply, establish a low-carbon society, promote economic structural reform and foster the strategic emerging industry" [17]. In addition to discussing the environmental benefits of deployment policies in clean energy transition, it is equally important to address the industrial growth benefits of clean energy deployment policies in China.

In general, previous studies support the link between demand-side policies that aims to encourage clean energy deployment and the development of clean energy industries [23-26]. The comparison of wind energy industry development in multiple countries demonstrates a clear relationship between the success of a country's wind energy industry worldwide and the country's deployment policies that created a sizable and stable domestic market for wind power [25]. Studies examine the solar PV industry also indicate the significant impact of domestic market deployment policies on the growth of the PV

industry [27-29]. Although China's PV industry did not rely on the domestic PV market initially [27], a strong domestic market was crucial to the survival and expansion of the Chinese PV manufacturing industry following the trade disputes with both the European Union and the US [28]. Following the success of using deployment policies to scale up the wind and solar PV industry, a critical question arises as to whether there are any common features from the deployment policies in the wind and solar PV sector that can guide future policy making to support other emerging clean energy technologies as well. To facilitate China's clean energy transition, designing deployment strategies for various emerging clean energy technologies are required to complement the development of wind and solar PV power generation. For instance, energy storage technologies are extremely important for integrating the intermittent wind and solar power generation into power grids. With China's rapid development of wind and solar PV in the north and northwest, significant grid integration challenges for wind and solar occurred since 2013 due to limited transmission capacity and relatively low local power demand. In two of the five northwestern provinces, Gansu and Xinjiang, PV penetration rates in 2015 were only 8% and 5.4%, however more than 30% of the electricity generated from PV there was not integrated into the grid in either 2015 or 2016 [30]. Energy storage is an effective way to mitigate grid integration challenges and provide flexibility as well as stability to power grid operations [31,32]. A comparative study on the associations between market-creating deployment policies and the development of China's wind, solar PV and energy storage industry will shed light on the key characteristics of the effective deployment policies that promote the development of clean energy industries.

Chapter 4 analyzes the role of deployment policies in promoting clean energy industry development in China's wind, solar PV and Lithium-ion battery industries. I conduct a comparative case study to analyze the conditions under which deployment policies are effective to support the clean energy industrial growth. I argue from the development of China's wind and solar PV industries that deployment policies will be effective to support industrial growth when potential end uses of the clean energy technology are relatively few and concentrated. I then use the findings from wind and solar PV industries to discuss the case of China's battery energy storage sector. I find that there are multiple use cases of storage system in the power grids, which makes battery storage deployment policies (such as direct subsidies) less effective in promoting the Li-ion battery industry compared to the role of deployment policies played in the wind and solar industries. In contrast, wind and solar have less use cases than storage, which makes deployment policies for wind and solar more effective in promoting the growth of the manufacturing industry.

Chapter 5 is the concluding chapter. I summarize the findings in Chapters 2-4. The three chapters intend to provide an integrated framework that can be used by policy makers to evaluate the multiple (both environmental and industrial growth) benefits of deployment policies to facilitate clean energy transition in the future.

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Chapter 2: Climate, Air Quality and Human Health Benefits of Various Solar Photovoltaic Deployment Scenarios in China in 2030

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 2,500 and 2,800 GW of which PV capacity, meeting current targets, could represent 14% to 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 Fig. 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.

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 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 400GW PV in 2030 (Fig. 1). Capacity factors for both types of PV for each province are calculated using satellite-derived surface irradiance data and the PVLIB-Python model [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% to 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 development 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 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: *SI 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 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 to 58°N, 60°E to 156°E). The model has 31

vertical layers from the surface (32m) 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 *SI 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 (Fig. 1a) 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, Fig. 1b). 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* (Fig. 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% to 1.7% for NO_x, 1% to 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 Fig. 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 (Fig. 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 (Fig. 2e to 2h). Modest reductions (around 0.3 $\mu g/m^3$) occur in annual mean population-weighted $PM_{2.5}$ concentrations across China in *Skewed_Provincial* (Fig. 2e). Compared to *Skewed_Provincial*, larger reductions in $PM_{2.5}$ (0.5 to 0.6 $\mu g/m^3$) occur in the eastern and southern provinces, while reductions decrease (0.4 to 0.6 $\mu g/m^3$) in the northwestern provinces in *Balanced_Provincial* (Fig. S7a). 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 (Fig. S7b and F7c). For example, annual average reductions in Shaanxi, Ningxia, and Shandong now reach 1 to 1.5 μg/m^3. Although Fig. 2c and 2d 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 (Fig. 2g and 2h), 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 Fig. 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 (Fig. 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 to 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. Fig. 2i to 2l 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 (5,000 to 14,000) avoided premature mortalities. Deploying more utility-scale PV in the northwest without inter-provincial transmission (*Skewed_Provincial* scenario) has the least health benefits with only 6,400 (2,800 to 9,500) 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 to 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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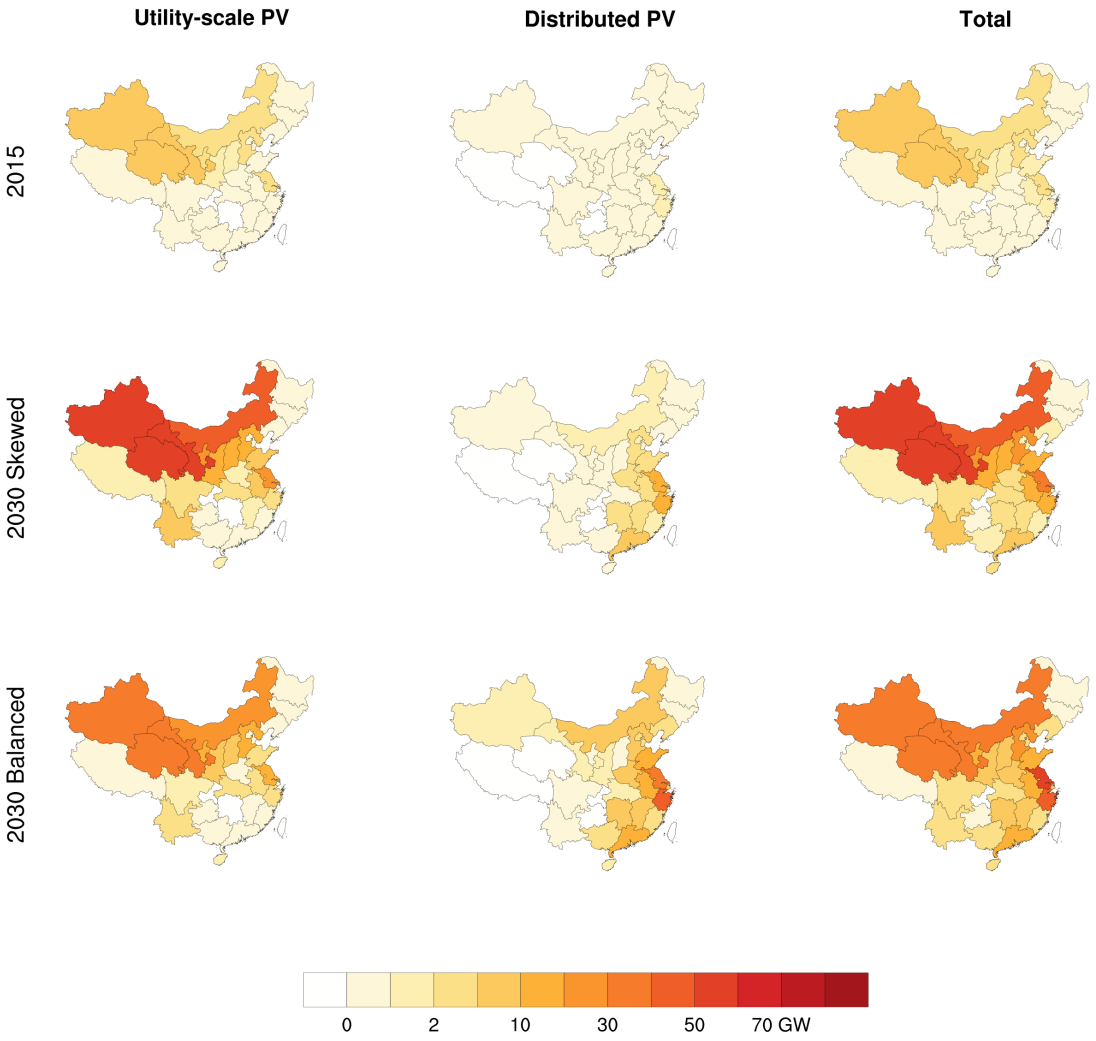


Fig. 1. PV installed capacity (GW) by province for a) for 2015; b) for 2030 Skewed deployment (1:6 ratio of utility to distributed PV); and c) for 2030 Balanced deployment (1:1 ratio of utility to distributed PV).

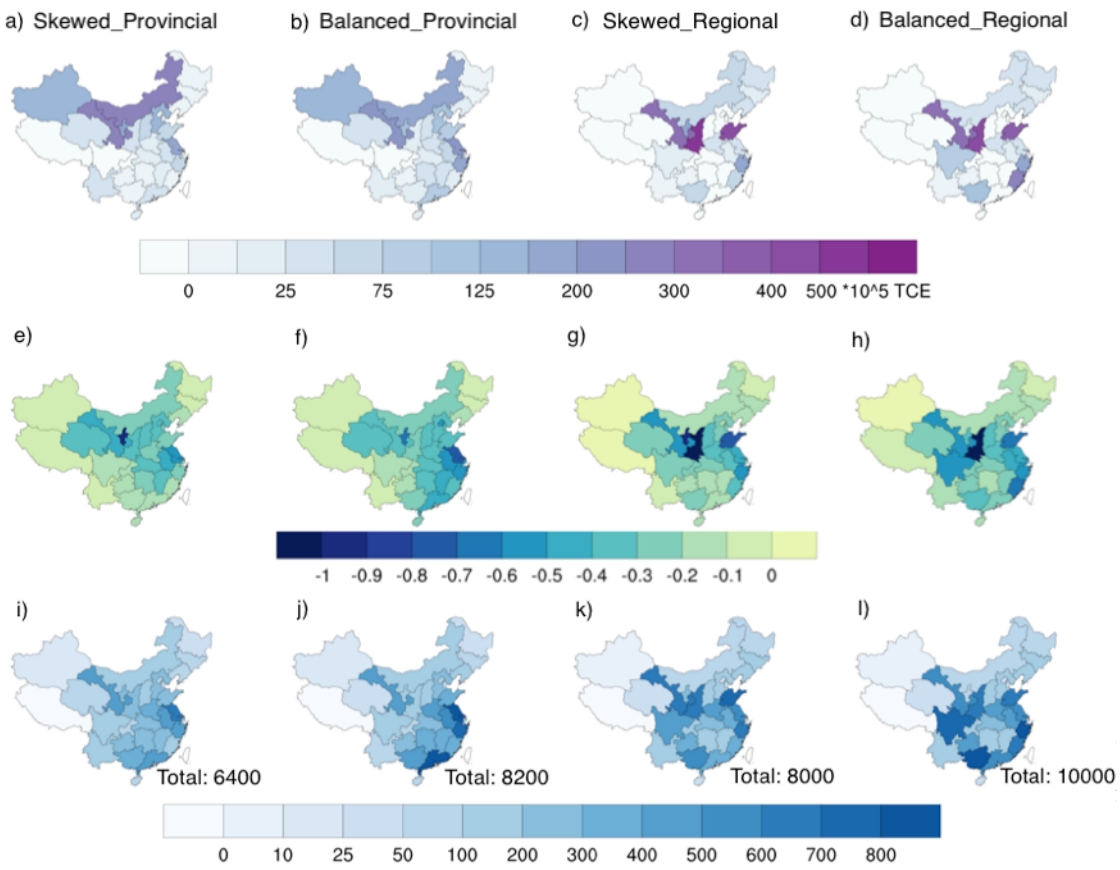


Fig. 2. Carbon mitigation and air pollution reduction benefits of various PV deployment scenarios: a) to d): projected reduction in coal consumption resulting from solar PV deployment by province and national totals (unit: 10^5 ton coal equivalent (TCE)); e) to h): differences in annual mean population-weighted $PM_{2.5}$ in the four scenarios compared to the base case (unit: $\mu g/m^3$); i) to 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).

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

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

Chapter 3: Air Quality, Health and Climate Implications of Replacing Small Solid Fuel Heating Stoves with Gas or Electric Heating in China

1. Introduction

China's Beijing-Tianjin-Hebei (BTH) region suffers from severe ambient $PM_{2.5}$ pollution. Although more than 30% lower than in 2013, the annual average $PM_{2.5}$ concentrations in the region still exceeded 60 $\mu g/m^3$ in 2017 [1]. This is far above the World Health Organization's Air Quality Guideline (10 $\mu g/m^3$) for annual mean $PM_{2.5}$ concentrations necessary to avoid human health effects [2]. Recent studies find that residential space heating, especially that provided by small household heating stoves using solid fuels such as raw coal, coal briquettes and biomass, is a major source of high $PM_{2.5}$ concentrations in winter in the BTH region [3-6]. The small-scale and widely distributed consumption of residential solid fuels makes it infeasible to implement the end-of-pipe control measures used in the power and industry sectors (e.g. flue-gas desulfurization for SO_2 and selective catalytic reduction for NO_x). Therefore, transitioning to clean heating alternatives is critical for reducing air pollutant emissions from the residential sector.

Since 2013, both central and provincial/city governments in the BTH region have encouraged the use of clean energy for heating, encouraging the use of natural gas, electricity, industrial waste heat, geothermal and solar energy, to replace small heating stoves using solid fuels [7-10]. Among these technologies, natural gas and electricity are the most promising options for large-scale adoption because alternatives face more stringent resource or geographic constraints. Natural gas is the cleanest fossil fuel with relatively low carbon intensity (assuming minimal leakage) and air pollutant emissions

compared to coal or biomass. Electric heating can reduce pollution from solid fuel consumption because of the installation of highly effective air pollution control devices in the power sector and their absence in the residential sector as well as the potential to incorporate low-carbon energy sources. Both central and provincial governments have implemented a series of deployment incentives for gas and electric heating. These include installation subsidies for new heating devices, reduced gas prices, and reduced retail electricity rates at night during the heating season [7,10].

The environmental and health implications of gas and electric heating depend heavily on the heat generation efficiency of the heating devices as well as the choice of fuel. Previous studies have demonstrated that different gas sources, such as conventional gas, liquified natural gas (LNG), or coal-based synthetic natural gas (SNG) can result in substantial variations in CO_2 emissions when substituted for coal in the residential sector [11,12]. The use of natural gas will reduce the emissions of air pollutants and CO_2 emissions relative to coal, but significant CO_2 emissions remain.

Electric heating requires additional electricity generation, hence the efficiency of electric heaters and the source of electricity determine the additional CO_2 and air pollutant emissions resulting from the additional power generation. Both resistance heaters and air-source heat pumps have been deployed in the BTH region but have vastly different heat generation efficiencies. Resistance heaters directly convert electricity to heat. Air-source heat pumps, on the other hand, use a refrigerant system including a compressor and condenser to extract heat from ambient low-temperature sources and release the heat indoors [13]. Electricity is therefore only used to operate the motor instead of being converted directly to heat. Because of the different heat generation mechanisms, air-source

heat pumps require only one-fifth to one-half of the electricity needed by resistance heaters per unit heat generated. The range in electricity required for heat pumps results from their lower efficiency at low temperatures. In China the dominant source of electricity remains coal (~74% and ~67% of electricity was generated from coal-fired power plants in 2012 and 2016, respectively) [14,15]. Increasing coal consumption in the power sector due to electric heating could potentially offset some CO_2 and air pollutant emission reductions achieved by replacing small heating stoves. However, as China transitions towards a cleaner power generation mix with more renewable generation such as from wind and solar, the air quality and climate co-benefits of replacing small heating stoves with electric heating devices will be further enhanced compared to relying on the current coal-dominant power generation mix [16].

Despite the importance of residential heating replacement choices, there is limited analysis to date that quantifies and compares air quality and climate implications of various gas and electric heating strategies in China. Most existing studies focus on the contribution of residential heating and in particular, residential coal combustion for heating, to ambient $PM_{2.5}$ pollution [3,4,6,17-20]. For example, while Liu et al. (2016) [4] and Archer-Nicholls et al. (2016) [3] demonstrate the significant contribution of residential heating to ambient air pollution and related premature mortalities in the BTH region and in all of China, respectively, the implications of using clean heating alternatives to mitigate the impacts of small heating stoves are not addressed in their studies. Qin et al. (2018) examines the air quality and carbon implications of choosing various gas sources for coal replacement in China without comparisons between gas substitution and electrification strategies. Xu et al. (2016) compare both energy consumption and CO_2 emissions resulting from using heat

pumps, household coal stoves or coal-fired heating boilers in the BTH region, without quantifying the air quality and human health implications of these options [18]. Zhao et al. (2018) [20] discuss the range of air quality and health improvements that result from replacing household solid fuels with natural gas or electricity but did not consider the implications of the electricity and gas sources, nor did they include the effect of stove replacements on CO_2 emissions.

