Using Existing Infrastructure to Realize Low-Cost and Flexible Photovoltaic Power Generation in Areas with High-Power Demand in China

Mingkun Jiang, Jiashuo Li, Wendong Wei, ..., Haoqi Qian, Jianmin Liu, Jinyue Yan

wandongwei@sjtu.edu.cn (W.W.)
jinyue.yan@mdh.se (J.Y.)

HIGHLIGHTS
- Idea using existing infrastructure for low-cost and flexible PV generation proposed.
- The PV$_{pp}$ potential at 1,082 power plants was estimated.
- The PV$_{pp}$ potential for China's coal-fired power generation sector is up to 4 GW.$e$
- 87% of PV$_{pp}$ systems can achieve plant-side grid parity.

PV$_{pp}$ potential capacity: 4 GW to 11 GW
PV$_{pp}$ potential generation: 5 TWh to 13 TWh
PV$_{pp}$ generation cost: 87% of PV$_{pp}$ systems achieve plant-side grid parity

Advantage of PV$_{pp}$ systems:
- Solar curtailment
- Land cost
- etc.

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Using Existing Infrastructure to Realize Low-Cost and Flexible Photovoltaic Power Generation in Areas with High-Power Demand in China

Mingkun Jiang,1,2,9 Jiashuo Li,3,9 Wendong Wei,4,5,* Jiawen Miao,6 Pengfei Zhang,3 Haoqi Qian,7 Jianmin Liu,8 and Jinyue Yan6,10,*

SUMMARY

This study develops a new concept involving using the existing infrastructure for photovoltaic (PV) generation to reduce the costs associated with increased land use and to avoid curtailment due to the mismatch between power supply and demand. We establish a method to estimate the technological potential and economic performance of the PV systems deployed in coal-fired power plants in China. The potential capacity of the examined 1,082 units in China reaches 4 GW, which is equivalent to 32% of China’s newly installed distributed PV capacity in 2019. A total of 87% of PV systems achieve plant-side grid parity compared with desulfurized coal benchmark electricity prices. To the best of our knowledge, this is the first study that investigates the use of rooftops and coal storage sheds in power plants to facilitate low-cost, flexible PV power generation, thus opening a new channel for future PV generation development.

INTRODUCTION

Photovoltaic (PV) technology is widely accepted as a practical solution to climate change and environmental pollution due to the burning of fossil fuels (Hu et al., 2015; Jerez et al., 2015; Creutzig et al., 2017). It has experienced a stunning compound global annual growth rate that has exceeded 40% over the last 15 years (Arnulf, 2019). By the end of 2019, the world’s installed PV generation capacity reached 583 GW, which accounted for 23% of the total renewable energy capacity (IRENA, 2020). In China, a high proportion of electricity is still generated from fossil fuel combustion, which contributes more than 40% of the national carbon emissions (Wei et al., 2020; Luo et al., 2020). China has a strong desire to transition to renewable energy. Driven by this goal, China has been the largest PV installer in the world since 2015, and China had a cumulative PV capacity of 204 GW by the end of 2019 (NEA, 2020).

As the benefits of PV technology, such as reducing pollution emissions and maintaining sustainability, have been widely recognized (King and van den Bergh, 2018; Bogdanov et al., 2019), PV technology is also becoming increasingly attractive as it becomes more economically competitive with fossil fuel power generation (Yan et al., 2019; Green, 2019; He et al., 2020). As the prices for PV modules consistently hit new lows, the soft costs associated with land use and grid connection account for an increasing proportion of the total (Strupeit, 2017; Steffen et al., 2020; Yu et al., 2018). In addition, solar curtailment is a crucial hindrance to PV growth. Regarding issues such as limited flexibility, output fluctuations, transmission congestion, and the mismatch between supply and demand, the power grid restricts, at times, the delivery of PV-derived electricity (Bird et al., 2016; Collins et al., 2018; Sgouridis et al., 2019). In 2019 alone, 4.6 TWh of PV generated electricity was abandoned in China. In regions such as Tibet, the curtailment ratio was up to 24.1% (NEA, 2020). Accordingly, several approaches have been considered to mitigate solar curtailment, such as energy storage (Riesen et al., 2017; Zeraati et al., 2019), demand response (Zhao et al., 2013; Brouwer et al., 2016; Mahmoudi et al., 2017; Rahmani et al., 2017), forecast methods (Litjens et al., 2018), etc. However, these solutions are either expensive or immature. Hence, the future deployment of PV systems must pursue quality over quantity. Blindingly increasing capacity will aggravate the mismatch between power supply and demand, which is not beneficial and may even exacerbate existing problems.

