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HARVARD-CHINA PROJECT
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Rising Cost Advantages of Solar Power in China

and Coupled Electricity Storage for Greater Grid Compatibility

A Research Brief for Non-Specialists on a Recent Study in
Proceedings of the National Academy of Sciences

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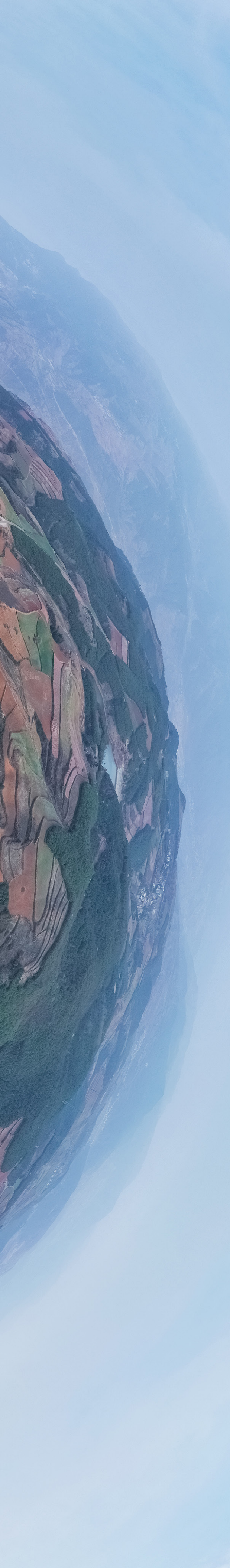

Acknowledgements

This Research Brief is based on the findings of the following study published as the cover article of *PNAS*:

> Xi Lu, Shi Chen, Chris P. Nielsen, Chongyu Zhang, Jiacong Li, Xu He, Ye Wu, Shuxiao Wang, Feng Song, Chu Wei, Kebin He, Michael P. McElroy, and Jiming Hao. 2021. “Combined solar power and storage as cost-competitive and grid-compatible supply for China’s future carbon-neutral electricity system.” *Proceedings of the National Academy of Sciences*, 118, 42. Available at https://doi.org/10.1073/pnas.2103471118.

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For more information about the Harvard-China Project on Energy, Economy and Environment and its research collaborations with colleagues at Tsinghua University in China, see www.chinaproject.harvard.edu.

Key Takeaways

- Solar photovoltaic (PV) power generation will almost inevitably take a pivotal role in reaching China's carbon neutrality goals. Its installed capacity is projected to increase more than 14 times by 2060.

- China has vast lands available to install solar power stations, as well as abundant solar radiation. The potential for solar power generation far exceeds national electricity demand.

- The generation cost of most of China's solar power potential was already lower than that of coal power as of 2020, and this cost competitiveness is projected to extend nationwide by 2023. The cost advantage of solar power over coal power will only grow, as much as 10-fold by 2060.

- The biggest challenge to such an expansion of solar power is its variability, as it must be integrated into a grid designed around inflexible coal power. The growing cost advantage of solar compared to coal generation, however, will be sufficient to invest in storage technologies paired with solar PV to reduce variability while maintaining its cost competitiveness.

- Coupled solar-plus-storage systems could serve nearly 50% of China's power demand in 2060 in a grid-compatible manner. Much of the electricity delivered would not only be cost-competitive and carbon-free, but reliable and dispatchable.

- The cost advantages of solar power have implications for electrifying energy end-use sectors, where introducing solar power could reduce prices of final products and services. This could accelerate the phasing out of traditional production processes fueled by fossil energy sources.

- The growing cost advantages of solar power in China may have lessons for regions of the world with inadequate access to electricity but strong momentum in development of energy infrastructure, including in Asia and Africa. Given their rich solar resources, cost-competitive solar power (sometimes coupled with storage) may open broad opportunities to meet surging electricity demand without carbon emissions and at lower costs than currently recognized.