Here we conduct, for the first time, an integrated assessment of the air quality, health and climate implications of various gas and electric heating scenarios in the BTH region. We choose the year 2012 as our base case because all households that were not covered by district heating used small stoves with coal and/or biomass for space heating [21]. Starting from the 2012 base case, we design two counterfactual gas heating and six electric heating scenarios in which we replace all existing small heating stoves in the BTH region (Table 1). For gas heating, we assume either conventional gas or coal-based synthetic natural gas is used for heating. For electric heating, we assume either resistance heaters or air-source heat pumps are used. We also vary the source of electricity generation for residential heating and use either the BTH power generation mix, the North Grid generation mix (including Beijing, Tianjin, Hebei, Shanxi, Shandong and part of Inner Mongolia, See Fig. S1 for the North Grid), or a projected 2030 low-carbon power generation mix from Peng et al. (2018) [16] that is consistent with China's 2030 carbon reduction target. The BTH power generation mix is less coal-intensive than the North Grid mix as both Shanxi and Inner Mongolia are coal-producing provinces and heavily dependent on coal in their power sector. The 2030 low-carbon power mix has a significantly lower share of electricity generated from coal (52%) and higher share of

renewable generation (20% from wind and solar) than the 2012 BTH mix (70% coal and 2% renewable generation) [14]. We compare changes in $PM_{2.5}$ concentrations, $PM_{2.5}$-related premature mortalities and greenhouse gas (GHG) emissions in each scenario relative to the base case. The state-of-the-science Weather Research and Forecasting model with Chemistry (WRF-Chem) is used to simulate changes in $PM_{2.5}$ concentrations due to emission changes [22]. The $PM_{2.5}$-related health impacts are calculated based on the integrated exposure response functions developed by the Global Burden of Disease study [23].

2. Results

2.1 Gas and electricity supply constraints of replacing small heating stoves

We find that replacing all small household heating stoves in the BTH region in 2012 would require ~13.5 billion cubic meters (bcm) additional gas supply. The additional gas consumption would increase China's 2012 national and residential sector gas consumption by ~10% and ~50% [21], respectively. Given the average growth rate of gas consumption between 2007 and 2016 (~13%) [24], the additional gas demand would require China to allocate nearly all of the increased gas supply to the BTH region in order to replace all small heating stoves. Although the Chinese government has set a target for annual SNG production of ~30 bcm by 2017 and ~50 bcm by 2020 [12], the actual production of SNG in 2017 was only 2.6 bcm [25]. This indicates a significant supply challenge of using gas for residential gas heating for all households in the BTH region.

Due to the difference in heat generation efficiencies, deploying resistance heaters requires ~102 TWh additional electricity generation, whereas deploying heat pumps requires only ~34 TWh additional generation. If all the additional electricity is supplied by

the BTH power generation mix, using resistance heaters and heat pumps would have required an increase in the 2012 electricity generation in the BTH region of approximately 33% and 9% [14], respectively. Depending on current capacity factors, the 33% increase in electricity generation would likely require expansion of both the BTH region's power generation fleet and power transmission as well as distribution capacity. In contrast, given that China's thermal power plants decreased their annual average operating hours from ~5500h in 2005 to less than 5000h in 2012 [26], a 9% increase in total electricity generation could likely be accommodated by the existing BTH power generation fleet. If the additional electricity is supplied by the North Power Grid, using resistance heaters and heat pumps only requires an increase of electricity generation in each province within the North Power Grid by 8% and 3%, respectively.

In terms of heating fuel supply and energy security, we find electric heating using heat pumps faces the least fuel supply constraint. In contrast, the use of natural gas requires a significant expansion of China's gas production and import and exacerbates the existing gap between China's gas supply and demand.

2.2 Air pollutant emission implications of replacing small heating stoves

Residential heating is a major source of ambient air pollutants. For the BTH region in 2012, the emission inventory in the base case (Multi-resolution Emission Inventory for China) attributes 8% SO_2, 15% primary $PM_{2.5}$, 21% black carbon (BC), 34% organic carbon (OC), 9% VOC, and only 2% NO_x emissions to residential heating [27]. We find both gas and electric heating strategies lead to significant air pollutant emission reductions compared to actual 2012 emissions, except for NO_x which is emitted from central power plants and increases in electric heating scenarios. This is because on the

one hand, both conventional gas and SNG have lower emission factors and higher energy efficiency than either coal or biomass. On the other hand, while SO_2 and PM end-of-pipe control measures were installed in the majority of power plants in 2012, NO_x controls were not installed in all power plants at the beginning of China's 12th Five-Year Plan period (2011-2015) [28]. However, in 2012 stringent NO_x emission controls were placed on existing and new power plants so in the future NO_x emissions will decrease [28]. In addition, solid fuel combustion in residential stoves is not a significant source of NO_x emissions due to the lower combustion temperature in residential stoves than in power plants.

Among all heating replacement scenarios, deploying heat pumps with the 2030 low-carbon power mix achieves the largest emission reductions, with SO_2, NO_x, and $PM_{2.5}$ emissions decreasing by 7.5%, 1.5%, and 14.9% compared to actual 2012 emissions, respectively. Deploying resistance heaters with the 2012 North Grid power mix achieves the smallest emission reductions (0.5% and 13% for SO_2 and $PM_{2.5}$) and increases NO_x emissions by 7.3% compared to 2012 emissions. This is because first, resistance heaters require three times as much electricity as heat pumps; second, the 2030 power mix assumes all coal-fired power plants install NO_x pollution controls and the share of zero-emitting renewable energy sources is ten times more than either 2012 power mix; and third, the average power sector emission factors are significantly lower in the BTH region than in the North Grid region in 2012, especially for SO_2 and NO_x (Fig. 1). The other three provinces in the North Grid region (Inner Mongolia, Shandong, and Shanxi) all had more high-emitting subcritical coal plants than the BTH region. Across all scenarios, however,

we find little variation in BC, OC, and VOC reductions as power generation is not a major source of these pollutants.

2.3 Air quality and health implications of replacing small heating stoves

We find that replacing small solid fuel heating stoves with either gas or electric heating options would all bring substantial air quality improvements to the BTH region. Consistent with the air pollution emission reduction results, using heat pumps with the low-carbon power mix achieves the largest reductions in ambient $PM_{2.5}$ concentrations. The annual population-weighted average $PM_{2.5}$ concentrations decrease by 20%, 16%, and 14% compared to 2012 concentrations in Beijing, Tianjin, and Hebei, respectively. Using resistance heaters with the 2012 BTH power mix brings the smallest reductions in ambient $PM_{2.5}$ concentrations among all scenarios. However, it still reduces annual population-weighted average $PM_{2.5}$ concentrations by 19%, 14%, and 13% in Beijing, Tianjin and Hebei, respectively. This is because unlike inefficient solid fuel combustion with no end-of-pipe control measures in small heating stoves, control measures for SO_2 and particulate matter were already employed in the majority of coal-fired power plants in 2012 [29,30]. In addition, small heating stoves are much closer to people than power plants. Hence the exposure to $PM_{2.5}$ from emissions from heating stoves are significantly greater than the exposure to $PM_{2.5}$ from power plants. The increase in NO_x emissions in scenarios with resistance heaters and the 2012 power mixes do not lead to significant changes in ambient $PM_{2.5}$ concentrations because primary $PM_{2.5}$ emissions are the main contributor to winter ambient $PM_{2.5}$ concentrations in the BTH region, as indicated in previous studies [4,6].

Although replacing all small heating stoves could decrease ambient $PM_{2.5}$ concentrations by 13-20% in the BTH region, reductions in premature mortalities related

to $PM_{2.5}$ are only around 5-5.5% in the BTH region across all scenarios (Fig. 2). This is because the concentration-response relationships of exposure to ambient $PM_{2.5}$ for most respiratory and cardiovascular diseases are concave with smaller reductions in premature mortalities at high ambient PM2.5 concentrations. Thus, decreases in the health impacts resulting from $PM_{2.5}$ reductions are relatively small due to the BTH region's high baseline $PM_{2.5}$ concentrations [31]. Among all scenarios, using heat pumps with the low-carbon power source achieves the largest health benefits, with 7,380 (5,280; 11,450, with the range representing the 95% confidence interval of relative risk due to exposure to $PM_{2.5}$) avoided premature mortalities in the BTH region in 2012.

We find slight increases in ambient $PM_{2.5}$ concentrations in Inner Mongolia when heat pumps are deployed in the BTH region using the North Grid power mix and in both Inner Mongolia and Shanxi when resistance heaters are deployed. The increase in $PM_{2.5}$ concentrations is the result of additional air pollutant emissions from power generation. In addition, because Inner Mongolia and Shanxi are located upwind of the BTH region, $PM_{2.5}$ mitigation in the BTH region has little benefit for them. The increased $PM_{2.5}$ concentrations also indicate a potential trade-off of relying on the North Grid for electric heating in the BTH region in 2012. However, in 2030, given the new stringent coal power sector emission regulations combined with increased penetration of non-fossil electricity generation, we expect these trade-offs will decrease markedly. The possibility of importing electricity from neighboring provinces could also reduce pressure on the BTH regional grid from additional electric heating.

2.4 Changes in greenhouse gas emissions from replacing small stoves with gas or electric heating

2.4.1. The Beijing-Tianjin-Hebei region

We find significant GHG reductions from replacing small solid fuel heating stoves with either gas stoves using conventional gas or with heat pumps using any of the electricity sources (Fig. 2). Compared to using small solid fuel heating stoves which emit ~63 Mt CO_2 in the BTH region, using conventional gas for heating reduces residential heating emissions by 60% (~41.5 Mt) and total CO_2 emissions in the BTH region by 3.2%. This is comparable to the reductions achieved using electric heat pumps with the 2012 BTH and North Grid power mix (2.9% and 2.6% reduction in regional CO_2 emissions, respectively) and less than that achieved using heat pumps with the 2030 low-carbon power mix (3.5% reduction in regional CO_2 emissions). This indicates that with increased penetration of low-carbon electricity, using heat pumps is the best long-term strategy bringing the largest air quality and carbon mitigation benefits from replacing solid fuel residential small stoves.

In contrast to heat pumps and gas stoves using conventional gas, we find significant increases in total CO_2 emissions when gas stoves are fueled by SNG, or when resistance heaters are used with either the BTH or North grid 2012 power mix (Fig. 2). The substantial difference in CO_2 emissions between conventional gas and SNG is also observed in previous studies because of the energy-intensive SNG production process in which coal is converted to natural gas. Increases in CO_2 emissions from resistance heaters occurs because they are far less efficient than heat pumps for heating and can even be less efficient than some household heating stoves. Combining the power generation efficiency of coal-fired power plants (~35%), power transmission efficiency (~93%), and heat generation efficiency of resistance heaters (~97%), the total energy efficiency of resistance heaters is around 32%, which is even lower than some of the household coal boilers [18]. In contrast,

the heat generation efficiency of heat pumps is ~300% when temperatures are above -5 degrees Celsius [13], hence the total energy efficiency of heat pumps is ~98%. Our results thus highlight the long-term benefits of utilizing heat pumps and the air quality and carbon trade-offs of using SNG or resistance heaters as replacements for small residential heating stoves.

In our analysis of using natural gas heaters, we further consider the implications of methane leakage in gas transmission and distribution. We calculate total GHG emissions (CO_2 equivalent, CO_2e, including both CO_2 and methane emissions) from gas transmission, distribution and combustion following the method in Qin et al. (2017) [32] under the 100 and 20-year global warming potential (GWP_{100} and GWP_{20}). We assume methane leakage rates in gas transmission and distribution are 0.32% and 0.09%, respectively, which are the mean leakage rates reported in Qin et al. (2017) [32]. Compared to using solid fuel stoves, using conventional gas for heating emits only ~20 Mt or ~18 Mt of CO_2e emission reductions under GWP_{100} or GWP_{20}. Using SNG for heating, on the other hand, *increases* CO_2e emissions by ~6 Mt or ~8.5 Mt under GWP_{100} or GWP_{20}.

2.4.2. All northern provinces

Given the similar-scale air quality benefits but significantly diverging climate implications, we also construct six hypothetical scenarios in which we compare GHG emissions from gas and electric heating in China's 15 northern provinces (Table S1). These provinces were chosen because they require residential space heating in winter and account for more than 95% of China's total space heating demand [24,33]. Due to decreased carbon intensity of the power sector between 2012 and 2016, and the likely decarbonization trend through 2030 we compare GHG emissions from eight new scenarios: 1) using gas stoves with

either conventional gas or SNG; 2) using resistance heaters with either the 2012, 2016 or a hypothetical low carbon grid in 2030 provincial power generation mix from Peng et al. (2018) [16] ; or 3) using heat pumps with either the 2012, 2016, or the hypothetical 2030 provincial power mixes. Because the heat generation efficiency of heat pumps is positively correlated with ambient temperature, the amount of electricity needed and CO_2 emissions occurring from power generation thus vary with both the ambient temperature and the carbon intensity of the provincial power sectors.

We find that in 2012 most northern provinces would have had lower GHG emissions when using gas stoves with conventional gas than if either resistance heaters or heat pumps were employed, with the exceptions of Beijing, Gansu, and Qinghai (Region 2 in Fig. 3). This is because of the relatively high carbon intensity of provincial power sectors in 2012, mainly due to the large numbers of inefficient small coal-fired power plants that still operated at that time. However, in 2016, we find more provinces had lower GHG emissions when using heat pumps than when using gas stoves (Region 3 in Fig. 3). The primary reason is that the carbon intensity of power generation in nearly all provinces substantially decreased between 2012 and 2016, due to the new more stringent efficiency standards for coal-fired power plants in China and the replacement of small coal-fired power plants with more efficient supercritical/ultra-supercritical coal plants. In addition, the average temperature in 2012 was lower than in 2016 (Table S1), thus increasing the efficiency of air source heat pumps in 2016. If we assume ambient temperature in the 2030 scenarios is the same as in 2016 and use the hypothetical 2030 low-carbon power mix, we find that almost all northern provinces (except for Heilongjiang under GWP_{100}) will have lower GHG emissions when using heat pumps than when using gas stoves (Region 3 in

Fig. 3). As China is committed to further decarbonizing its power sector and climate change is likely to result in warmer winters, the use of heat pumps will result in lower GHG emissions than gas heating in more provinces in the near future.

3. Discussion and Conclusions

3.1. Air quality and GHG emissions

We find substantial variations in CO_2 emissions from various gas and electric heating options although all bring significant air quality improvements to the heavily polluted BTH region. We find using air-source heat pumps with the low-carbon power generation mix brings the greatest air quality and carbon co-benefits. This is because first, air-source heat pumps are more efficient than resistance heaters and require significantly less additional electricity; and second, as China further decarbonizes its power sector, heat pumps have greater potential to reduce CO_2 emissions from residential heating than natural gas. Although natural gas emits significantly less CO_2 than other fossil fuels, it is still a source of greenhouse gas emissions and its use in the residential sector lead to further development and future commitment to fossil fuel infra-structure.

In addition, we also find potential air quality and carbon trade-offs from either using SNG for gas heating or using resistance heaters with a carbon-intensive power mix. In fact, we note that although China has relatively ambitious production targets for SNG (~30 bcm in 2017 and ~60 bcm in 2020) [12], in reality China only produced ~2 bcm SNG in 2017 and a large number of the proposed projects were halted or are still under construction [25]. Several reasons have been cited to cause the delay, such as the regulated natural gas prices, relatively higher production costs in some of the early projects, and potential concerns with the carbon and water footprints of SNG production [11,34,35]. The large-scale application

of SNG in residential heating has a long-term environmental impact of the SNG production infrastructure, as it would require China to rapidly scale up the construction of the proposed projects to secure SNG supply. Therefore, any future large-scale adoption of gas heating in the residential sector should prioritize the use of conventional gas over SNG. Due to the higher electricity consumption of resistance heaters and the associated cost burden for households, local governments in Beijing have recognized the significant differences in efficiencies between resistance heaters and heat pumps and encouraged the use of heat pumps in heating electrification campaigns after 2015 [36]. However, other provinces in northern China, such as Tianjin and Hebei still provide subsidies for both heat pumps and resistance heaters because resistance heaters cost approximately 40-50% of heat pumps for the same household [37,38]. Our results suggest that local governments should consider shifting the subsidies from resistance heaters to focus more on heat pumps. Because heat pumps use less electricity, a heat pump promoting policy would bring greater air quality improvements and larger reductions in CO_2 emissions than resistance heaters when residential small solid fuel heating stoves are replaced.

3.2. Gas and electricity supply constraints

In terms of both gas and electricity supply, our results indicate that significant supply constraints would occur under scenarios with large-scale gas heating in the BTH region and even more so if gas was utilized more broadly across northern China. A complete replacement of small heating stoves with gas heating would have doubled the total gas consumption in the BTH region in 2012. Given that China imported more than 35% of the gas it consumed in 2017 [25], large-scale use of gas for heating would significantly widen the gap between China's gas supply and demand. Without significant scaling up of

domestic gas production, such as from shale gas and coal-bed methane, the increased gas demand would exacerbate China's reliance on the global gas import market and increase China's exposure to price volatility and supply shocks. A similar supply-side challenge exists if resistance heaters are used in the BTH region, as the ~30% increase in power generation would also require the lengthy process of building new power plants and transmission capacity. However, using heat pumps would only require an increase of 10% from the 2012 power generation level in the region, which can be managed through increasing the operating hours of existing power plants which currently have excess capacity, and potentially utilize wind power that is currently being curtailed in the northern provinces.