China has the largest number of coal-fired power plants (CFPPs). PV systems can be installed on the rooftops and coal storage sheds of the plants to reduce costs. The power load in the plants can also be utilized to consume the
excessive output from PV systems to avoid curtailment. Therefore, the integration of PV technology with CFPPs deserves attention. Many studies have focused on the integration potential and feasibility of PV technology (Strzalka et al., 2012; Byrne et al., 2017; Yang et al., 2020a). Compared with rooftop PV systems, building-integrated photovoltaics (BIPV) are perceived as more architecturally appealing. Furthermore, as no extra land is needed, the cost of the system can be reduced, and thus, BIPV can reduce the total cost of building materials and the building cooling loads as well (Ballif et al., 2018; Lufkin, 2019; Shukla et al., 2017). By integrating PV technology with agriculture, agrivoltaic systems avoid the competitive relationship between PV land use and agricultural land use while also reducing evaporation and providing shade to protect crops from excessive heat (Barron-Gafford et al., 2019; Marrou, 2019; Dinesh and Pearce, 2016; Amaducci et al., 2018). Moreover, by investigating the potential of PV integration into campuses, industrial parks, and shopping malls, studies have found that the PV output can effectively replace fossil energy consumption, thereby reducing the carbon footprint (Lee et al., 2016; Feng et al., 2018; Colmenar-Santos et al., 2016). The important advantage of these buildings over residential buildings is the higher usability of the rooftops. Because the peak load occurs during the day, the PV output will also match the power consumption profile well. In a study by Jiang et al., the idea of integrating PV into coal-fired power plants to supply auxiliary power demand was proposed (Jiang et al., 2019). Qi et al. reported the feasibility of installing PV on the cooling towers in power plants (Qi et al., 2020). Yang et al. investigated the potential of substituting coal-fired power plants with distributed PV systems in China (Yang et al., 2020b). However, none of the previous studies have considered the potential of using the rooftops and power load of CFPPs to reduce the cost and enhance the flexibility of the PV system.

To the best of our knowledge, an assessment of the integration of PV systems with CFPPs (called PVpp systems) at the national level has not been conducted to date. Our study attempts to demonstrate the concept, potential generation capability, and economic performance of PVpp systems. A case study is conducted to verify the cost reduction and flexibility enhancement of PVpp systems. We establish a method to estimate the PVpp potential of 1,082 Chinese CFPPs, investigate the potential for grid parity, and study the economic performance by creating five scenarios (see Transparent Methods in the Supplemental Information for details). The results may provide countries with a high share of coal-fired power generation, such as China and India, with a new approach to PV development.

RESULTS
The Concept of PVpp
As shown in Figure 1, a PVpp system uses the roofs and surfaces of the CFPP infrastructure, including suitable buildings (B) and coal storage sheds (E) to deploy PV panels. The output of the PVpp system is
transmitted to the power grid or end-users by existing transmission towers and lines (F). The system is also connected to the local electricity distribution networks in the power plant, making it possible to distribute the excessive output to the auxiliaries, such as pumps and compressors, to avoid curtailment. The output of the PV system will first be sold to end-users or to the power grid to obtain higher income than using it on-site. When the PV pp system lacks transmission access or the system’s generation becomes excessive during low load periods, the output can be consumed on-site by the power plant. As a consequence, potential PV curtailment can be avoided. Moreover, the economic costs of the PV pp system are effectively reduced, as the need to rent both the land and roof is avoided.

**PV pp Systems Enhance Flexibility and Reduce the System Cost**

PV pp systems use the power load of CFPPs to consume any excessive output and avoid curtailment due to insufficient system flexibility and transmission congestion. Thus, CFPPs must be capable of consuming the excessive output from PV pp systems. Accordingly, a case study is conducted to verify this. The case plant, which is located in Xinjiang, has an available area of 23,931 m² and a PV pp potential of 3.84 MWe. The potential PV generation is estimated to be 5.16 GWh annually. In comparison, the annual electricity demand of the plant is 162.80 GWh, according to the actual data provided by the case power plant. Hence, the ratio of PV output to local electricity demand is only 3.17%. We select the winter solstice and summer solstice, i.e., the day with the shortest sunshine duration and the day with the longest sunshine duration, to conduct hourly energy flow simulations. As depicted in Figures 2A and 2B, as the PV pp system output is merely equivalent to a marginal fraction of the electricity demand of the plant, the entire PV generation at any time on a given day is much lower than the demand of the power plant, not to mention the excessive portion. Consequently, the excessive output can be consumed by the power plant. Thus, curtailment can be avoided, and the flexibility of the PV pp system can be enhanced.