Source Article: Xi Lu, Shi Chen, Chris P. Nielsen, Chongyu Zhang, Jiacong Li, Xu He, Ye Wu, Shuxiao Wang, Feng Song, Chu Wei, Kebin He, Michael P. McElroy, and Jiming Hao. 2021. "Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system." *Proceedings of the National Academy of Sciences*, 118, 42. Available at: https://doi.org/10.1073/pnas.2103471118.

Significance of Solar Power in China

China's solar power capacity is expected to increase 14-fold by 2060.

As the world's largest CO_2 emitter, China has set an ambitious target to achieve carbon neutrality by 2060. Electrifying final energy demand sectors and decarbonizing the electricity system have been recognized as two pivotal requirements to achieve net-zero emissions. Among all low-carbon electricity sources, solar power has gained momentum the fastest, both globally and in China, attributed to rapid technology and manufacturing innovations that have driven costs sharply downwards. Although the detailed pathway to carbon neutrality remains unclear due to many uncertainties in an exceedingly complex energy system, both international and Chinese reports forecast installed solar power capacities in China of higher than 3500 GW in 2060, more than 14 times that of 2020.

PNAS OCTOBER COVER

Given large spatial differences in the natural conditions needed for solar power generation and a fast-changing PV production industry in China, strategic planning to realize China's solar potential requires systematic evaluation of solar PV's technical feasibility, economic cost, and compatibility with the power grid. The study summarized in this Research Brief (Lu et al. 2021[1]) seeks to model these three characteristics in sequence using a common analytical framework, emphasizing spatial differences and evolution over time. The results suggest that solar power indeed has huge potential to drive decarbonization of the power system in a cost-competitive and grid-compatible manner. The findings not only have implications for long-term renewable deployment strategies but shed light on opportunities for "solar-plus-storage" options to leverage growing cost advantages of solar PV to decarbonize energy consumption in several key sectors.

[1]Xi Lu, Shi Chen, Chris P. Nielsen, Chongyu Zhang, Jiacong Li, Xu He, Ye Wu, Shuxiao Wang, Feng Song, Chu Wei, Kebin He, Michael B. McElroy, and Jiming Hao. 2021. "Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system." *Proceedings of the National Academy of Sciences*, 118, 42, https://doi.org/10.1073/pnas.2103471118.

SOLAR ASSESSMENT

STRUCTURE AND METHODS

Three criteria for successful solar expansion: technical feasibility, cost-competitiveness, and grid compatibility

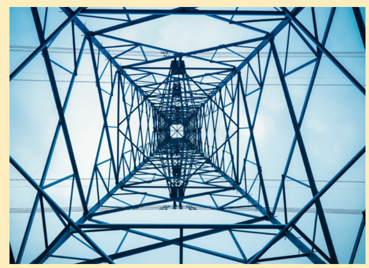
Successful application of utility-scale solar power requires suitable land conditions, electricity sales revenues that meet the expectations of investors, and characteristics allowing the grid to accept and transmit the solar power to end users. The study tests the potentials according to all three criteria from 2020 to 2060.

TECHNOLOGY

Utility-scale solar power best suits vast, unused, and relatively flat land types to deploy PV arrays. The study first uses slope and types of land use as criteria to screen for suitable areas. Next, it quantifies the potential installed capacity per unit land area across the nation, which differs in part because panel tilt and spacing depends on angles of incoming solar radiation differing by latitude. From these factors, the study derives the total potential installed capacity. A power generation model is developed to calculate total solar power generation on an hourly basis given the potential installed capacity. The model also considers the intensity of solar radiation, affected by altitude and cloudiness, and the impacts of temperature and shading. Based on hourly data for all locations ("cells" in a grid overlaying the country), annual power generation potentials are totaled for each regional power system and for the whole nation.

ECONOMIC COMPETITIVENESS

Declining trends in capital costs for PV have accelerated in the last decade compared to longer-term trends dating back to the 1980s. The study adopts a learning model to simulate the rate of cost decline and derives future capital costs after applying it to the projections of future installed capacity. Next, the capital costs and a number of other factors are modeled to estimate the cost of electricity for each grid cell over the course of a year. These are then compared to the price that coal-fired power plants sell electricity to the grid under longstanding regulated pricing to judge when solar power reaches price parity and to generate trajectories of pricing parity for all locations across the country suitable for solar farms.