3.3. Policy implications

China's residential sector will have a greater impact on the nation's future CO_2 emissions as rapid urbanization is expected to continue. Zhou et al. (2018) [39] project future CO_2 and primary energy consumption of China's building sector up to 2050 and their analysis demonstrates the significant increases of CO_2 emissions from the building sector due to rapid urbanization and residents' increasing desire for comfortable lifestyles in China. Within the building sector, space heating accounts for the largest contribution to primary energy consumption among all household energy needs, hence efficient household heating strategies with less energy consumption and related CO_2 emissions is critical to reduce the increasing CO_2 emissions from the building sector in the future. The environmental implications of future heating strategies also depend on the building structure and applications of energy-saving designs. Due to limited insulation and building envelope design, the majority of current rural households in the BTH region have relatively low

energy efficiencies compared with urban households and urban households in China have poor energy efficiencies compared with the most efficient buildings in Europe [35]. Therefore, policies and further subsidies for retrofitting rural households to increase energy efficiencies, such as energy-saving building facades, insulation, windows etc., would further increase the air quality benefits of gas and electric heating in the BTH region.

Finally, we note that our analysis focuses primarily on the air quality and climate implications of deploying heat pumps and resistance heaters. The large-scale implementation of heating electrification requires detailed and careful economic analysis as well. Although initial capital costs are higher for heat pumps than resistance heaters, operating costs are lower and significant health and greenhouse gas mitigation benefits exist when heat pumps are chosen. Thus, it would be beneficial to have a comprehensive analysis of these factors in order to develop policy mechanisms and incentives to encourage the uptake of heat pumps. In addition, the importance of considering the critical infrastructure for gas and electric heating is also beyond the scope of this paper. It would be valuable to consider the challenges of installing and upgrading current household gas and electricity distribution systems in order to facilitate the adoption of gas or electric heating, especially in rural households where the distribution system requires significant investment from both government, gas companies and grid operators.

4. Methodology

We use the Multi-resolution Emission Inventory for China (MEIC) for the year 2012 [27] as our base case (*Base*). We then assume all rural households and the urban households that were not covered by district heating would switch to either gas-based or electric heating in the BTH region in 2012. We do not displace district heating that was supplied

by coal-/natural gas-fired boilers or combined heat and power (CHP) generation in our study. We estimate the total heating demand for rural and urban households that used small heating stoves by multiplying the total floor space area of the households by the average household annual heating demand from surveys of building energy efficiency in rural and urban areas in Beijing, Tianjin and Hebei in 2012. The detailed calculations are included in the supplementary information (*SI Methods*)

We calculate changes in air pollutant and GHG emissions in each heating replacement scenario due to the removal of small stoves and increased gas consumption or power generation. To remove residential heating emissions, we replace the base case residential emissions in each month with the residential emissions in July. This is justified because non-heating residential emissions (cooking and water heating) are constant throughout the year and there is no heating activity in July. For gas heating, we calculate the total gas demand by assuming that household gas stove efficiencies are 90%. Air pollutant and GHG emission factors for gas combustion, transmission, distribution and upstream production are from Qin et al. (2018) for both conventional gas and SNG [11]. For electric heating, we assume the efficiency of resistance heaters is 97% [18], while the efficiency of air-source heat pumps, aka the coefficient of performance (COP), is assumed to be a function of the ambient temperature during the heating season in Beijing, Tianjin and Hebei, based on the methods in Chen et al. (2014) [13]. Emissions from the additional power generation are calculated as the sum of the power generation multiplied by the average power sector emission factors of each pollutant. The average power sector emission factors for each electricity source are defined as the total power sector emissions of each pollutant (kg) divided by the 2012 or 2030 power generation (kWh) [40].

We simulate air quality for January, April, July, and October 2012 in *Base* and for January alone in all heating replacement scenarios using WRF-Chem v3.6. We then calculate changes in the number of premature mortalities of four cardiovascular and respiratory diseases due to changes in ambient $PM_{2.5}$ concentrations in each WRF-Chem grid box based on the Global Burden of Disease study [23]. Detailed model configurations and calculations are included in the SI.

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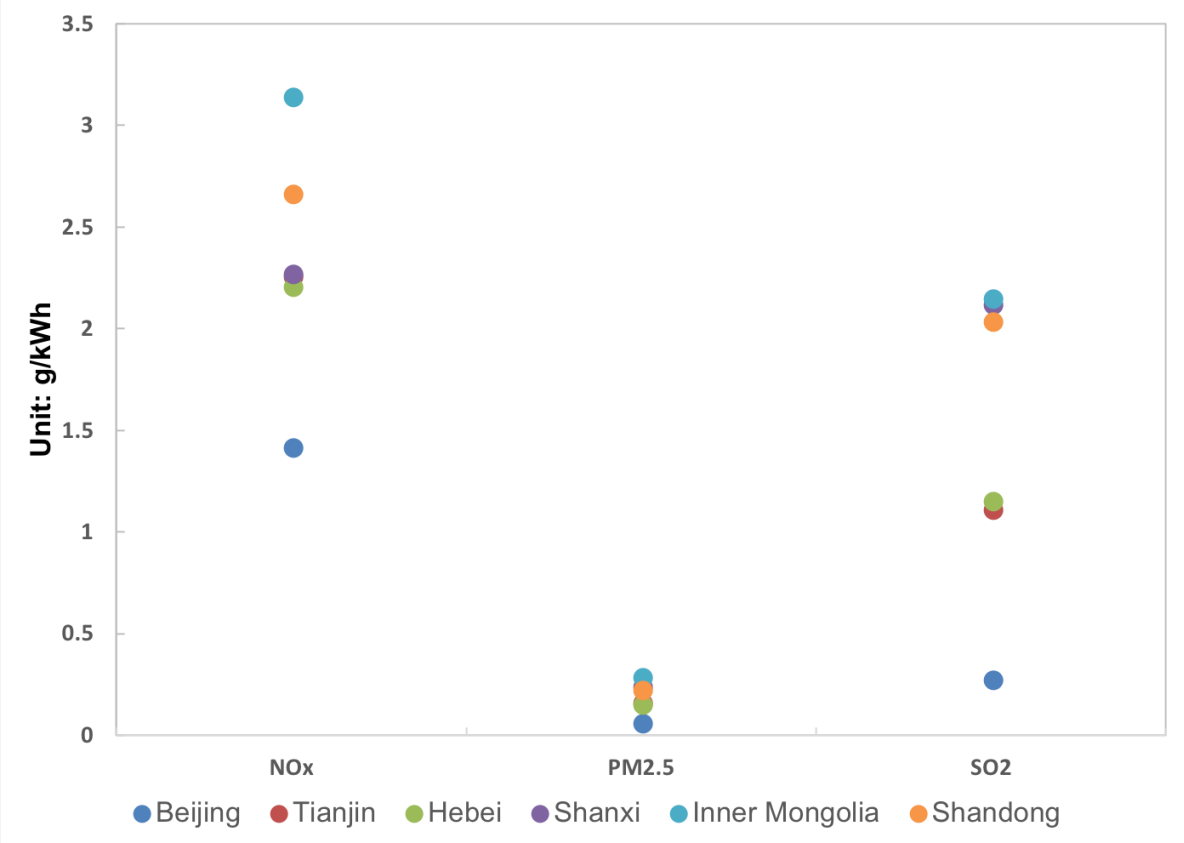


Fig. 1. Average 2012 power sector NO_x, $PM_{2.5}$ and SO_2 emission factors in each province within the North Power Grid (unit: g/kWh).

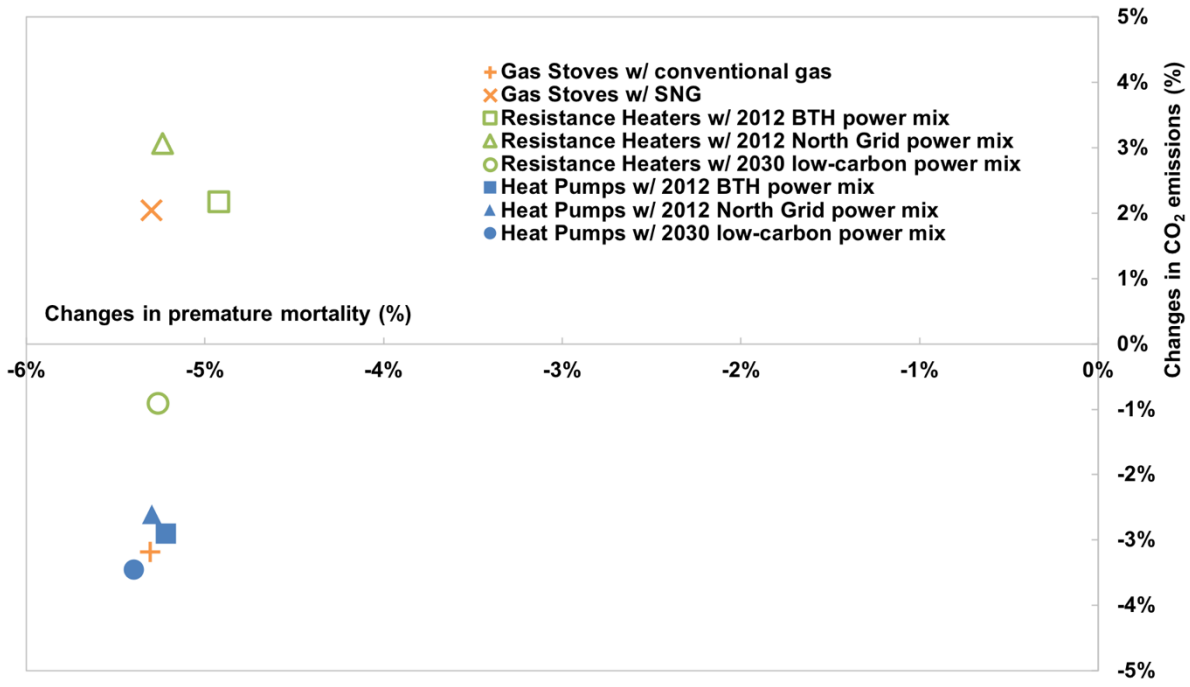


Fig. 2. Comparison of CO_2 emission changes (%) and avoided premature mortalities (%) under various heating replacement scenarios compared to 2012 base case.

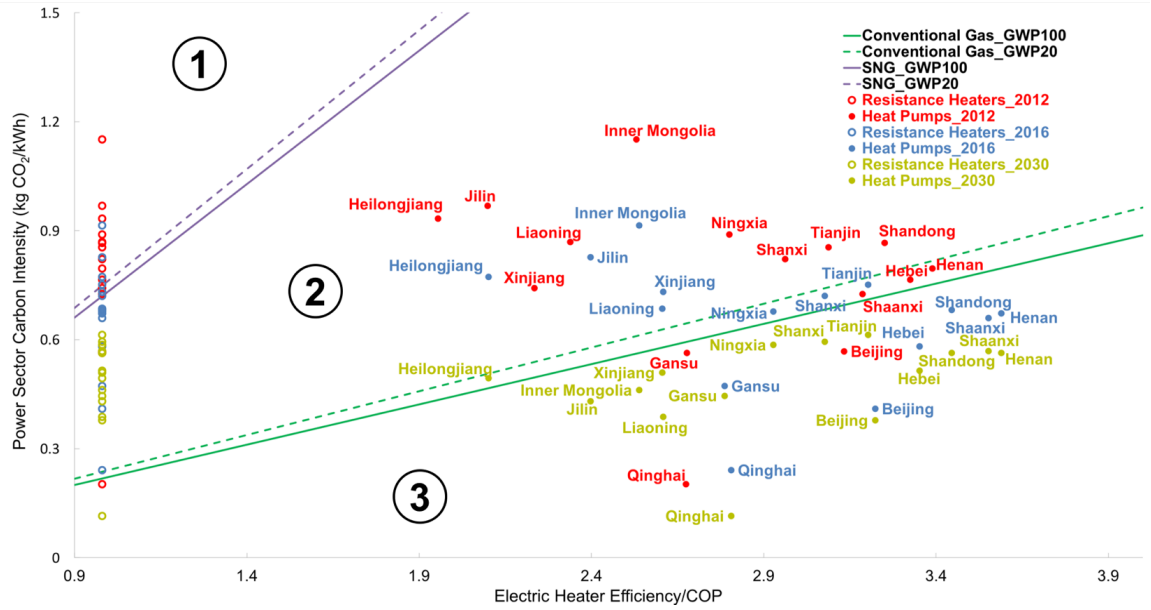


Fig. 3. Comparison of GHG emissions from gas and electric heating per unit heat generated in China's 15 northern provinces. The purple (green) lines indicate equivalent emissions for SNG and all types of electric heaters (for conventional gas and all types of electric heaters). Region 1, above the purple line, indicates that electric heaters will have higher emissions than either SNG or conventional gas; Region 2, between the purple and green lines, indicates that electric heaters will have higher emissions than conventional gas, but lower emissions than SNG; Region 3, below the green lines, indicates that electric heaters will have lower emissions than either SNG or conventional gas. Open circles indicate resistance heaters (assuming an efficiency of 97%) and closed circles indicate heat pumps (assuming an efficiency which varies as a function of average provincial winter temperature). Emission factors of electric heaters are determined by the provincial electric grids in 2012 (red), 2016 (blue) and a hypothetical low carbon grid for 2030 (dark yellow).

Table 1. Heating replacement scenarios

Heating Fuel	Stove Type	Heating fuel source
Gas	Gas stoves	Conventional gas
		Coal-based synthetic natural gas (SNG)
Electricity	Resistance heaters	2012 BTH regional power grid
		2012 North Power Grid (BTH region + Shandong, Shanxi, and Inner Mongolia)
		2030 BTH low-carbon power grid
	Air-source heat pumps	2012 BTH regional power grid
		2012 North Power Grid (BTH region + Shandong, Shanxi, and Inner Mongolia)
		2030 BTH low-carbon power grid

Chapter 4: Fostering the Battery Energy Storage Industry: What Lessons can we Learn from China's Wind and Solar Photovoltaic Industries?

1. Introduction

Energy storage is an effective way to mitigate grid integration challenges of intermittent renewable energy technologies (such as wind and solar photovoltaic) and provide increased flexibility as well as stability to power grid operations. Depending on the capacity and scale of energy storage systems, storage could be an integral component of a resilient and efficient power grid through applications such as load shifting, frequency regulation, voltage regulation, and providing peaking capacity etc. [1].

Currently, pumped-hydro storage has the largest installed capacity among all storage technologies in China, with 28.3 out of the total 28.9 GW installed capacity of energy storage projects coming from pumped-hydro in 2017 [2]. While the installed capacity of battery energy storage projects was only 0.4 GW in 2017, the growth rate of battery storage was 45% relative to 2016, which was significantly higher than the growth rate of either total energy storage capacity (19%) or pumped-hydro capacity (4.3%) [2]. Lithium-ion (Li-ion) energy storage is the most-deployed battery storage technology and is regarded as the most feasible near-term option due to the significant cost reduction potential of Li-ion batteries [1,3]. Li-ion battery storage accounted for ~60% of all battery storage projects in 2017 (in terms of total installed capacity) and is projected to reach 2 GW in 2020, representing a nearly 9-fold increase from the 2017 level (0.23 GW) [2].

The importance of energy storage in China's clean energy transition prompted China's National Energy Administration (NEA) to publish the country's first national

policy guidance for energy storage development in 2017 [4]. The policy guidance highlights the important role of energy storage in China's future energy system and the government's commitment to creating a competitive energy storage industry. In terms of specific policy instruments, however, the policy guidance provides limited information on how to design and implement policies to foster and develop China's energy storage sector. In particular, it does not address several key issues such as how to design specific policies to promote the deployment of energy storage capacity in the power sector or how to support of the storage industry in terms of promoting technological innovations and strengthening manufacturing capabilities.

Policies that facilitate the diffusion of clean energy technologies, also called "deployment policies", are crucial in triggering capacity additions as well as inducing technological advancements and industrial growth [5-8]. The enactment of deployment policies, such as feed-in tariffs (FiTs) and renewable portfolio standards, has been proved to induce innovations and growth in manufacturing capabilities in the clean energy sector. For example, Lewis and Wiser (2007) [8] find in many cases a clear relationship between a manufacturer's success in its home country market and its eventual success in the global wind power market. Lund (2009) [7] demonstrates the positive market impacts in the case of solar PV from public market incentive programs. Hoppmann et al. (2013) [6] find a strong coupling between technological innovations and domestic deployment policies.

Although the importance of deployment policies in supporting the clean energy industry is well documented in previous studies, there is relatively little empirical research that systematically compares the impact of deployment policies on industrial growth and international competitiveness of various other technologies. Thus, understanding the

variations in the benefits of using deployment policies to support industrial growth is critical to determine whether deployment policies are the best policy option to support China's battery energy storage industry.

Here I conduct a comparative case study analyzing the key factors that determine the effectiveness of deployment policies in promoting the domestic clean energy industry. I select China's wind and solar PV industries as the two cases used to evaluate the variations in deployment policy design from two specific perspectives. Section 2 discusses the theoretical perspective of the relationships between deployment policies, in particular, direct deployment subsidies, and industrial growth of the clean energy sector. Section 3 introduces the comparative case study approach and the selected cases of China's wind and solar industries. Section 4 compares the wind and solar industries in terms of the connections between the domestic market and the manufacturing industry, as well as the variety of end uses within the power sector. Section 5 analyzes China's battery energy storage sector from the same two perspectives as in Section 4. Section 6 concludes and summarizes the main policy implications.