Another advantage of PV pp systems is that when deploying PV in power plants, there is no need to pay land rent, rooftop rent, or grid connection fees. Therefore, the system cost decreases effectively. The results of the case study show that the PV pp system reduces the cost by 15% and 21% per watt in comparison to...
distributed PV system and a centralized PV system, respectively (see Figure 2C). Because the PVpp system uses local loads to consume the excessive output, it does not need storage devices, such as batteries, to deal with the excessive output. Therefore, the PVpp system cost is reduced 54% per watt compared with a PV with storage system (see Table S5 for details). Consequently, the levelized cost of electricity (LCOE) of the PVpp system is the lowest among the four PV systems. Specifically, the LCOE of the PVpp system is 0.27 CNY/kWh. In contrast, the LCOEs of the distributed PV system, the centralized PV system, and the stand-alone PV system are 0.31 CNY/kWh, 0.34 CNY/kWh, and 0.54 CNY/kWh, respectively. Accordingly, the lower LCOE of the PVpp system proves to be a cost advantage over other systems.

**PVpp Technical Potential Is Enormous in China**

The potential PVpp capacity for China’s 1,082 existing CFPPs with an available rooftop area of $2.46 \times 10^7 \text{ m}^2$ amounts to 3.96 GWe, which is equivalent to approximately 32% of the newly installed distributed capacity in China in 2019 (NEA, 2020). As illustrated in Figure 3, the potential PVpp system capacity varies from 2 to 13 MWe. Figure 4B shows that PVpp systems mainly range in size between 2 MW and 5 MW. Jiangsu province exhibits the highest potential capacity at 321 MWe, whereas Tibet has a minimal potential capacity of 3 MWe (see Figure 4A and Table S6). Eastern China, where the potential is the highest, exhibits 43% of the total potential PVpp capacity.

The potential annual generation of the PVpp systems in China is estimated to be 4.69 TWh. The annual generation amounts of PVpp systems vary from 2 GWh to 16 GWh (see Figure 4B). Eastern China has 45% of the total PVpp potential generation, northwestern China has 12% of the total PVpp potential generation, and central China has 11% of the total PVpp potential generation.

The ratio of the PVpp output to the electricity demand of power plants is vital if we want to use the local loads of CFPPs to enhance the flexibility of the PVpp systems and avoid PV curtailment. According to the annual electricity demand data of the 934 power plants in the dataset we used, the ratio of PVpp systems’ output to the electricity demand of 83% of power plants is less than 5% (see Figure 4C), which indicates that...
CPFFs are capable of consuming the excessive output of PV pp systems to enhance flexibility and avoid curtailment.

**PV pp Systems Have Competitive Generation Costs and Strong Economic Performance**

The LCOEs of PV pp systems vary from 0.27 CNY/kWh to 0.46 CNY/kWh. We applied the user-side grid parity index and plant-side grid parity index (GPI p) developed by Yan et al. to measure the grid parity potential (Yan et al., 2019). The user-side grid parity index is further divided into an industrial and commercial (I&C) user-side grid parity index (GPI iu) and a residential user-side grid parity index (GPI ru). As depicted in Figure 5, the user-side grid parity indices of all PV pp systems are lower than 1, which means all of the PV pp systems in the 1,082 power plants can re a c hu s e r - s i d eg r i dp a r i t y .H o w e v e r ,t h es i t u a t i o no nt h ep l a n t - s i d ei s s l i g h t l y d i f f e r e n t , w i t h 941 of the 1,082 plants achieving plant-side grid parity compared with the local desulfurized coal benchmark electricity prices. The PV pp systems that fail to achieve plant-side grid parity are located primarily in Xinjiang, Sichuan, Ningxia, Inner Mongolia, and Guizhou. The natural endowment in Guizhou impedes the PV pp systems from reaching user-side grid parity. However, the situation on the plant-side is slightly different, with 941 of the 1,082 plants achieving plant-side grid parity compared with the local desulfurized coal benchmark electricity prices. The PV pp systems that fail to achieve plant-side grid parity are located primarily in Xinjiang, Sichuan, Ningxia, Inner Mongolia, and Guizhou. The natural endowment in Guizhou impedes the PV pp systems from reaching plant-side grid parity because the local solar radiation is insufficient. However, it is worth noting that although the solar radiation is abundant in Xinjiang, Ningxia, and Inner Mongolia and the LCOEs of these systems may be lower than others, the PV pp systems in these regions still cannot achieve grid parity due to the rather low local desulfurized coal benchmark electricity prices. Hence, the PV pp systems in these regions face increased challenges in reaching grid parity.