GRID COMPATABILITY

Daily and seasonal cycles of sunshine, as well as weather, determine natural variations of solar power generation. Possible mismatches of solar generation with power demand on the one hand can require non-solar generation units to meet demand, for example after sunset, or on the other hand can induce curtailment (forced wastage) if solar supply outweighs demand. Large-scale penetration of solar in the power grid will require effective solutions to its inherent variability. Utility-scale battery storage of electricity, application of which is growing as its costs decline, is a prospective solution. The study thus further evaluates the possibility of combining solar and storage systems to address the inherent variability, including the cost-competitiveness of such coupled systems with coal-fired power. The potential is calculated using an hourly optimization model to minimize the variability of the power supply after absorbing the solar generation, taking account of the hourly dynamics of matching the output of the combined systems with the demand.

Left image: Solar plant by Visoot; Middle: Hong Kong skyline vy Vichie; Right: Pylon by Chungking

Key Results

Systematic evaluation of solar potentials including full consideration of resources, diverse economic factors, and solar generation variability suggests that solar power is almost certain to play a critical role in China's future power system. This is rooted not only in large land availability and technical potentials, but also in striking cost advantages that grow as time goes on. Those cost advantages are large enough to allow additional investment in coupled storage facilities to supply electricity to the grid that is not only clean but also reliable and dispatchable, and yet still cost competitive with coal-fired power.