2. Relationships Between Deployment Policies and Clean Energy Industrial Growth

2.1. Choosing deployment policies to support clean energy industrial growth

Research on deployment policies indicates that clean energy firms invest more to produce new products and upgrade their current manufacturing capacity when they expect to serve larger and stable markets [7,9]. Typically, deployment policies target technologies that have achieved a certain maturity level but have not been adopted by the market on a large scale due to higher costs or a high degree of technological uncertainty [10]. These policies aim to induce technological innovation and economies of scale, thereby increasing the

adoption of clean energy technologies. Previous studies have shown that market deployment measures, in particular direct deployment subsidies such as feed-in tariffs, in general lead to growing industrial activities [11-14]. Therefore, a strong connection between the domestic market and the manufacturing industry is essential for deployment policies to play an important role in promoting industrial growth.

The strong connection between the domestic market and the manufacturing industry is determined by both the technology's intrinsic characteristics and specific market conditions. Technological characteristics of different clean energy technologies affect the patterns of technological learning, manufacturing process, and the interactions with downstream users. Schmidt and Huenteler (2016) [15] differentiate various clean energy technologies based on two dimensions: complexity of the product architecture and scale of production process. Based on the dimensions, they define technologies as "design-intensive" technologies when there are complex sub-systems and components of the clean energy products (e.g. wind turbines, and solar PV panels), as well as intensive interactions between product designers, manufacturers and end-users. In contrast, they define technologies as "process-intensive" technologies when the clean energy product contains relatively less complex sub-systems and is more standardized, however, the production process is more complicated and require substantial manufacturing capabilities and economies of scale to develop the industry. Complex sub-systems in product design requires manufacturers to master continued technology adaptation and performance improvement in order to remain competitive in the market [15,16]. If technology adoption involves learning-by-using and interactions between manufacturers and end-users, then a large and stable domestic market can provide the manufacturers with proximity to their

downstream customers and extensive leaning opportunities with relatively lower transactions costs or lower market entry barriers than foreign markets. In contrast, if the production processes only require improving manufacturing capabilities and achieving economies of scale, then manufacturers can increase their competitiveness even if they export all of their goods with little interactions with end-users [16].

In addition to technological characteristics, the link between domestic market and manufacturing industry also depends on manufacturing firms' specific market conditions. If the export-oriented firms face more volatility from foreign demand due to changing market environment in foreign countries, then these firms would need support from their home country to maintain their business operations. In this case, domestic deployment policies will help create and increase domestic demand for the same type of clean energy products. If manufacturing firms that are mainly export-oriented can maintain or reduce their exposure to the volatility of export markets, then the domestic market is less significant to the firms since they can secure orders from foreign countries.

2.2. The variety of use cases of clean energy technologies and their impacts on the effectiveness of choosing deployment policies to support industrial growth

The strong connection between domestic market and the manufacturing industry creates the necessary condition for deployment subsidies to promote clean energy industrial development. I further analyze under what conditions will deployment subsidies be more effective in promoting industrial development. I argue that *the number of potential use cases* of a technology affects the effectiveness of deployment subsidies for that technology. A *use case* of a specific technology is defined as a specific source of value creation (economic application) created by the technology for a specific user group. Some

technologies are typically employed for one single purpose (e.g. wind turbines are installed only for power generation) by mainly one user group (e.g. developers of power generation projects), while other technologies have a variety of applications for different user groups (e.g. energy storage projects can provide multiple service such as facilitating renewable energy integration, providing frequency regulation and voltage regulation services to the grid etc.). The latter type of technology is defined as "multi-purpose technologies" by Battke and Schmidt (2015) [10]. A multi-purpose technology has the potential to create economic value in different ways and for different users. As the applications of the technologies differ in terms of users, value drivers and competing technologies, each application can be conceptualized as a separate niche market in which a technology can develop.

I argue that direct deployment subsidies work better for technologies that have single or few use case(s) than for multi-purpose technologies. Designing the type and range of deployment subsidies in single use case takes less time and policy resources than identifying and differentiating carious use cases and user groups user groups that apply for the subsidies. In addition, the effectiveness of deployment subsidies will be better evaluated in the case of single-purpose technologies. For a specific technology, the potential economic value each use case brings to the system and the costs of applying each use case could vary significantly. For example, solar panels can be either ground-mounted or installed on rooftops. These two use cases have different per unit costs and benefits to both project owners and grid operators. On the cost side, due to different project sizes and different components of balance-of-system costs, ground-mounted PV projects usually have lower unit installation costs ($ per MW) than rooftop PV projects [17]. On the benefit

side, while ground-mounted PV projects usually work as an independent power generation plant, rooftop PV projects first serve the power demand of the household/buildings to which they are attached and then send any remaining electricity back to the grid. This involves dealing with the multiple sectors in the power system, such as power generation, power distribution and retail. The differences in the costs and benefits of various use cases imply that it could be more difficult for policy makers to determine the exact range of deployment subsidies in order to bridge the profitability gap of clean energy technologies. Even if governments are able to introduce an application-specific deployment subsidy that has different incentive structures for each individual use case, implementing this type of subsidy will be more difficult than a single direct subsidy scheme because of the huge resources needed to determine each subsidy level and the difficulty of considering the interactions among different use cases. For instance, governments may need to conduct more extensive studies to identify all potential use cases and calculate their economic projections for a multi-purpose technology than a single-use technology. Differentiating each use case also involves dealing with various stakeholders, which in turn increases the transaction costs needed to engage with different stakeholders.

In addition to the difficulty of designing and implementing direct deployment subsidies for multi-purpose technologies, supporting multi-purpose technologies also requires enabling policies that facilitate the adoption of multi-purpose technologies. In some cases, deployment subsidies alone are not sufficient to create a substantial market for clean energy technologies or increase the economic feasibility of clean energy projects[18,19]. Policies and incentives are needed to tackle other market or regulatory barriers to adopting clean energy technologies. For example, the integration of intermittent

wind and solar power initially benefited from favorable electricity prices paid to wind/solar developers in China. However, due to the lack of other facilitating policies, such as a market-oriented reform of the inter-regional power transmission mechanism, excess renewable energy generation is not fully integrated into the grid. For example, in two of the five northwestern provinces, Gansu and Xinjiang, PV penetration rates in 2015 were only 8% and 5.4%, however more than 30% of the electricity generated from PV there was not integrated into the grid in either 2015 or 2016 [20]. Severe curtailment issue affected several wind and solar manufacturers in China due to the declining domestic demand in northwestern China, which is currently China's largest market for wind and solar due to the area's higher wind speed and more abundant solar radiation compared to other regions of China [20]. This indicates the limitations of direct deployment subsidies for supporting wind and solar power technologies in China. Because multi-purpose technologies often involve various points of interactions, there is greater need for policies that enable the functioning of multi-purpose technologies in different use cases and the interactions among various use cases. Therefore, in the case of multi-purpose technologies, direct deployment subsidies may not be the most effective policies to create a sustainable market for clean energy technologies and induce industrial growth. Instead, supply-side incentives, such as research and development (R&D) subsidies, and favorable manufacturing incentives (such as lower taxes and cheaper land etc.) are more effective to promote industrial growth, especially in the early phases of technology deployment [21,22].

In conclusion, I argue that strategies of promoting industrial growth by directly subsidizing deployment of clean energy technologies work well only when the potential use cases of those technologies are few and concentrated. If the clean energy technology

has multiple use cases, a direct deployment subsidy will fail to address the profitability gap of each single use case or the system-level interactions among different use cases. From the perspective of promoting industrial growth, demand-side incentives for multi-purpose technologies require more resources to implement, therefore, it would be more effective to design and implement targeted manufacturing-specific incentives and policies that remove the market or regulatory barriers to each use case.

3. Data and Methodology

To test the theory of the effectiveness of deployment subsidies, I select China's wind and solar industries as the main cases. Both industries formed strong connections between domestic market and the manufacturing sectors in China. More than 90% of wind turbines produced by Chinese wind manufacturers are installed in China and the Chinese wind manufacturers only account for a small share of global wind turbine exports [16]. Most of China's export of wind turbines have gone to other developing countries, rather than to mature markets in Europe and the United States [6]. Although initially the Chinese solar PV manufacturers predominantly focused on the overseas markets, more than 50% of the solar panels produced by Chinese manufacturers are now installed domestically, following China's dramatic growth in solar PV deployment after 2013 [16]. However, direct deployment subsidies, in this case the feed-in tariffs, played significantly different roles in the development of these two industries. On the one hand, China's deployment policies for wind was a pre-requisite to achieving successful growth of the Chinese wind power industry [7,8]. On the other hand, however, the Chinese PV industry became the global manufacturing leader without a significant home market initially. China's share of global solar panel production increased from less than 2% in 2003 to 35% in 2007 and 58% in

2013, while significant deployment subsidies for PV projects only occurred after 2013 in China to complement the supply-side manufacturing incentives for solar firms [18]. I also compare China's wind and solar industries with the emerging battery energy storage industry. Although there are currently few deployment incentives for battery storage projects, I also analyze the variety of use cases within the battery storage sector to test whether direct deployment subsidies will be effective to induce the growth of China's battery energy storage industry.

To study the interactions between deployment studies and industry development, I conducted 22 in-depth, semi-structured expert interviews during Summer 2016 and 2017. The interviewees include project developers, corporate executives, R&D scientists, consulting firms, non-governmental organizations working staff, academics, and governmental officials (Table 1). An interview guideline was developed with different questions depending on the individual expertise. Data from each interview was carefully recorded and triangulated across other interviews or with published documents. In addition to the interviews, I also review the existing literature on the use of deployment policies in China's wind and PV industry and discussions on using deployment policies for the battery energy storage. Government policy documents and business reports of relevant companies, as well as news reports for information on deployment subsidies for China's clean energy technologies are also used.

4. Comparisons Between China's Wind and Solar Industry

4.1 China's wind industry

Wind turbines involve several thousand customized electrical and mechanical components. Designing a new generation of wind turbines takes many years, involves a high level of

innovation, and requires highly skilled mechanical and electrical engineers with experience in the field. Wind turbines must be adapted to different climate conditions, wind speeds, wind profiles, and local regulations concerning grid-connection, foundations and noise. The project design, installation, operation, and maintenance of wind-farms requires specialized skills (e.g., turbine siting), training (e.g., for industrial climbers), and equipment (e.g., installation cranes) [15].

The availability of a significant domestic market allowed domestic wind firms to build the capabilities and tacit knowledge involved in designing and integrating entire turbine systems and then to completely manufacture them locally. Hence there is a strong link between the domestic wind market and the success of wind turbine manufacturing firms. The creation of a domestic wind industry and the accumulation of indigenous technological capacities has been a central aim of the Chinese government ever since it started investing in domestic wind turbine manufacturing in the mid-1990s [6]. In 2011, four Chinese wind manufacturers (Goldwind, Sinovel, United Power and Mingyang) were already among the world's top 10 wind turbine manufacturers with a total share of 26.7% of the world market. At the same time, Chinese also had the world's largest wind installed capacity (~115 GW) [20].

Wind power generation technology has only one use case within the power system, which is generating electricity on the wholesale market, hence it can be regarded as a single-use technology. The single use case of wind technology makes it fairly simple to calculate the range of deployment subsidies that could increase the profitability of wind projects. China's has three different tiers of wind FiTs for different wind resource regions. The region that has the highest wind speed (Northeast and part of Northwest China)

receives the lowest FiTs (0.35 RMB/kWh) and the region with the lowest wind speed receives the highest FiTs (0.55 RMB/kWh) [20]. Since wind speed data is publicly available from China's meteorological observation network, designing the range of FiTs for wind only involves a survey of the costs of wind project development from the industry association and leading project developers.

4.1.2 China's solar PV industry

PV cells and modules are mass-produced goods that can be integrated relatively easily into different PV power systems. Crystalline silicon cell designs produced commercially were developed predominantly in the 1980s and 90s and are relatively easily accessible to new entrants by purchasing turn-key production lines [15]. Solar PV module performance predicted in numerical and analytical models is very close to actual performance. Therefore, the need for interactions between manufacturers and project developers are not as strong as in the case of wind. Because solar PV cells and modules are mass-produced goods, countries that were successful in creating a local silicon or cell manufacturing industry did not necessarily require the enactment of deployment policies and a robust domestic deployment market initially. China's quick catch up in solar cell manufacturing shows that a large global market, access to low-cost capital for manufacturing plant finance, and local manufacturing capabilities are much more important to building up a local solar cell industry than the existence of a large home market created by domestic feed-in tariffs.

However, Chinese solar manufacturing firms started to experience significant decline of demand from the global solar market after the 2008 financial crisis. The crisis prompted several European countries to phase down generous feed-in tariffs for solar PV installation and this resulted in PV demand from Europe decreasing drastically since 2010

[23-25]. Since more than half of the PV panels produced by Chinese solar manufacturers were sold to Europe, this created a significant shock to the Chinese solar industry. In addition, trade disputes started to emerge between China and the solar industry's main trade partners after the financial crisis. Chinese solar cell firms were subject to both antidumping and countervailing duties in the US and the minimum import prices commitment in the EU [26].

The rapid decline of European incentives and solar installations prompted the Chinese government to find alternative markets for China's solar manufacturing firms [27,28]. Therefore, the Chinese government introduced national solar feed-in tariffs following the experience of wind feed-in tariffs. However, unlike wind, solar PV can be utilized either as ground-mounted solar PV plants (utility-scale PV), or as distributed PV systems on the rooftops of residential, commercial and industrial buildings (distributed PV). Similar to wind projects, utility-scale solar PV projects are only deployed to generate electricity. However, distributed PV systems can be deployed to serve various needs from different types of system owners. Residential users deploy distributed PV systems mainly to reduce their retail electricity bills by using the electricity generated from PV panels. However, some owners of distributed PV systems plan to have significant financial returns from the solar panels, thus requiring a more stable potential revenues from distributed PV systems.

To increase the demand of solar PV panels in both use cases, the Chinese government engaged in multiple rounds of reviewing and revising the solar feed-in tariffs for both utility-scale and distributed PV. In August 2011, the National Development and Reform Commission (NDRC) issued the Notice on Perfecting Feed-in Tariff Policy of

Solar PV Power Generation, which determined the national feed-in tariffs for utility-scale solar PV projects [19,28]. In August 2013, this standard was further modified and the nationwide power generation was divided into three level resource areas, based on solar resource endowment. Meanwhile, the NDRC also set up feed-in tariffs for distributed solar PV projects as 0.42 RMB/kWh [20]. Because China's solar PV installation was predominantly concentrated in the northwestern provinces before 2013, the Chinese government intended to encourage a balanced deployment of utility-scale in the its northwestern provinces (where solar radiation is more abundant) and 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 [29]. However, 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 [30]. This trend continued in 2016, with 30 GW utility-scale and only 4 GW distributed PV installed [31]. Therefore, deployment subsidies for distributed solar alone are insufficient to significantly encourage the deployment of distributed PV.

Because solar PV has two different use cases, the process of designing appropriate feed-in tariffs for each use case takes more time and resources than designing wind feed-in tariffs. First, the mechanisms of utility-scale solar FiTs and distributed solar FiTs are completely different. The feed-in tariffs for utility-scale solar systems also have three tiers based on solar radiation resources, following the similar methodology as wind FiTs. In contrast, in addition to a uniform 0.42 RMB/kWh subsidy for all the electricity generated from PV, the feed-in tariffs for distributed solar differentiate between self-consumption of

solar-generated electricity and the additional electricity that goes back to the grid [11]. For the self-consumption part, the subsidy can be regarded as the "saved" retail electricity bills because of the solar-generated electricity. For the rest of the electricity, the distributed solar FiTs are the same as the wholesale electricity price of coal-fired power plants within the same province. To determine the appropriate range of subsidies, the Chinese government conducted multiple rounds of discussions with solar project developers, solar panel manufacturers, power grid companies, and existing users of distributed solar systems. Under the subsidy scheme for distributed PV system, the share of self-consumption electricity in total generation will have a great impact on the financial returns of a distributed PV project because retail electricity price is always higher than the wholesale price. A government official interviewed stated that the feed-in tariff scheme was designed based on the assumption that 80% of the electricity generated by PV is consumed by the system owners. In reality, the subsidy scheme fails to consider the difference in electricity consumption among residential, industrial and commercial consumers. This creates significant uncertainty in the financial returns of distributed PV projects.

To increase the deployment of distributed PV systems, the Chinese government revised the initial feed-in tariffs for distributed PV in 2014 [19], providing distributed PV system owners the flexibility to choose from the "self-consumption with excess electricity sold to the grid" subsidy scheme and the new "all sold to the grid" scheme. Under the new scheme, project owners can sell all the electricity generated from solar to the grid and receive a fixed tariff between 0.9 and 1 RMB/kWh. Distributed PV systems that were under the old subsidy scheme can also choose the new scheme. The new deployment policies are more specifically tailored for distributed PV owners that have higher and lower on-site

electricity consumption. The multiple versions of distributed PV subsidies indicate that for a multi-use technology, a single subsidy scheme will fail to encourage the deployment of clean energy technology in all of the use cases. However, to develop an application-specific subsidy scheme in which deployment subsidies are separately designed for different use cases, it may take multiple processes of experimenting with different subsidy designs to ultimately find an effective subsidy scheme. Moreover, as the technology evolves, the effective subsidy scheme may also need to be updated in accordance with the changing use cases.