As Figure 6A depicts, 26% and 27% of the PV pp systems’ lifetime profits exceed 20 million CNY in Scenarios I (half sold to I&C users and half fed into the grid, see Transparent Methods and Table S2 for the details of the scenarios) and II (half sold to residential users and half fed into the grid), whereas there are more PV pp systems with profits between 10 million CNY and 15 million CNY in Scenario II. In Scenario III (selling all output
to I&C users), 46% of the systems exhibit lifetime profits over 20 million CNY. In Scenarios IV and V, only 13% and 8% of the PVpp systems’ lifetime profits exceed 20 million CNY. These results indicate that if the output of a PVpp system is completely sold to the power grid (Scenarios V) or to the residents (Scenarios IV) without a subsidy, the profit will be minimal. By comparison, the PVpp systems in Scenario III demonstrate the greatest profitability.

The discounted payback period (DPBP) is highly correlated with the scenarios. Figure 6B shows that 46% and 54% of PVpp systems can recover their investments in the seventh year in Scenarios I and II, respectively. In Scenario III, the DPBP for 54% of the PVpp systems are less than or equal to six years, and the cash flow values of 124 PVpp systems are always positive. The DPBP in Scenario V is much longer, with 47% of the systems requiring more than ten years to reach the breakeven point.

The return on investment (ROI) measures the efficiency of investment. Figure 6C shows that the ROI values of most of the PVpp systems in Scenario I and Scenario II fall between 100% and 120% (the proportions are 38% and 44%, respectively). In Scenario I, 19% of the PVpp systems have ROI values greater than 120%. The ROI values of 15% of the PVpp systems exceed 120% in Scenario II. In Scenario III, the ROI values of 35% of the PV systems exceed 140%, whereas in Scenarios IV and V, the ROI values of most of the PVpp systems (48% and 74%, respectively) are less than 80%.

DISCUSSION
A Greater PV Potential Can Be Achieved by Making Use of Coal Storage Sheds

China’s coal-fired power plants are constructing coal storage sheds and enclosures to cover coal storage yards to reduce dust pollution and meet the increasingly stringent environmental protection regulations. The surfaces of coal storage sheds and enclosures are also suitable for PV deployment, increasing the available area in power plants. Because the coal storage shed construction is an ongoing project, we predicted how much PVpp potential would be increased if all power plants in China installed coal sheds or enclosures. According to our measurement, the coal storage sheds and enclosures can provide an area of $4.30 \times 10^7$ m$^2$, which increases the potential capacity by 6.91 GWe. The generation capacity is believed to be 8.20 TWh of electricity a year. That is, the PVpp capacity and annual generation potential of the 1,082 power plants could reach 10.87 GWe and 12.89 TWh, respectively. This potential capacity is equivalent to approximately 89% of the newly installed distributed PV capacity in China in 2019 (NEA, 2020).

With greater potential PVpp capacity comes greater electricity generation, but the power plant can still consume excessive electricity easily. According to Figure 7A, the ratio of the PVpp output to power plants’ electricity demand is typically between 3% and 8% when both the available rooftop and coal storage shed areas are considered. The ratio is less than 10% in 79% of power plants. Furthermore, the lifetime revenue of PVpp systems also increases significantly (see Figure 7B).
PVpp Systems Are Capable of Avoiding Curtailment

The flexibility of a power system refers to “the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales” (IEA, 2018). When the power grid is congested, distributed PV systems and centralized PV systems without storage devices curtail their output, as they cannot cope with excessive output. This situation is an indication of insufficient system flexibility. Consuming excessive output on-site is a practical solution to curtailment. The total output of most PVpp systems is less than 8% of the CFPPs’ electricity demand (See Figure 4C). When PVpp systems cannot feed the output into the power grid, the CFPPs can easily consume the excessive portion. The massive electricity demand of power plants enhances the flexibility of the PVpp system. It guarantees that the output of the PVpp can be consumed rather than curtailing it. Given that the PVpp can accommodate excessive electricity on-site, another advantage of the system is that it does not need an additional transmission infrastructure, which will cause a large amount of carbon emissions during the construction (Wang et al., 2019), to transmit the excessive electricity.