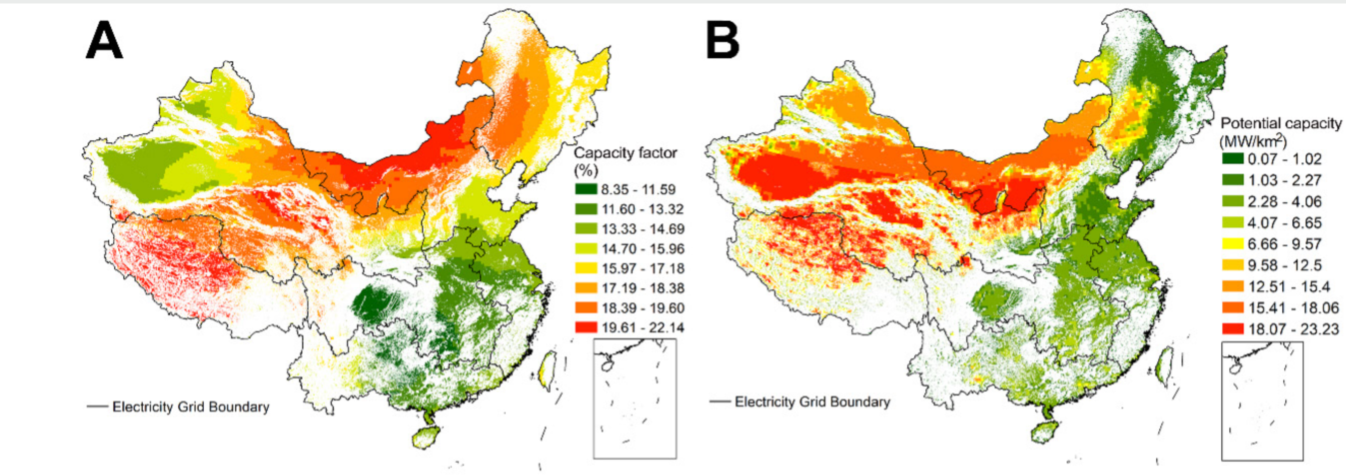


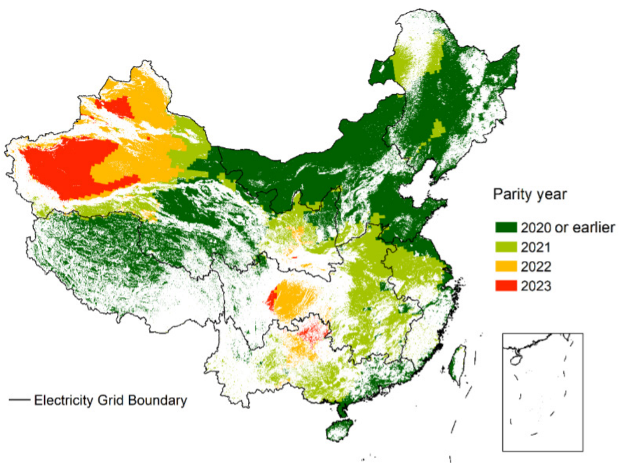
Figure 1. Distribution of technical potentials of utility-scale solar PV of China in 2020, in terms of (A) efficiency of system generation (capacity factor) and (B) capacity in megawatts per square kilometer.

Vast but imbalanced: Total solar power potential is 13 times national electricity demand

The results suggest that on geophysical and technical (but excluding economic) grounds, utility-scale solar had the potential to generate a gargantuan 99.2 PWh electricity in 2020, more than 13 times the electricity demand for that year, using a total potential installed capacity of 64.3 TW. More realistically, if half of the growth in electricity demand in 2060 relative to 2020 is met by solar power, it would require only 4.5% of the total potential capacity in that year. Although the total solar potential is high, its distribution is very uneven within the nation, both in terms of the efficiency of solar power generation and the potential installed capacity. **Figure 1A** shows the distribution of the "capacity factor," a measure of the efficiency of solar output, in which higher numbers reflect higher power generation for a given unit.[2] Solar productivity is highest across northern China and Tibet. **Figure 1B** shows the locations where solar farms can be most densely deployed—regardless of their productivity—which helpfully largely coincide with the areas with the highest efficiency in **Figure 1A**. The five provincial-level jurisdictions of Xinjiang, Inner Mongolia, Tibet, Qinghai and Gansu contain 85.4% of the national potential capacity. Unfortunately, the concentration of solar potentials in the west and north is mismatched with the distribution of national electricity demand, which is greatest in coastal, eastern China. To realize the transmission of power from the richest resource areas to the load centers would require expansion of the power grid.

[2] Capacity factor is the projected actual electricity output—taking account of night hours, cloudiness, and other limitations—divided by the maximum technical output of the solar PV systems, effectively as if the sun could shine unimpeded 24 hours a day and 365 days a year.

Figure 2. Year that Solar Power Generation Reaches Price Parity with Coal Power in Different Areas of China



Around the corner: Solar generation will be cost-competitive with coal power nationwide by 2023

The so-called "bus-bar" price, the lowest price acceptable to solar power stations under a reasonable expectation for profit, is used by the study to characterize the cost-competitiveness of solar power. As of 2020, the national average bus-bar price for solar electricity was 0.34 Chinese yuan (CNY)/kWh (equal to 4.93 US cents/kWh, in 2019 currency). The Tibet grid had the lowest price, at 0.29 CNY/kWh (4.20 US cents/kWh) and the Central China grid the highest, at 0.43 CNY/kWh (6.23 US cents/kWh).

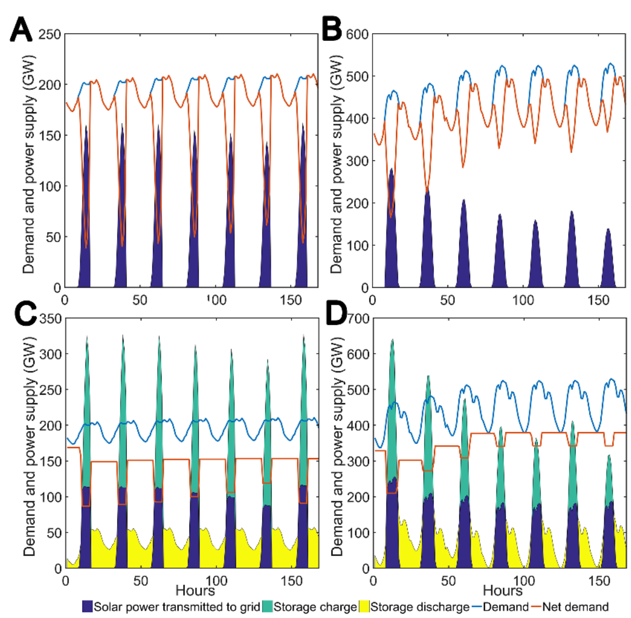
As of 2020, 78.6% of the potential solar power generation, or 79.7 PWh, had reached price parity with local coal power, and the study estimates that parity would be achieved nationwide by 2023. Solar power in the North, Northeast, East, and Tibet grids is projected to achieve full price parity with coal in 2021, followed by the Central, Northwest, and South grids in 2023 (Figure 2). And importantly, the national average bus-bar price for solar is expected to further decline to 0.09 CNY/kWh (1.30 US cents/kWh) by 2030 and 0.03 CNY/kWh (0.43 US cents/kWh) by 2060.