The multiple uses of solar PV systems in the power sector also indicate that deployment subsidies alone may not be sufficient to increase PV deployment. For example, development of distributed PV is sometimes constrained by the availability of rooftop resources [19,32]. According to the interviews, solar project developers often invest substantial time and resources to find owners of commercial and industrial buildings who are willing to install solar panels on their rooftops. In addition, when the customers of distributed PV systems move out from the building, the new property owner may refuse to continue permitting solar panels on the rooftop. Without policies to tackle the issue of rooftop resource availability, deployment subsidies for distributed PV are not sufficient to significantly increase the deployment of solar panels on the rooftops of commercial and industrial buildings.

Given the multiple applications of solar PV in the power system, I find that deployment policies for solar PV did not effectively accelerate distributed PV deployment. In order to target each use case of solar PV, it takes more resources to design specific deployment policies for both utility-scale and distributed PV. In addition, because

distributed PV systems require more interactions and coordination among different actors (rooftop owners, project developers, and power grid companies), deployment subsidies alone would not achieve the intended large-scale adoption of solar PV technologies in eastern China.

5. Analyzing China's Support for the Battery Energy Storage Industry

Similar to wind turbines, lithium-ion batteries also involve a large number of sub-systems and components [33-35]. The value chain of the Li-ion battery sector includes processing raw materials, manufacturing cathode active materials, the electrolyte, the binder and separator, as well as electrode foils [20]. Besides the complex value chain, Li-ion batteries have multiple areas for performance improvement, such as the energy density, power requirements (speed of charging/discharging), cycle life, safety, and costs etc. [36]. To manage the interactions among different technological characteristics, close interaction between battery manufacturers and energy storage project developers is critical, especially in the early phase of battery deployment in which storage system operators still need to tackle various performance and safety issues to better serve the needs within the power system [20]. Therefore, a strong connection between the domestic market and the manufacturing sector also exists in the Li-ion battery industry. The intensive manufacturer-user interactions and the diverse performance criteria for battery energy storage application justify the use of demand-side policies to promote the battery storage industry through creating opportunities for battery manufacturers to improve product design based on the interactions with domestic downstream storage system operators [36].

In terms of the variety of use cases, battery energy storage is also a multi-purpose technology because battery storage can be used for different purposes in the power system.

The use cases of battery energy storage projects can be divided into three categories: (1) power generation, (2) transmission and distribution, and (3) end-consumer [1,3,10].

First, in the power generation category, the applications of Li-ion batteries are wholesale energy arbitrage and renewable energy integration. In the application of wholesale energy arbitrage, electricity will be stored in batteries when wholesale electricity price is lower than a certain wholesale price level ("pre-determined level") and the electricity stored in batteries will be sold on the wholesale market when electricity price is higher than the pre-determined level. In this case the battery system can be regarded as both a consumer and generator of electricity in the wholesale market. Battery systems that undertake wholesale arbitrage can also be managed to reduce the peaking demand of the power grids, as system operators can store electricity in low-demand time periods and discharge the batteries during peak demand periods. This will significantly decrease the need to invest in new peaking capacity (currently peaking capacity is mostly provided by gas-fired power plants or oil-fired power plants) to serve the growing electricity demand. Battery systems can also facilitate the integration of intermittent renewable energy into the grids and reduce curtailment of renewable power generation. Given the increasing renewable integration challenges due to mismatch between renewable energy generation and electricity demand as well as the lack of inter-regional transmission capacity, Li-ion battery storage is a promising option to smooth the output of intermittent renewable power generation and reduce curtailment when electricity demand is low.

Second, in the transmission and distribution category, battery storage projects can provide important ancillary services such as frequency and voltage regulation, as well as reserve capacity. In order to keep the frequency of the grid alternating current and the grid

voltage level within permissible limits, there needs to be a balance between demand and supply at each instant. This can be done at different time scales by adjusting power generation, using demand response or electricity storage. Primary control reserve stabilizes the system frequency in the time frame of seconds, followed by secondary control reserve (in the time frame of seconds up to 15 minutes) [18,37,38]. The fast response of Li-ion batteries makes them suitable for frequency and voltage regulation. Battery storage systems can also delay the construction of transmission and distribution systems, especially in remote areas where the costs of extending the existing transmission and distribution systems could be higher than investing in a standalone battery system.

Third, in the end-consumer category, battery storage projects can be employed as retail electricity arbitrage when there are significant differences between retail electricity prices in peak-demand and low-demand periods. For example, commercial and industrial retail electricity prices in Jiangsu are significantly different in peak-demand and low-demand periods [2], hence several large factories in Jiangsu installed behind-the-meter energy storage systems to engage in retail electricity arbitrage to reduce the costs of electricity and create additional revenue stream. There is also increasing demand for residential battery storage system combined with residential distributed solar PV systems. The PV-plus-storage system can also facilitate residential users reducing their retail electricity bills. For example, residential PV owners in some parts of the US have to pay additional demand charges to the utilities for their yearly maximum power consumption [39]. In this case using batteries to reduce the peak consumption can lower the total retail electricity bill and also increase a residential household's independence from the grid in case there is system-wide break down of power grids.

In summary, battery energy systems have multiple use cases within the power system. The applications span from generation, transmission and distribution to end-use consumers. Thus energy storage systems can create value in different ways and for different user groups. In addition, there are also substantial variations in the development status and profitability of each battery system use case. Some applications, such as behind-the-meter energy arbitrage and ancillary services have proven commercial viability and have been deployed in several countries [3,10,38]. However, other applications, such as PV-plus-storage application and renewable energy integration are still unable to operate with positive economic benefits without deployment subsidies. In some countries, storage applications such as frequency/voltage control and wholesale energy arbitrage are currently not permitted due to the lack of regulatory permission to give storage projects the same status as other power generation facilities [40,41]. Therefore, it is clear that a single direct deployment subsidy is not able to address the regulatory barriers and profitability gap of every possible use case of battery storage systems.

Given the multiple use cases of battery storage systems in the power system, I argue that direct deployment subsidies may not be the best policy option to support China's Li-ion battery manufacturing industry. To better support the industry, subsides should be allocated to the battery manufacturers directly to induce technological innovation and industrial growth. In addition, the Chinese government should also consider clearing the current market and regulatory barriers to battery storage applications in the power system in order to develop a large-scale battery storage deployment in the power system.

6. Conclusions and Policy Implications

Comparing China's wind, solar PV, and Li-ion battery industries, I find that a strong connection between domestic deployment and the manufacturing industry is the necessary condition for deployment policies to induce industrial growth. Both wind and Li-ion battery technologies involve complex sub-systems and constant manufacturer-user interactions to improve product design. Therefore, a strong domestic market provides the perfect opportunity for wind and battery manufacturers to learn from interacting with downstream users and improve their product design and manufacturing capabilities. Although product design of solar panels requires less manufacturer-user interactions than wind or Li-ion batteries, a strong domestic market would also provide solar panels manufacturers with substantial demand, which will help them achieve economies of scale and cost reduction through learning-by-doing. In addition, after the declining demand for solar panels from the EU and the US, Chinese solar manufacturers formed a stronger connection with the domestic solar market in order to keep growing their businesses. Therefore, the strong domestic market-manufacturer connections make it possible for deployment policies to induce industrial growth.

However, the role that deployment policies have played in promoting industrial growth vary significantly across the wind, solar and Li-ion battery storage sectors. I find that systematic strategies of promoting industrial development by subsidizing deployment of technologies work well only when the potential use cases of those technologies are relatively few and concentrated. Li-ion battery storage has multiple use cases across generation, transmission and distribution, as well as the end-consumer sectors of the power system. Thus designing deployment subsidies for Li-ion battery storage requires

substantial efforts to identify and differentiate each use case, as well as to calculate the range of subsidies for each use case. The multiple use cases of Li-ion battery technology also indicates that there are various stakeholders involved in the application of battery storage in the power sector. From the analysis of each storage use case, I find that the majority of storage use cases require not only direct deployment subsides, but also policies that enable the application of storage technology in the power sector. For example, battery storage system are not eligible to provide ancillary services in China's power system (except for Shanxi and Hebei, which have the only two storage application demonstration projects) [40,41]. Therefore, in order to effectively promote market adoption of clean energy technologies and promote the manufacturing industry, future deployment design for battery storage should first remove the market and regulatory barriers to storage application in China. At the same time, the Chinese government should prioritize using supply-side policies to directly support the Li-ion battery manufacturing industry, which could lead to cost reductions of storage technologies through continued innovation and improved manufacturing capabilities.

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Table 1. Summary of Interviews

Industry	Organization	Number	Positions
Wind	Government research institutes	2	Researcher, Energy Research Institute, National Development and Reform Commission
	Universities	2	Professor, Tsinghua University
Solar	Government officials	2	Deputy Department Director, Department of New Energy, National Development and Reform Commission of Jiangsu
	Government research institutes	1	Researcher, Energy Research Institute, National Development and Reform Commission
	Universities	2	Professor, Tsinghua University
	Manufacturing firms	4	Chief Executive Officer; Chief Financial Officers; Head of Government Relations; Head of Department of Research and Development
	Industry Associations	1	Vice President, China Solar Photovoltaic Association
Storage	Universities	2	Professor, Chinese Academy of Science
	Government research institutes	2	Researcher, Grid-integration of storage technologies
	Industry Associations	2	Vice President; Head of Research Department
	Li-ion manufacturing firm	2	Head of Research and Development

Chapter 5: Conclusion

China's coal-dominated energy system has resulted in both air pollution and climate change challenges. A large-scale clean energy transition toward significantly less coal and other fossil fuel consumption is necessary for China to tackle the greenhouse gas mitigation and regional air pollution at the same time. To facilitate the clean energy transition, the Chinese government has designed and implemented various deployment policies to accelerate the adoption of clean energy technologies across different sectors. To justify the use of deployment policies, the Chinese government has focused on simultaneously achieving multiple benefits, such as reducing greenhouse gas emissions, improving air quality, and fostering strategic industries, from implementing various deployment policies. My dissertation uses three case studies to compare the climate, air quality and industrial growth co-benefits of various deployment policies within China's energy sector.

Chapter 2 focuses on China's solar PV deployment. I compare two types of deployment policies for solar PV in China: *policies that encourage utility-scale PV deployment in northwestern China without enabling inter-provincial transmission of PV electricity* and *policies that encourage distributed PV deployment in eastern China with inter-provincial transmission of PV electricity*. The results indicate that the latter deployment policies would achieve greater climate and air quality co-benefits from displacing coal generation in 2030, because they maximize displacement of the dirtiest coal-fired power plants and minimize PV curtailment, which is more likely to occur

without inter-provincial transmission in the Northwest. The results highlight two potential deployment policy options that can achieve greater climate and air quality co-benefits from solar PV, which are *shifting PV deployment from utility-scale PV to distributed PV*, and *enabling inter-provincial transmission of PV electricity*.

Chapter 3 focuses on China's residential sector. The residential sector is a significant contributor of China's severe air pollution in recent years. Both central and local government have designed deployment incentives to encourage the adoption of clean residential heating choices such as gas and electric heating. I compare the climate and air quality implications of using gas or electric heating to replace all small solid fuel heating stoves in the Beijing-Tianjin-Hebei region in 2012. I find that deploying air-source heat pumps with low-carbon electricity brings the greatest greenhouse gas mitigation and air quality improvement. As China further decarbonizes the power sector, the advantage of heat pumps compared to gas heating will be more significant in the future. I also find that two deployment options of clean heating will lead to air quality and climate trade-offs. Using coal-based synthetic natural gas (SNG) for gas heating and using resistance heaters with the carbon-intensive power mix both increases the BTH region's total greenhouse gas emissions while significantly reducing ambient air pollution.

Chapter 4 focuses on China's lithium ion battery storage deployment in the power sector. Battery storage is a promising option to facilitate the integration of intermittent renewable power sources into the grid. Thus the Chinese government is designing deployment policies for storage applications and also intends to use deployment policies

to support the growth of lithium ion battery manufacturing industry. Comparing between China's wind and solar industries, I find that promoting clean energy industrial development by subsidizing deployment of technologies work well only when the potential end uses of those technologies are relatively few and concentrated. Because battery storage involves multiple applications across the generation, transmission and distribution, and end-use sectors in the power system, designing appropriate deployment subsidies requires substantial efforts to identify and differentiate each use case, as well as to calculate the range of subsidies for each use case. Therefore, choosing deployment policies to support industrial growth will be less efficient than directly support the manufacturers of lithium ion batteries, such as offering R&D and manufacturing to manufacturing firms.

Based on the findings from these three case studies, I make the following suggestions for future research on the climate, air quality and industrial growth co-benefits of various deployment policies in the energy sector:

1. Conducting cost-benefit analysis of various deployment policies

Future research on evaluating the co-benefits of deployment policies should include a more comprehensive economic analysis of the costs to implement deployment policies and the potential economic benefits of various deployment policies. For example, the large-scale implementation of replacing residential small heating stoves requires detailed and careful economic analysis to understand the economic implications of residential heating replacement. Although initial capital costs are higher for heat pumps than resistance heaters, operating costs are lower and significant health and greenhouse gas

mitigation benefits exist when heat pumps are chosen. Thus, it would be beneficial to have a comprehensive analysis of these factors in order to develop policy mechanisms and incentives to encourage the uptake of heat pumps. A comprehensive economic analysis of the co-benefits of deployment policies requires inter-disciplinary work between economics and energy system analysis.

2. Evaluating the role of critical infrastructure to facilitate clean energy transition

One important implication from my dissertation is that China's future clean energy transition requires significant investment in energy infrastructure. To enable inter-provincial and inter-regional transmission of PV electricity, China is building several 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. To enable household adoption of electric heating, the power distribution system in the BTH region also needs to be expanded and upgraded in order to handle the increased power capacity from the residential sector. Future research should consider the need for infrastructure and the implications of deployment policies on infrastructure investment, which will have long-term climate and air quality implications.

3. Applying the analytic framework to other sectors and countries

The integrated assessment framework for analyzing the climate and air quality co-benefits of China's deployment policies can be applied to other sectors and countries in the future. For example, a similar study can be designed to quantify the co-benefits of

solar PV in other countries facing similar grid-integration constraints and mismatch between PV generation and electricity demand. The discussion on using deployment policies to support industrial growth can also be used to study whether the variety of use cases also affect the effectiveness of using demand-side policies to support industrial growth for other advanced technologies, such as advanced manufacturing technologies and advanced transportation technologies etc.

Appendix for Chapter 2

Climate, Air Quality and Human Health Benefits of Various Solar Photovoltaic Development Scenarios in China in 2030

1. China's regional power grids

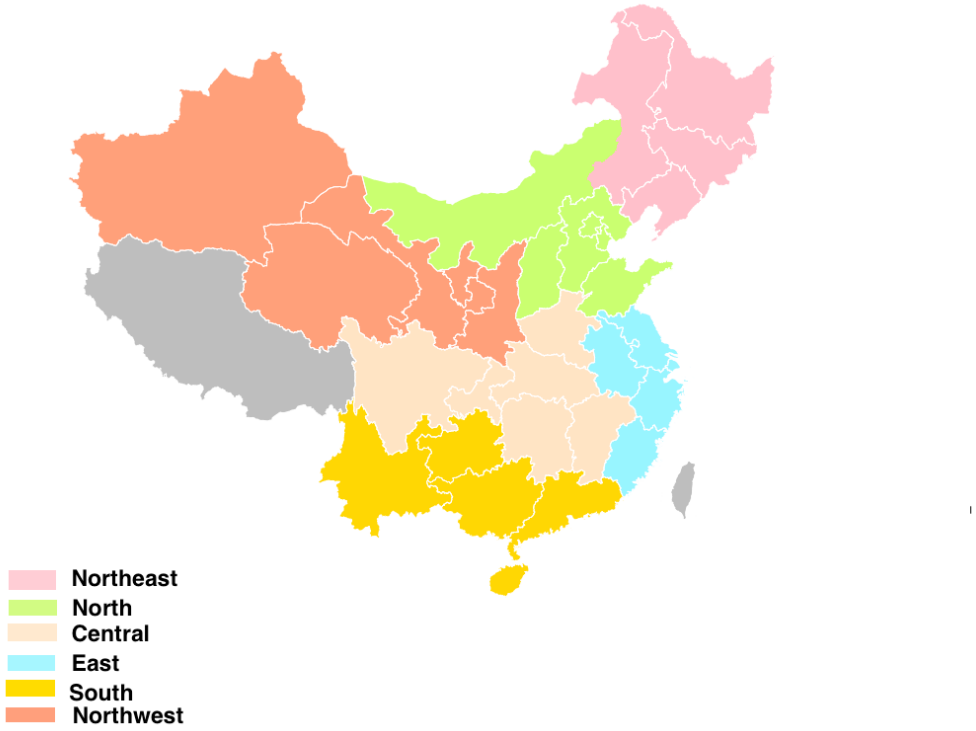


Fig. S1. China's six regional power grids (excluding Tibet)

2. Detailed methods for calculating capacity factors for both types of PV for each province

We apply the PVLIB-Python model, a solar PV performance model, to simulate PV electricity generation efficiencies at each 1º latitude by 1º longitude continental grid box globally. PVLIB-Python takes irradiance data as input and provides alternating current (AC) power as output. We further calculate PV capacity factors (the AC output divided by the designed maximum output power) to measure PV efficiency. We use surface solar irradiance from the NASA CERES-SYN1deg dataset including both clouds and aerosols. The model takes input of surface solar irradiance, first calculates the point-of-array-irradiance (POAI, irradiance received by a panel at any tilted angle), further takes the input of weather data to calculate the direct-current (DC) output power, and finally applying the inverter for the AC output power. In this process, both PV cell efficiency (solar energy converted to DC electricity) and inverter efficiency (DC to AC electricity) are considered. We applied the wrapper developed by Li et al. (2017) [1], which enables parallel computing for a large number of grid-point locations and time steps using the PVLIB-Python model, and increases the computing efficiency.