Xinjiang, Tibet, and Gansu suffer from high curtailment rates due to oversupply and transmission failings (NEA, 2019b). Despite the abundant solar resources, regulators had suspended solar projects in these regions to curb overcapacity and curtailment (NEA, 2019a). Restricting PV development is not a long-term solution, and the abundant solar resources in these regions should be utilized properly without aggravating the curtailment issue. Accordingly, the PVpp system exhibits its superiority in this situation.

PVpp Systems Are More Economically Competitive in the Upcoming Subsidy-free Era

Since first being announced in 2011 in China, the feed-in-tariff (FiT) has continued to decrease with technological progress, allowing solar PV to develop an economically competitive edge over traditional
generation technology. In 2013, the Chinese government set a subsidy of 0.42 CNY/kWh for distributed PV systems (NDRC, 2013). In 2019, the subsidy fell to 0.18 CNY/kWh for residential PV systems and 0.10 CNY/kWh for I&C PV systems (NDRC, 2019). As the subsidy-free era approaches, the PV systems need to be economically comparable to fossil fuel generation technology. The PV system cost has plummeted rapidly in recent years, mainly due to reduced PV module prices. As a consequence, the proportions of the balance of system (BOS) costs and nontechnical costs are increasing, which has become an impediment to the further decline in the costs of PV systems (Elshurafa et al., 2018). To cope with the transition of the incentive policy, the BOS costs and soft costs, such as grid connection fees and land rents, must be reduced effectively. As demonstrated above, the PVpp system provides a feasible and applicable way to reduce the costs by integrating the PV system with existing infrastructure at CFPPs. As Figure 8 depicts, assuming the four types of PV systems are deployed at same places, the number of the PVpp systems reaching grid parity is maximized; 941 PVpp systems (87% of the total amount), 727 distributed PV systems (67% of the total amount), and 448 centralized PV systems (41% of the total amount) achieve grid parity. PV with storage systems cannot achieve grid parity, as batteries drastically increase the cost.

**PVpp Systems Are More Profitable in Places with Abundant Sunshine and High Electricity Price**

The high generation potential, high electricity price, and abundant solar resources are favorable factors regarding the profitability of PVpp systems. Therefore, Guangdong and Shandong are ideal regions for PVpp deployment from an economic aspect. There is also a huge generation potential in Xinjiang and Inner Mongolia. However, given the relatively low electricity prices, the PVpp systems there will struggle to gain a satisfactory revenue. In addition, as Sichuan and Guizhou lack abundant solar resources, the systems’ performances in these regions will be limited, and the generation cost will also increase. These regions can deploy PVpp systems later when the PV system costs further decrease to compensate for the disadvantages.

**Deploying PVpp Systems Is a Feasible Way for Coal-Fired Electric Power Companies to Add Renewable Energy Capacity**

Many countries have adopted renewable portfolio standards to prompt the development of renewable energy (Carley et al., 2018; Stokes and Warshaw, 2017). In 2016, China’s National Energy Administration released the guidance for renewable portfolio standards, which proclaimed that the share of non-hydro renewable energy power generation of electric power companies should account for 9% of the companies’ total power generation (NEA, 2016). The electric power companies that fail to meet this requirement will
lose their electricity generation licenses. In the future, electric power companies might have to either expand their renewable capacity or buy renewable energy certificates to avoid penalties. Our study demonstrates that deploying the PV(pp) systems at CFPPs is feasible. In addition to the many technical advantages, PV(pp) systems also have excellent economic performance. Their good profit potential and short payback periods are significant to coal-fired power plants, as many of them have been suffering from financial loss (Yuan et al., 2016; Wang et al., 2019). Therefore, deploying PV(pp) systems is an option worth considering for coal-fired electric power companies to increase their renewable capacity.

