CLIMATE, AIR QUALITY AND HUMAN HEALTH BENEFITS OF VARIOUS SOLAR PHOTOVOLTAIC DEVELOPMENT SCENARIOS IN CHINA IN 2030

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Overview

Solar photovoltaic (PV) electricity generation can greatly reduce both air pollutant and greenhouse gas emissions. The Chinese government plans to massively increase solar PV installation and reach 400 GW installed PV capacity in 2030. However, different PV development pathways to achieve the installed capacity target will influence the range of air quality and climate benefits, as the benefits depend on how much electricity generated from PV is integrated into the power grids and the types of power plant being displaced. In particular, China's current PV deployment strategy focuses on utility-scale PV installations that are overwhelmingly located in China's northwestern provinces where solar radiation is abundant, while utilization of PV electricity within broader power girds is restricted by insufficient transmission capacity and limited incentives to promote power exchange and transmission. The rapid development of utility-scale PV in the northwest and the focus on local consumption have led to significant grid integration constraints in the northwestern provinces. This suggests potential drawbacks of continuing the current utility-scale deployment and utilization strategies in the future as more PV electricity would likely be curtailed in western China due to lack of demand.

There is limited analysis to date on the air quality and carbon emission impacts of choosing various solar PV deployment and utilization strategies in China. Variations in PV electricity generation and utilization by location and variation in the air pollutant emissions from the power plants being displaced lead to differences in air quality and climate co-benefits of PV deployment. We estimate the climate, air quality, and related human health benefits of various 2030 PV development scenarios in China all including the government goal of 400 GW projected national installed capacitybut varying the location of PV installation and the extent of inter-provincial PV electricity transmission.

Methods

We use a 2030 coal-intensive power sector projection developed by the International Institute for Applied System Analysis (IIASA) as the counterfactual base case (*Base*). Starting from this base case, we construct four scenarios all with 400 GW PV installed capacity in 2030. In the first scenario (*Current_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 (*Current_Regional*). We include both changes in the deployment and utilization strategies in the last scenario (*Balanced_Regional*).

Capacity factors for both types of PV for each province are calculated using satellite-derived surface irradiance data [1] and the PVLIB-Python model [2]. 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 provincial or regional grid depending on the existence of inter-provincial transmission. Any PV electricity that exceeds the 30% cap is curtailed.

Grid-integrated PV electricity is assumed to displace the least efficient subcritical coal plant with the highest air pollutant emission factors in each provincial or regional grid first. We use the Weather Research and Forecasting model with Chemistry (WRF-Chem) to simulate the changes in $PM_{2.5}$ concentrations due to air pollutant emission reductions. The air pollution-related health impacts are calculated as changes in premature mortality of four respiratory and cardiovascular diseases that are associated with long-term ambient $PM_{2.5}$ exposure based on the integrated exposure response functions developed by the Global Burden of Disease study [3].

Results

After imposing the 30% grid integration constraints, 26% of the projected electricity generated from PV panels is curtailed in *Current_Provincial* (487 TWh total PV electricity generation), especially in the northwestern provinces where electricity demand is low while solar PV generation is high. In contrast, all generated PV electricity could be integrated into the grids without curtailment in *Balanced_Provincial* (585 TWh total PV electricity generation). 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 and grid upgrades and transmission are available. Shifting deployment to the east and expanding inter-provincial transmission would help reduce integration constraints.

Inter-provincial transmission could facilitate PV electricity displacement of the dirtiest coal-fired power plants within a regional grid first. Therefore, the CO_2 reductions benefits are larger than in the *Current* scenarios and *Balanced_Regional* has the largest CO_2 reductions (460 million tons) among the four scenarios while *Current_Provincial* has the smallest reductions (million tons). In addition, the *Regional* scenarios concentrate coal-fired power plant displacement in the provinces that have the highest SO_2 and NO_x emission factors within each regional grid, which leads to the *Balanced_Regional* scenario also having the largest air pollutant reductions.

Deploying equal capacities of distributed and utility-scale PV with inter-provincial transmission (*Balanced_Regional* scenario) has the greatest health benefits with 10,000 (5,000 to 14,000, the numbers in parenthesis indicate 95% CI of the relative risk functions) avoided premature mortalities. Whereas deploying more utility-scale PV in the northwest without inter-provincial transmission (*Current_Provincial* scenario) has the least health benefit with only 6,400 (2,800 to 9,500) avoided deaths.

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. 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 compared to the *Provincial* scenarios without inter-provincial transmission. 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.

Conclusions

There are substantial variations in the climate, air quality and human health co-benefits of various PV development 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. Deploying distributed PV in the east and enabling inter-provincial transmission could alleviate the grid-integration constraints in the northwest and achieve greater air quality-related health benefits via maximizing the opportunities to displace the highest-emitting coal-fired power plants first. Our conclusions are robust under various assumptions of the level of grid integration of solar PV. 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. The framework used in this 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.

Distributed PV deployment and inter-provincial transmission both increase co-benefits of PV development. Therefore, the Chinese government should actively direct future investment in the solar field to shift towards distributed PV by building a clear and stable policy framework for distributed PV development that addresses the legal, financial and business challenges. In addition, we propose the Chinese government create a market-oriented power exchange system and use incentives to promote power interconnections across provinces and regions.

References

[1] NASA (2017) Cloudes and the earth's radiant energy system (CERES). http://ceres.larc.nasa.gov/.

[2] Andrews RW, Stein JS, Hansen C & Riley D (2014) Introduction to the open source PV LIB for python photovoltaic system modeling package. *Photovoltaic Specialist Conference (PVSC)*, 2014 IEEE 40th: 0170-0174.

[3] Burnett RT*, et al* (2014) An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ Health Perspect* 122(4): 397-403