In this study, Canadian Solar CS5P 220M is used as the PV module, with maximum output power of 220 W and peak efficiency of 12.94%. ABB MICRO-0.25-I-OUTD-US 208Vac is the inverter applied to the model with designed efficiency of 96%. Combined together, the peak PV system efficiency is 12.42%.

3. Detailed methods for determining the order of coal-fired power plant displacement in the *Regional* scenarios

In the *Regional* scenarios, we determine the order of subcritical coal power plant displacement by the damage-weighted $PM_{2.5}$ precursor emissions calculated as

$$EF^{i}_{eff,j} = \left(1.75 \times EF^{i}_{SO_2,j} + EF^{i}_{NO_x,j}\right) (1)$$

$EF^{i}_{eff,j}$ is the effective emission factor for the specific category of coal-fired power plant j in province i (unit: kt/PJ)

$EF^{i}_{SO_2,j}$ is the SO_2 emission factor for the specific type of coal-fired power plant j in province i (unit: kt/PJ)

$EF^{i}_{NO_x,j}$ is the NO_x emission factor for the specific type of coal-fired power plant j in province i (unit: kt/PJ).

The emission factors for SO_2 and NO_x are from the ECLIPSE_v5a_CLE scenario in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model. For each air pollutant, subcritical coal plants are further disaggregated into different categories according to the end-of-pipe control technologies they employ in GAINS and presented as the percentages of total coal use for electricity generation. The 1.75 weighting is obtained from a related study to the health impacts of SO2 and NOx from the power sector, considering their relative contributions to the formation of secondary inorganic aerosols [2].

4. Detailed methods on spatial and temporal allocations of emissions in the base case and PV scenarios

We map provincial annual emissions in the ECLIPSE_v5a_CLE scenario and all four PV scenarios onto gridded (0.25 degree by 0.25 degree) and monthly emission profiles following the spatial and temporal patterns from the MEIC 2012 emission inventory. In detail, for each province $i, i \in [1,31]$ in China, each sector $j, j \in [1,5]$ (power, industry, transportation, residential, and agriculture) and each month $m, m \in [1,12]$, there are gridded (0.25 degree by 0.25 degree) MEIC emissions for each pollutant ($MEIC_{i,j,m}^{k}$, k represents all grid boxes that belong to Province i). There are also annual emissions in MEIC for each grid box for each pollutant ($MEIC_{i,j,a}^{k}$, a means annual total emission).

In the GAINS emission inventory there are only annual provincial total emissions for each sector ($\mathrm{GAINS}_{\mathrm{i,j,a}}^{\mathrm{Base}}$ for the base case emissions). In particular, coal-fired power plants in GAINS are divided into 18 different categories based on their efficiency levels and air pollutant emission factors (unit: g/kWh electricity generated). The ECLIPSE_v5a_CLE scenario does not have a plant-level database of all coal-fired power plants, thus only the aggregated electricity generation data in each category is provided in the GAINS model. In the four PV scenarios, we calculate the annual provincial total emissions for each pollutant ($\mathrm{GAINS}_{\mathrm{i,j,a}}^{\mathrm{Sce}}$) by subtracting the sum of emissions from the coal plants that are displaced by PV in each category in the base case ($\mathrm{GAINS}_{\mathrm{i,j,a}}^{\mathrm{Base}}$). The emissions of each pollutant from those displaced coal plants are calculated as the product of the electricity generated from those coal plants in the base case and the emission factors of each pollutant. We displace coal plants from the category with the most polluting (defined as the highest SO_2 and NO_x emissions combined) subcritical coal-fired power plants to the category with the least polluting coal plants. The most polluting subcritical coal plants are also the least efficient ones, and have the highest CO_2 emission factor accordingly. To get the gridded monthly GAINS emissions, we assume that the GAINS emissions follow the same spatial and temporal pattern as MEIC and calculate the gridded emissions using Equations (2) and (3).

$$GAINS_{i,j,m}^{Base,k} = MEIC_{i,j,m}^{k} \times \frac{GAINS_{i,j,a}^{Base}}{\sum_k MEIC_{i,j,a}^{k}} \quad (2)$$

$$GAINS_{i,j,m}^{Sce,k} = MEIC_{i,j,m}^{k} \times \frac{GAINS_{i,j,a}^{Sce}}{\sum_k MEIC_{i,j,a}^{k}} \quad (3)$$

We use the same methods for emissions outside China, where we map the annual country-specific emissions in ECLIPSE_v5a_CLE onto gridded (0.1 degree by 0.1 degree) monthly profiles following the spatial and temporal patterns from the HTAP 2010 emission inventory.

5. More details on WRF-Chem model configurations:

Table S1. Physical and chemistry options used in WRF-Chem simulation

Model configurations	
Atmospheric process	WRF-Chem scheme
Cloud microphysics	Lin et al. scheme
Long-wave radiation	RRTM scheme
Short-wave radiation	Goddard shortwave
Surface layer	MM5 similarity
Boundary layer	Yonsei University scheme
Cumulus parameterization	Grell 3D scheme
Land surface	Noah land surface model
Chemistry option	RADM2 chemical mechanisms and MADE/SORGAM aerosols including aqueous chemistry
Photolysis	Fast-J photolysis

6. Detailed calculations of health impacts associated with air pollution

Changes in the number of premature deaths of each disease associated with $PM_{2.5}$ pollution in each 27 km by 27 km WRF-Chem grid box are calculated as follows:

$$\Delta Mort_i = POP * MR_{Base,i} * [RR_i(C_{Sce}) / RR_i(C_{Base}) - 1] \quad (4)$$

$\Delta Mort_i$ is the change in premature mortalities in each WRF-Chem grid box due to disease *i* in 2030;

POP is the projected population in each grid in 2030 (total provincial population is included in the Eclipse_v5a_CLE scenario, county-level population distribution follows the same pattern as the 2010 China census data [3]. We use ArcGIS 10.0 to map county-level population onto WRF-Chem grid boxes).

$MR_{Base,i}$ is the baseline mortality rate for disease *i* in 2013 [4],

$RR_i(C_{Sce})$ is the relative risk (RR) for disease *i* at the $PM_{2.5}$ concentration (C) in each scenario (*Sce*). We use RR functions from the Global Burden of Disease study (3), with linear interpolations for non-integer concentration levels,

$RR_i(C_{Base})$ is the relative risk for disease *i* at the $PM_{2.5}$ concentration in the base case.

7. Comparison of capacity factors obtained with one-axis tracking systems applied in utility-scale PV plants and those obtained with fixed arrays in distributed PV systems by province

Table S2. Capacity factors of utility-scale and distributed PV by province

Province	Capacity factors for utility-scale PV	Capacity factors for distributed PV
Anhui	0.1437	0.1393
Beijing	0.1998	0.1907
Chongqing	0.1159	0.1103
Fujian	0.1426	0.1413
Gansu	0.2208	0.2025
Guangdong	0.1526	0.1437
Guangxi	0.1405	0.1330
Guizhou	0.1266	0.1189
Hainan	0.1690	0.1549
Hebei	0.1877	0.1795
Heilongjiang	0.1919	0.1885
Henan	0.1487	0.1438
Hubei	0.1353	0.1298
Hunan	0.1270	0.1210
Jilin	0.1908	0.1840
Jiangsu	0.1436	0.1402
Jiangxi	0.1527	0.1345
Liaoning	0.1832	0.1775
Inner Mongolia	0.2273	0.2134
Ningxia	0.2222	0.2043
Qinghai	0.2503	0.2272
Shaanxi	0.1755	0.1638
Shanghai	0.1436	0.1402
Shandong	0.1556	0.1514
Shanxi	0.1983	0.1867
Sichuan	0.1762	0.1642
Tianjin	0.1599	0.1582
Tibet	0.2715	0.2391
Xinjiang	0.2273	0.2106
Yunnan	0.1882	0.1726
Zhejiang	0.1498	0.1411

8. Projected percentage of provincial electricity generation derived from PV in the *Skewed* and *Balanced* PV deployment scenarios in 2030.

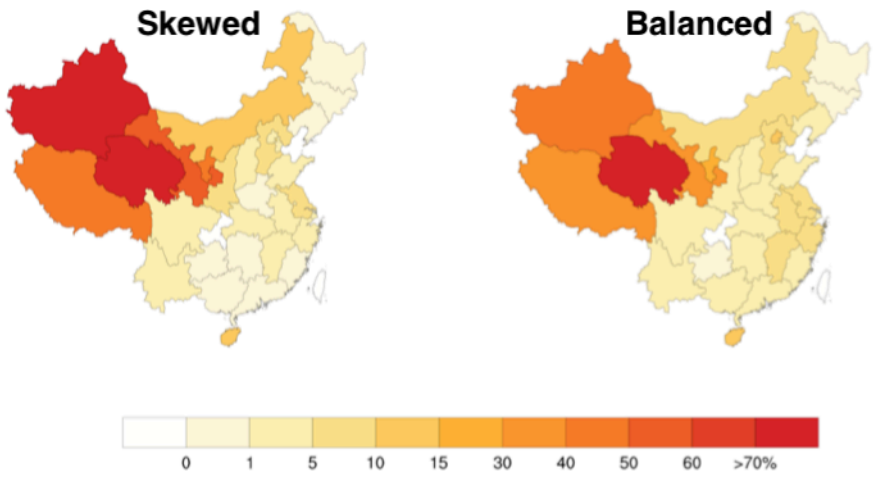


Fig. S2. Projected percentage of provincial power generation derived from solar PV in 2030.

9. Gridded SO_2 and NO_x emission reductions in each scenario compared to the base case

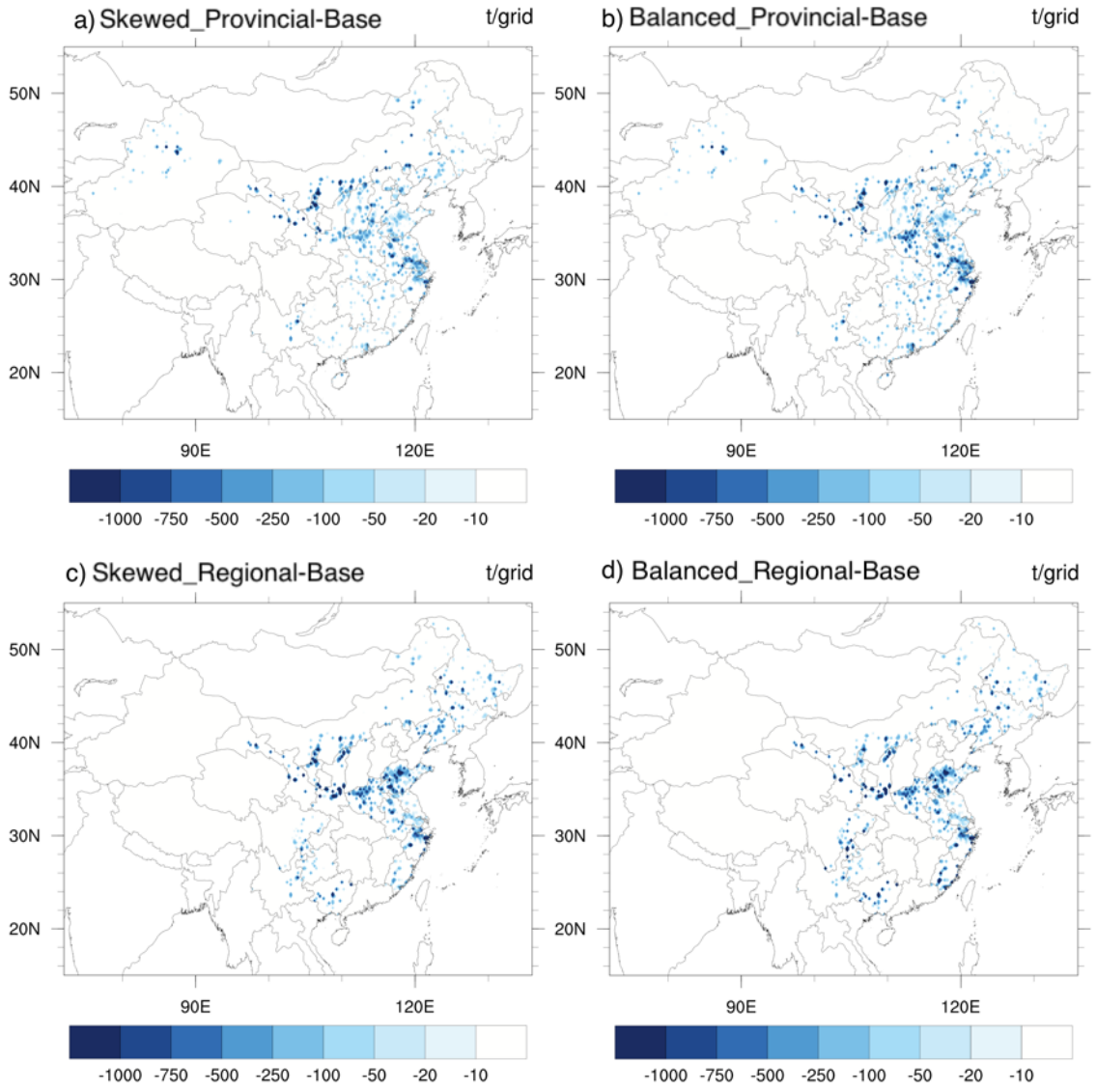


Fig. S3. Gridded annual 2030 SO_2 emission reductions in each scenario (grid size: 0.25 by 0.25 degree) compared to the base case (Base).

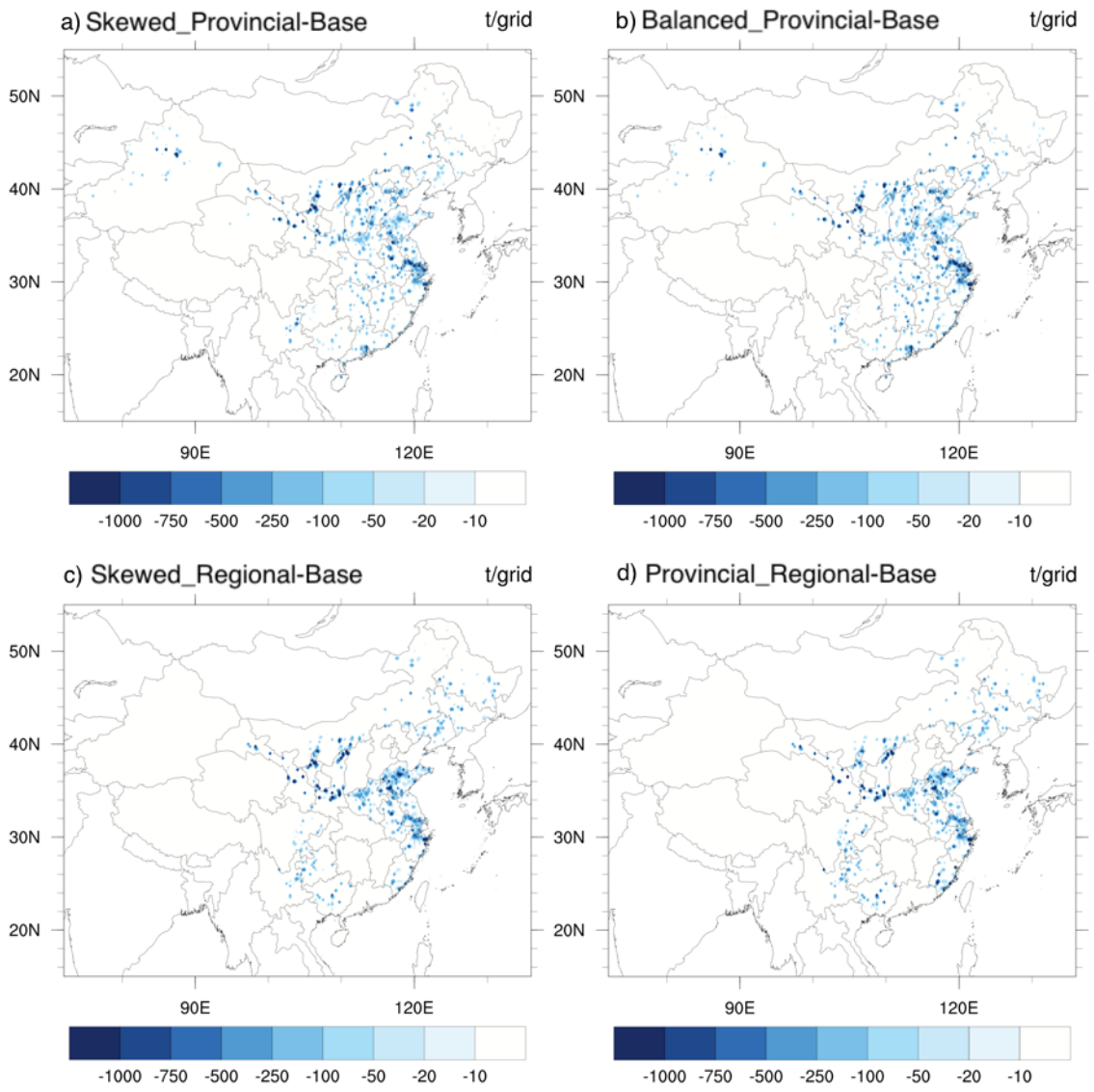
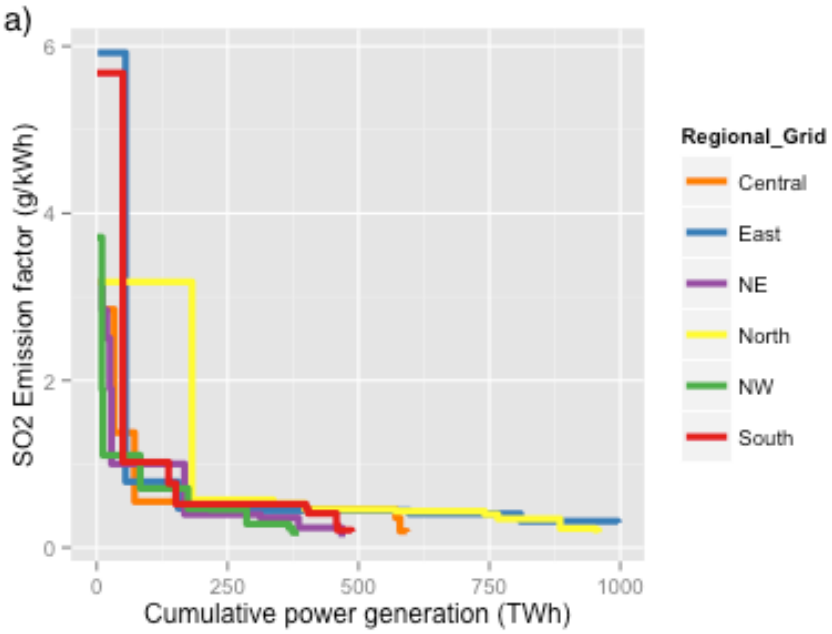


Fig. S4. Gridded annual 2030 NO_x emission reductions in each scenario (grid size: 0.25 by 0.25 degree) compared to the base case (Base).