Cheap and reliable: Solar power generation, coupled with storage, could meet 43.2% power demand in 2060

After establishing a significant generation cost advantage, solar power could be paired with electricity storage facilities to create combined systems to deliver electricity that is not only cost-competitive but flexible enough to facilitate its grid integration. By pairing solar with storage capacity of equal size, the systems could serve 5.2 PWh of annual demand without curtailment in 2030, and 7.2 PWh of demand in 2060. The incorporation of storage increases the grid-compatible potential in 2060 by 4 PWh compared with solar-alone power plants. To illustrate the limited compatibility of electricity supply with demand of solar systems without storage, see the first row of hourly dispatch plots in Figure 3 for two grid regions: Northwest and East China. Without added storage, an extreme ramping-up requirement for additional power from non-solar sources appears after sunset, and the electric load after absorbing the solar power ("net demand," indicated by red lines) would vary enormously. But such challenges to grid operations could be dramatically alleviated by incorporating storage systems, as shown in the second row in Figure 3 for the same regions, by routine storage of surplus solar power at midday and discharging it toward evening or early morning to better match demand.

Figure 3. Hourly Dispatch to Achieve Maximum Penetration of Grid-Compatible and Cost-Competitive Solar Power in a Representative Week of January 2060.

Top row: Hourly demand and solar supply without storage for the Northwest (A) and East China (B) grids. Bottom row: Hourly demand and solar supply with added storage for the same Northwest (C) and East China (D) grids.



Implications for the Economy and World

The results of the study suggest that solar-plus-storage systems could serve as a technologically feasible, cost-competitive, and grid-compatible basis for a carbon-neutral power system in China.

They have far-reaching implications for final energy demands of many sectors, notably where electrification is rapidly penetrating transportation, industry, and building energy use. If powered by solar, the costs of energy use in these increasingly electrified sectors could see rapid declines in the future. This would bring down the prices of final products such as hydrogen, synthetic methane, liquid fuels, and ammonia, and services like freight transport and building heating and cooling, even as they also decarbonize. Such cost reductions could increase the competitiveness of these products and services and accelerate the phasing out of traditional production processes fueled by fossil energy sources.

The growing cost advantages of solar power may also open new options for other parts of the world, especially those with inadequate electricity access but strong momentum in energy infrastructure development. As quantified in earlier research by the same team (Chen et al. 2019[3]), the technical potentials of solar power in countries included in the Belt and Road Initiative were more than 40 times their electricity demand in 2016. Those regions are very likely to experience a similar cost decline as China. In light of the natural richness of their solar resources, solar power could open up broad opportunities to meet surging electricity demand with lower costs as it also helps countries transition towards carbon-neutral energy systems at the same time.

[3] Shi Chen, Xi Lu, Yufei Miao, Yu Deng, Chris P. Nielsen, Noah Elbot, Yuanchen Wang, Kathryn G. Logan, Michael B. McElroy, and Jiming Hao. 2019. "The potential of photovoltaics to power the Belt and Road Initiative." *Joule*, 3, 8, 1895-1912. https://www.cell.com/joule/fulltext/S2542-4351(19)30275-2

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