10. Variations of SO_2 and NO_x emission factors of coal-fired power plants across regional grids in the 2030 base case and their impacts on emission reduction results.

The criteria we use to determine the order of coal displacement gives more weight to SO_2 than NO_x emissions (1.75 to 1 ratio of emission factors) based on their relative contributions to the formation of secondary aerosols [5]. In addition, SO_2 emission factors vary more than NO_x emission factors because of variations in the sulfur content of coal burned in each province. Therefore coal power plant displacement in our study occurs predominantly in provinces that have the highest SO_2 emission factors in the power sector (Fig. S5). Thus, the regional scenarios concentrate coal-fired power plant displacement in the provinces that have the highest SO_2 emission factors within each regional grid.



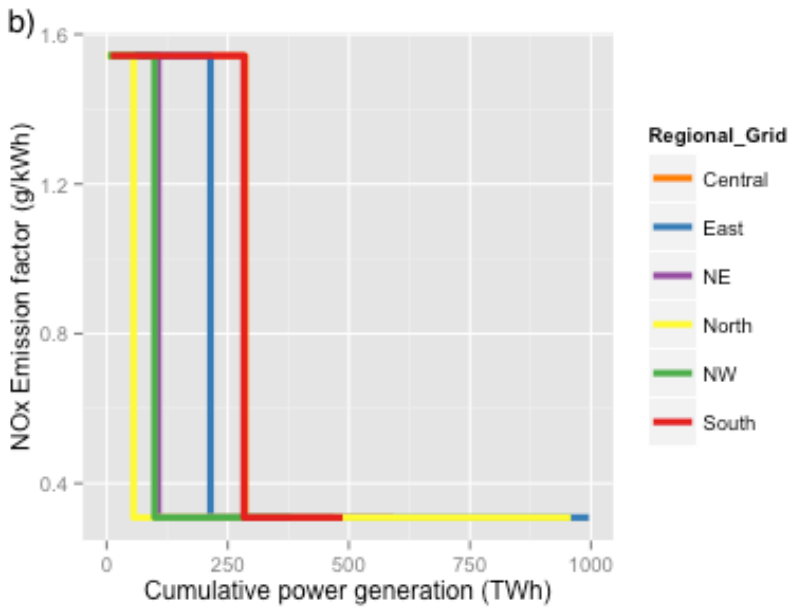


Fig. S5. a) SO_2 and b) NO_x emission factors of subcritical coal-fired power plants (unit: g/kWh) in each regional power grid in 2030 in the ECLIPSE_v5a_CLE scenario. Emission factors are plotted from highest to lowest in each regional grid and presented as cumulative power generation (TWh) on the x-axis.

11. 2030 base case monthly and annual mean $PM_{2.5}$ concentrations

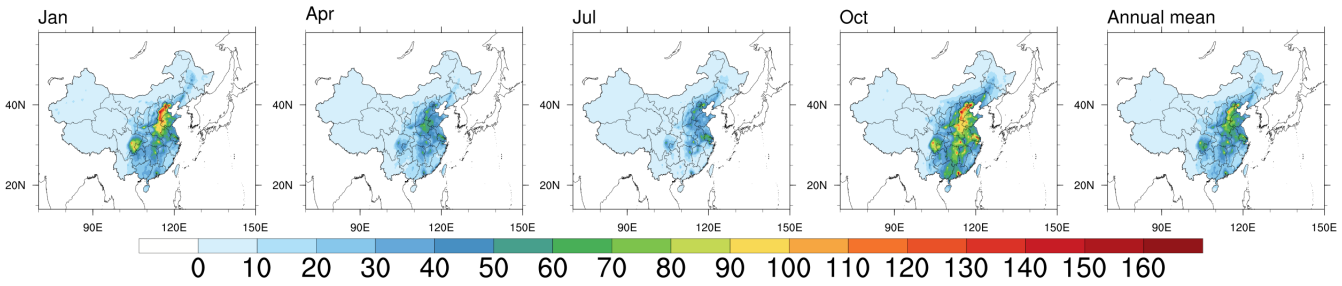


Fig. S6. 2030 base case monthly and annual mean $PM_{2.5}$ concentrations (unit: μg/m^3).

12. Differences of annual mean $PM_{2.5}$ concentrations between *Skewed_Provincial* and other three scenarios

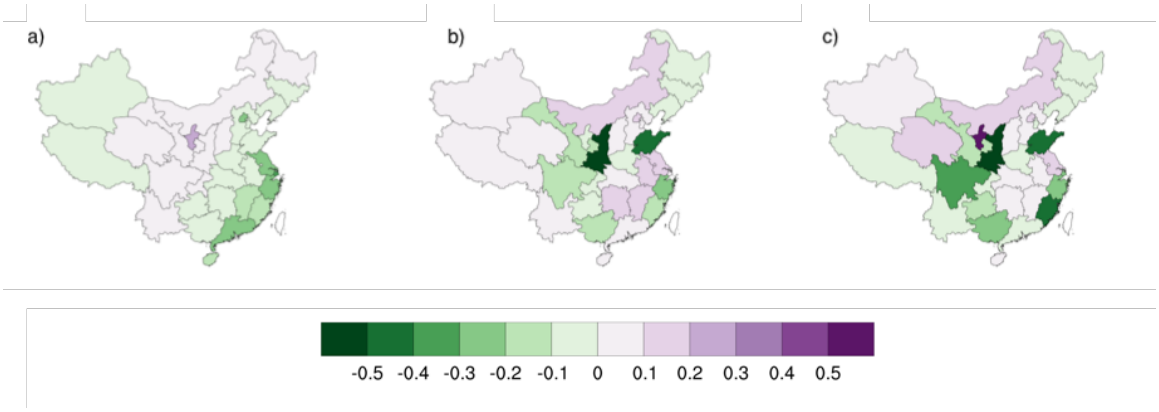


Fig. S7. a) to c): Differences between *Skewed Provincial* and the other three scenarios (a) *Balanced_Provincial – Skewed_Provincial*; (b) *Skewed_Regional – Skewed_Provincial*; (c) *Balanced_Regional – Skewed_Provincial* (unit: μg/m^3). Purple (green) indicates a lower (higher) population-weighted $PM_{2.5}$ in the *Skewed Provincial* scenario than in the other scenarios.

13. Monthly mean $PM_{2.5}$ reductions resulting from each PV scenario

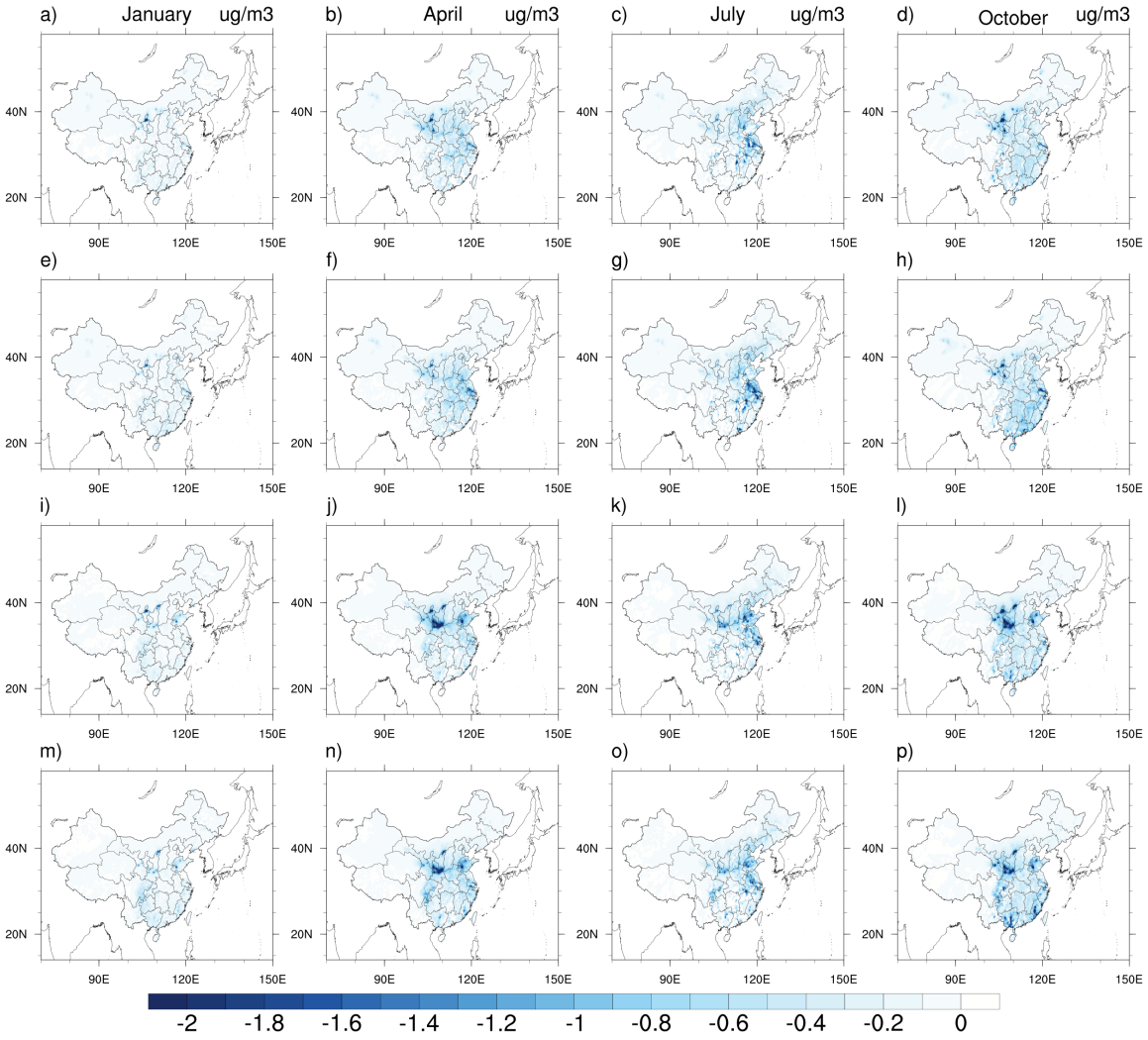


Fig. S8. Monthly $PM_{2.5}$ reduction in the four PV scenarios compared to the *Base* case. a) to d): *Skewed_Provincial*; e) to h): *Balanced_Provincial*; i) to l): *Skewed_Regional*; m) to p): *Balanced_Regional* (unit: $\mu g/m^3$).

14. Monthly average utility-scale and distributed PV capacity factors

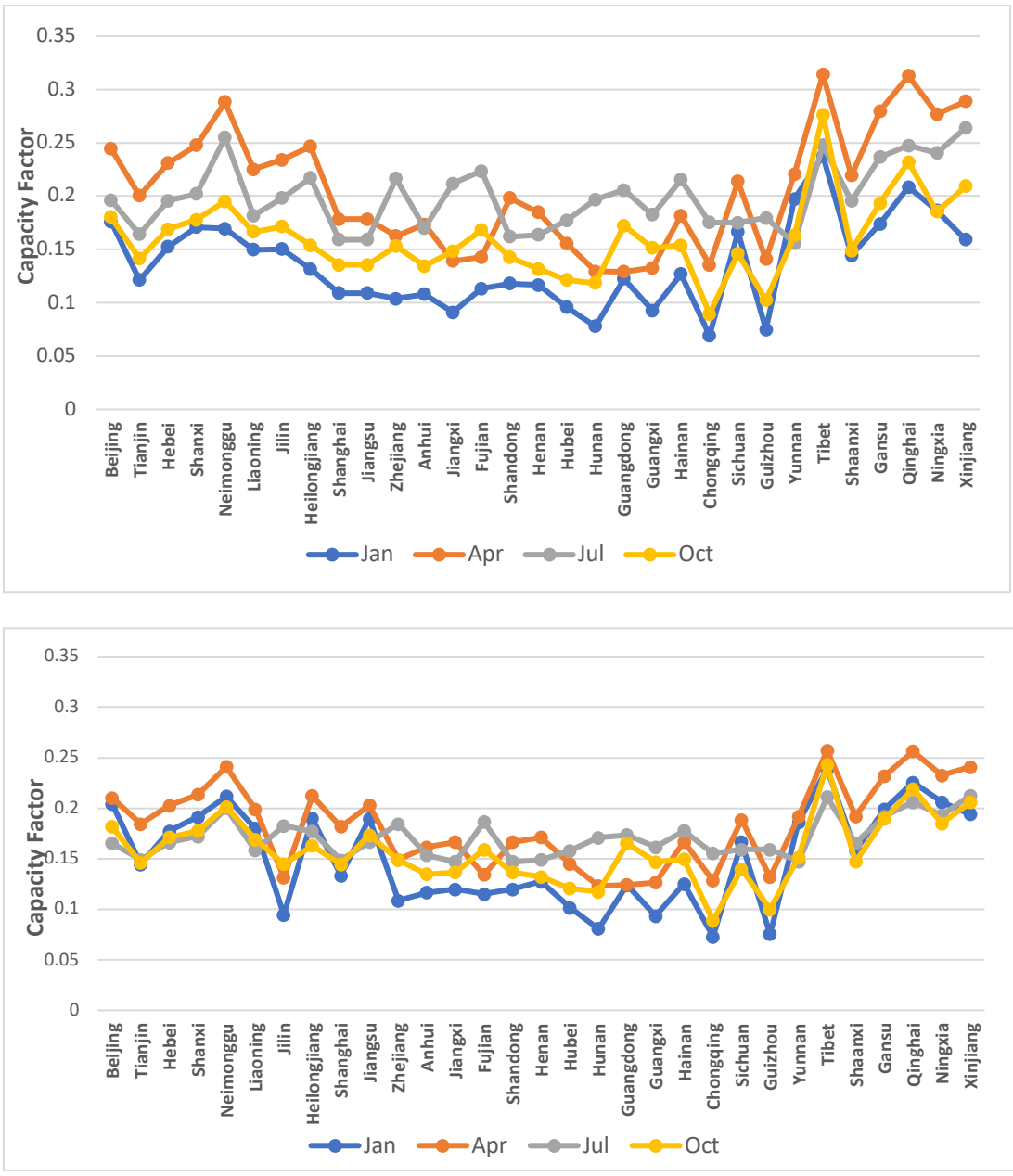


Fig. S9. Monthly average utility scale (top) and distributed (bottom) PV capacity factor for each province.

15. Uncertainties in our results

Uncertainties affect our integrated assessment findings regarding: emissions, displacement strategies, air pollution simulations, and health implications of emission reductions. For example, the absolute amounts of CO_2 reductions and air quality improvements are subject to actual 2030 energy consumption and related emissions, which may deviate from the coal-intensive power sector projection in the base case. In addition, variations in air pollutant reductions are largely driven by the projected provincial variations in SO_2 and NO_x emission factors for coal plants in the base case. However, our findings that deploying PV in the east with inter-provincial transmission maximizes the co-benefits would not change since the possibility of displacing the highest-emitting plants first via transmission and thus resulting in less curtailment in the east than in the northwest still hold.

There are also uncertainties related to the criteria (e.g. damage-weighted $PM_{2.5}$ precursor emissions) used to order the coal power plant displacement. The use of different criteria will markedly affect the selection of provinces in which coal power plants are displaced and the resulting emission reductions in each province. Instead of using the coal displacement rule based on the damage-weighted $PM_{2.5}$ precursor emission factors (1.75*SO_2 emission factor + NO_x emission factor) presented in the main results, we test coal displacement results following three alternative strategies: 1) only using SO_2 as the indicator (SO_2_indicator); 2) only using NO_x as the indicator (NO_x_indicator); 3) using the 1 to 1 ratio of SO_2 and NO_x emission (SO_2+NO_x_indicator), and 4) using the damage-weighted $PM_{2.5}$ precursor emissions plus also weighted by population density in each province (SO_2+NO_x_indicator_weighted by population, calculated as provincial

population divided by the area of the province, unit: person/km^2) [3]. We use the Skewed deployment pattern with inter-provincial PV electricity transmission as the example to show the difference. As shown in Fig. S10, the provinces where significant coal displacement occurs vary depending on the indicator used. Thus the displacement strategy employed is critical in determining the emission reduction benefits of solar PV.

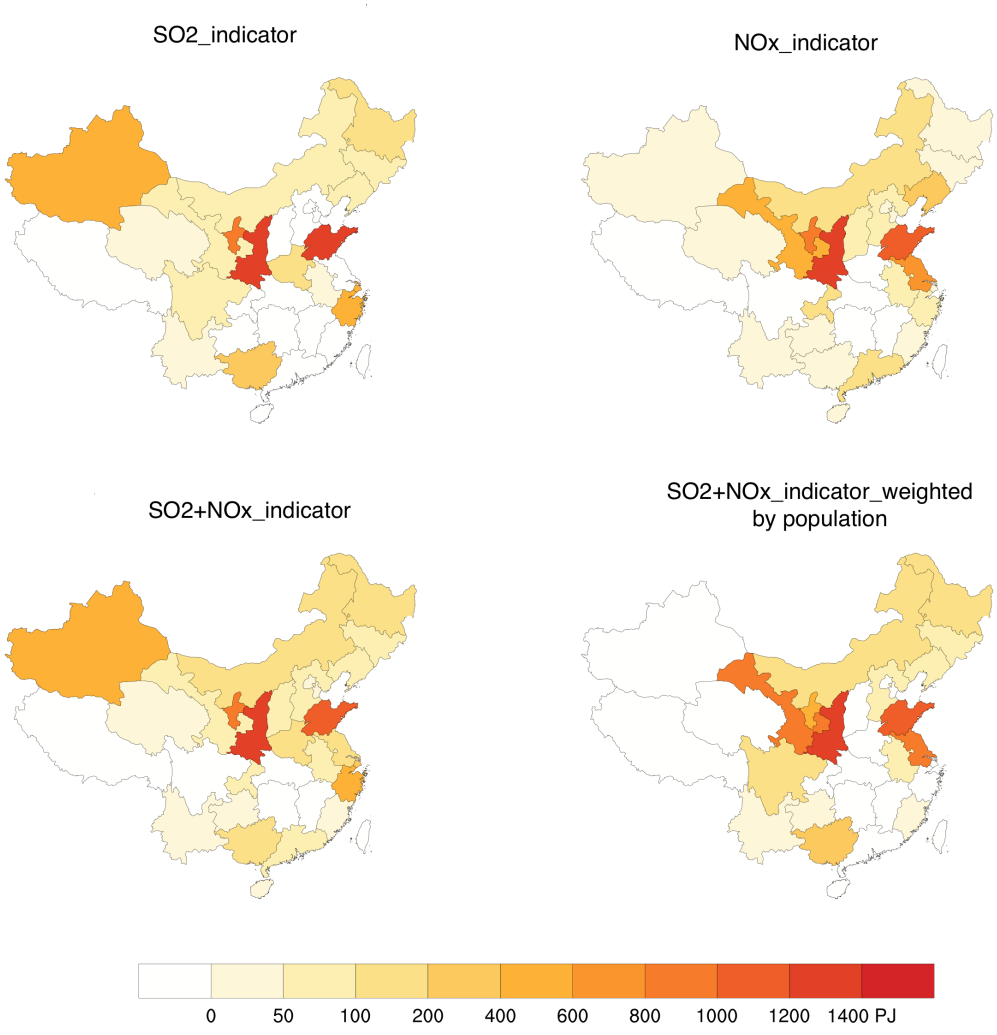


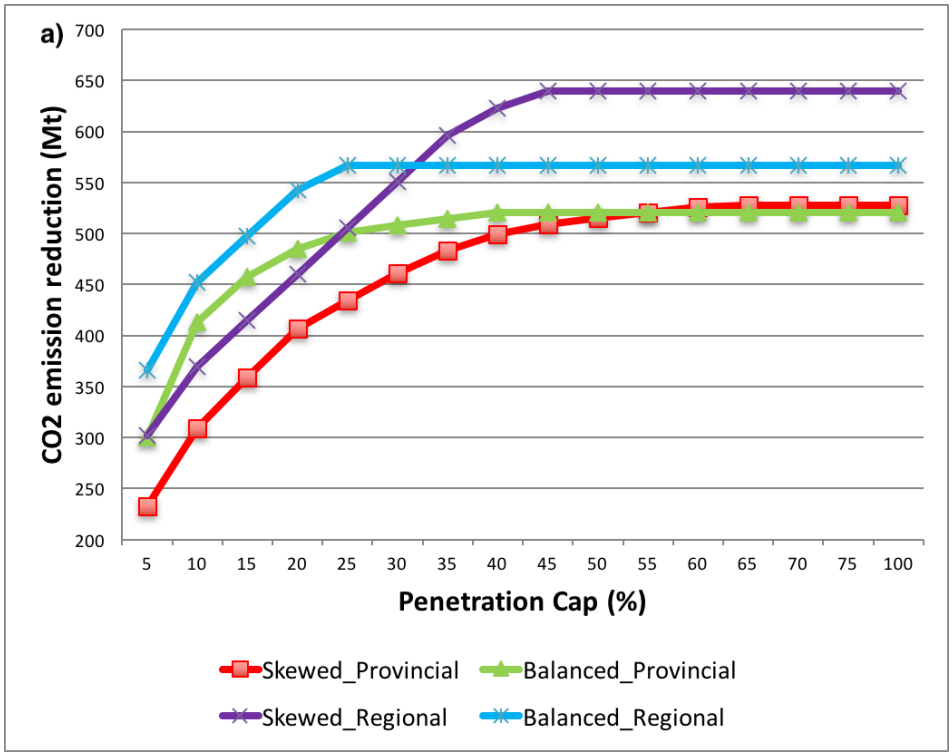
Fig. S10. Coal displacement results (unit: PJ) using different coal displacement metrics

16. Sensitivity analysis of the implications of various levels of PV grid integration

In our analysis in the main results, we imposed a cap on PV penetration of 30% for each province or grid, depending on the scenario. Here we conduct a sensitivity analysis evaluating the impact of a range of PV penetration caps (from 5% up to 100%) on grid-integrated PV electricity generation, carbon and air pollutant emission reductions (Fig. S11). We find that enabling inter-provincial PV electricity transmission in the *Regional* scenarios always results in more CO_2 and damage-weighted $PM_{2.5}$ precursor reductions (calculated as $1.75*SO_2 + NO_x$) compared to the *Provincial* scenarios without inter-provincial transmission. This indicates that inter-provincial transmission not only reduces the grid-integration constraints of PV, but also effectively prioritizes the displacement of less efficient and more high-emitting coal-fired power plants. If we only utilize PV electricity within the province where it is generated, some supercritical or ultra-supercritical power plants with higher generation efficiency and more advanced pollution control technologies will be displaced.

The results vary slightly for deploying distributed PV in the east. Without inter-provincial transmission, deploying more distributed PV in the east (*Balanced_Provincial*) always leads to greater CO_2 and $PM_{2.5}$ precursor reductions than deploying more utility-scale PV in the northwest (*Skewed_Provincial*), regardless of the allowed maximum PV grid penetration. This is because the eastern provinces contain more high emitting power plants than the west and because without transmission lower-emitting and higher efficiency coal power plants in the west will be displaced with PV. However, with inter-provincial transmission, deploying more utility-scale PV in the northwest achieves greater CO_2 and air pollutant emission reductions once the penetration cap rises above 35%, primarily

because increasing grid-integrated PV electricity generation is possible after relaxing the grid-integration constraints. This suggests that dramatic expansion of power transmission that alleviates the grid-integration constraints would allow deployment of solar PV in provinces with the most abundant solar radiation and the delivery of PV electricity to provinces with the highest emission reduction potential, which would further increase the health and climate co-benefits of PV.



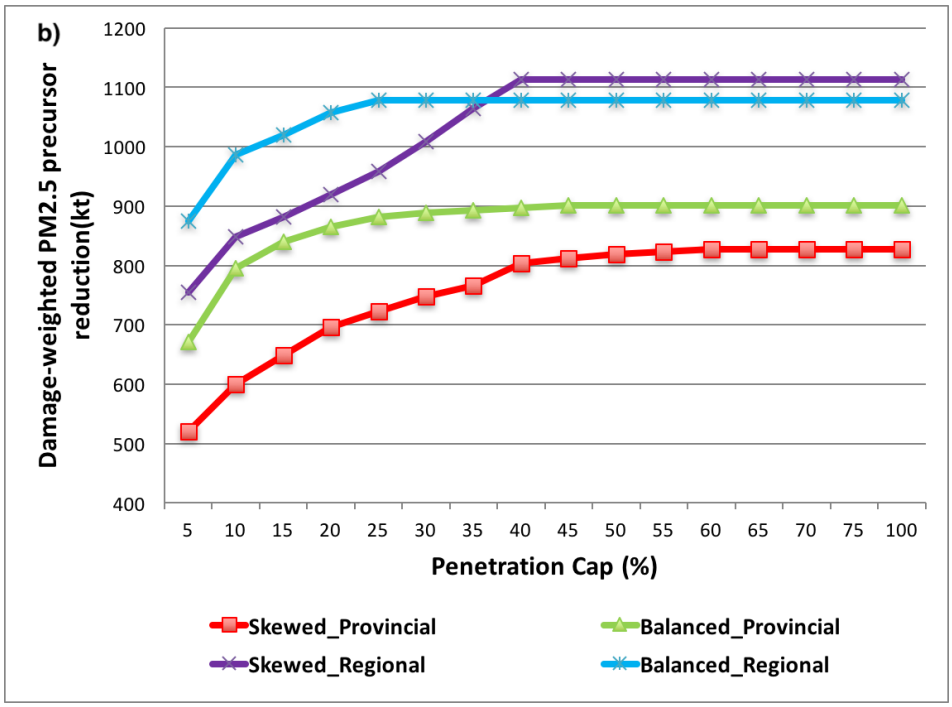


Fig. S11. (a) CO_2 and (b) damage-weighted $PM_{2.5}$ precursor ($1.75*SO_2 + NO_x$) reductions resulting from various PV penetration caps for each scenario.

17. Applicability of the integrated assessment framework used in this study to analyze the co-benefits of solar PV in other countries

In our study, we develop an integrated assessment framework to quantify the climate, air quality and related human benefits of solar PV generation in China. Our findings for China are consistent with previous findings in the US that suggest that installing solar PV panels in locations with the highest insolation and hence largest electricity generation may not generate the largest environmental benefits as these benefits depend heavily on local demand, available transmission and what power generation is displaced [6]. This framework used in our study could also be applied to studies of the co-benefits of solar PV in other countries facing similar grid-integration constraints and mismatch between PV generation and electricity demand. For example, there is growing recognition in India that concentrating PV generation in the states with the best solar resources will exacerbate grid integration constraints and a significant transmission investment is needed to increase environmental co-benefits [7]. Our integrated assessment framework could be used to quantify the air quality and climate co-benefits of various PV deployment scenarios in India and other countries.

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Appendix for Chapter 3

Air Quality, Health and Climate Implications of Replacing Small Solid Fuel Heating Stoves with Gas or Electric Heating in China

1. China's regional power grids



Fig. S1. China's six regional power grids (excluding Tibet)

2. Average heating season temperature in China's 15 northern provinces

Table S1. Average heating season ambient temperature in China's 15 northern provinces in 2012 and 2016

Province	2012 Average Ambient Temperature (°C)	2016 Average Ambient Temperature (°C)
Heilongjiang	-16.7	-14.9
Jilin	-14.9	-11.2
Xinjiang	-13.2	-8.5
Liaoning	-11.9	-8.6
Inner Mongolia	-9.5	-9.4
Qinghai	-7.7	-6.1
Gansu	-7.7	-6.3
Ningxia	-6.1	-4.5
Shanxi	-4.1	-2.7
Tianjin	-2.5	-1.1
Beijing	-2.0	-0.8
Hebei	-1.3	0.8
Shandong	-0.5	1.9
Shaanxi	0.4	3.3
Henan	1.2	3.7

3. Calculation of the increased gas and electricity demand to residential small solid fuel heating stoves in the BTH region

We first the estimate the heating demand in each electrification scenario. We use Equations (1) and (2) for rural ($H_{i,Rural}^{Demand}$) and urban areas ($H_{i,Urban}^{Demand}$), respectively:

$$H_{i,Rural}^{Demand} = H_{i,Rural} * S_{i,Rural} * Pop_{i,Rural} \quad (1)$$

$$H_{i,Urban}^{Demand} = H_{i,Urban} * (S_{i,Total} - S_{i,District}) \quad (2)$$

The definition and data source of all variables are included in Table S2. Since previous studies demonstrated that per capita floor area of urban residential buildings in the official statistics was significantly overestimated [1], we use the total completed floor area of residential buildings from the official statistical yearbooks for urban areas.

We then calculate the increased gas/electricity demand from replacing all residential small heating stoves in the BTH region. For gas heating, we use the total heating demand in both rural and urban areas and Equations (3) to calculate the additional gas demand (definition and data source of all variables are included in Table S2):

$$E_i^{Gas} = (H_{i,Rural}^{Demand} + H_{i,Urban}^{Demand})/[\eta_{gas} * (1 - \eta_{T\&D\ loss,gas})] \quad (3)$$

For electric heating, we use the total heating demand in both rural and urban areas and Equations (4) to calculate the additional electricity demand (definition and data source of all variables are included in Table S2):

$$E_i^{Electricity} = (H_{i,Rural}^{Demand} + H_{i,Urban}^{Demand})/[\eta_{electric} * (1 - \eta_{T\&D\ loss,power})] \quad (4)$$

Table S2. Summary of data for heating gas or electricity demand calculation

Variable	Definition	Source
$H_{i,Rural}$, $H_{i,Urban}$	Average rural/urban household heating energy demand (kJ/m²/a)	[2,3]
$S_{i,Rural}$	Per capita rural household living spaces in 2012 (m²)	[4]
$Pop_{i,Rural}$,	Rural population in 2012	
$S_{i,Total}$	Total completed urban residential floor area in 2012 (m²)	
$S_{i,District}$	Total district heating spaces in 2012 (m²)	
η_{gas}	Heat generation efficiency of gas stoves (%)	[5]
$\eta_{electric}$	Heat generation efficiency of resistant heaters or air-source heat pumps (%)	Resistance heaters: [6] Air-source heat pumps: [7]
$\eta_{T\&D\ Loss,gas}$	National average transmission & distribution loss for conventional gas (%)	[8]
$\eta_{T\&D\ Loss,power}$	National average transmission & distribution system electricity loss in 2012 (%)	[9]

4. WRF-Chem model configurations:

Table S3. Physical and chemistry options used in WRF-Chem simulation

Model configurations	
Atmospheric process	WRF-Chem scheme
Cloud microphysics	Lin et al. scheme
Long-wave radiation	RRTM scheme
Short-wave radiation	Goddard shortwave
Surface layer	MM5 similarity
Boundary layer	Yonsei University scheme
Cumulus parameterization	Grell 3D scheme
Land surface	Noah land surface model
Chemistry option	RADM2 chemical mechanisms and MADE/SORGAM aerosols including aqueous chemistry
Photolysis	Fast-J photolysis

5. Detailed calculations of health impacts associated with air pollution

Changes in the number of premature deaths of each disease associated with $PM_{2.5}$ pollution in each 27 km by 27 km WRF-Chem grid box are calculated as follows:

$$\Delta Mort_i = POP * MR_{Base,i} * [RR_i(C_{Sce}) / RR_i(C_{Base}) - 1] \quad (5)$$

$\Delta Mort_i$ is the change in premature mortalities in each WRF-Chem grid box due to disease *i* in each heating replacement scenario;

POP is the population in each grid in 2012 (total provincial population is from China's National Statistics [4], county-level population distribution follows the same pattern as the 2010 China census data [10]. We use ArcGIS 10.0 to map county-level population onto WRF-Chem grid boxes).

$MR_{Base,i}$ is the baseline mortality rate for disease *i* in 2012 [4],

$RR_i(C_{Sce})$ is the relative risk (RR) for disease *i* at the $PM_{2.5}$ concentration (C) in each scenario (*Sce*). We use RR functions from the Global Burden of Disease study [11], with linear interpolations for non-integer concentration levels,

$RR_i(C_{Base})$ is the relative risk for disease *i* at the $PM_{2.5}$ concentration in the base case.

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