Limitations of the Study
This article aims to introduce the concept of PV(pp) and to study its feasibility, so an empirical formula was used to model the PV generation without considering the impact of shade and temperature on the system performance. This method can be further improved in future work. The PV potential discussed in this article mainly focuses on the potential in the coal-fired power generation sector; however, the concept of PV(pp) applies to all energy-intensive industrial sectors, so future research can continue to explore the potential of integrating PV with other sectors.

Resource Availability

Lead Contact
Further information and requests for resources and data should be directed to and will be fulfilled by the Lead Contact, Jinyue Yan (jinyue.yan@mdh.se).

Materials Availability
This study did not use or generate any reagents.

Data and Code Availability
The power plant information was obtained from the Annual Compilation of Statistics for Power Industry (CEC, 2014). The specifications and construction plan for the case power plant and electricity demand data were provided by China Energy Investment Corporation. The satellite image data were from Google Earth software. The monthly meteorological data were obtained from the meteorological dataset WorldClim (Fick and Hijmans, 2017). The hourly solar radiation data used in the calculation of the case power plant were retrieved from Meteonorm software (version 7.1.3). PV policies were gathered from the official websites of the National Energy Administration (www.nea.gov.cn) and the National Development and Reform Commission (www.ndrc.gov.cn). This study did not generate any code. The preliminary data are available on request from the corresponding authors.
METHODS
All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION
Supplemental Information can be found online at https://doi.org/10.1016/j.isci.2020.101867.

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AUTHOR CONTRIBUTIONS
Conceptualization, J.Y.Y.; Methodology, J.Y.Y., W.D.W., and M.K.J.; Investigation, W.D.W., J.S.L., M.K.J., J.W.M., and J.Y.Y.; Formal analysis, M.K.J., W.D.W., J.S.L., J.W.M., and J.Y.Y.; Data Curation, W.D.W., J.W.M., and H.Q.Q.; Writing—Original Draft, M.K.J.; Writing—Review & Editing, M.K.J., W.D.W., J.S.L., P.F.Z., and J.Y.Y.; Visualization, M.K.J. and P.F.Z.; Supervision, J.Y.Y., W.D.W., and J.S.L.; Resource, W.D.W. and H.Q.Q.; Funding Acquisition, J.Y.Y., W.D.W., and J.S.L.

DECLARATION OF INTERESTS
The authors declare no competing interests.

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Supplemental Information

Using Existing Infrastructure to Realize Low-Cost and Flexible Photovoltaic Power Generation in Areas with High-Power Demand in China

Mingkun Jiang, Jiashuo Li, Wendong Wei, Jiawen Miao, Pengfei Zhang, Haoqi Qian, Jianmin Liu, and Jinyue Yan
Supplemental Figures and Tables

Figure S1. The PV array layout. Related to Transparent Methods (PV Generation Model).

Figure S2. Regression results of the available rooftop area. Related to Figure 3 and Transparent Methods equation 1.
Figure S3. Regression results of the coal storage yard area. Related to Transparent Methods equation 2.
Table S1. PV Panel Specifications. Related to Transparent Methods (PV Generation Model) section.

| Item                        | Parameters                                                                 |
|-----------------------------|---------------------------------------------------------------------------|
| Solar Cell                  | Monocrystalline silicon, 6 inches                                        |
| Dimensions                  | 1960 × 992 × 40 mm                                                        |
| Area                        | 1.944 m²                                                                  |
| Maximum power under STC ($P_{max}$) | 0.365 kW                                                                 |

Table S2. Business Models for the Different Scenarios. Related to Figure 6 and Figure 7B.

| Business model                                      | Electricity selling price                                                                 | Subsidy (CNY/kWh) |
|-----------------------------------------------------|-------------------------------------------------------------------------------------------|-------------------|
| Scenario I: Half sold to I&C users and half fed into the grid | Local desulfurized coal benchmark prices and electricity market prices for I&C users | 0.10              |
| Scenario II: Half sold to residential users and half fed into the grid | Local desulfurized coal benchmark prices and electricity market prices for residential users | 0.18              |
| Scenario III: All sold to I&C users                  | Electricity market prices for I&C users                                                   | -                 |
| Scenario IV: All sold to residential users           | Electricity market prices for residential users                                           | -                 |
| Scenario V: All fed into the grid                    | Utility-scale PV prices                                                                   | -                 |
Table S3. Hourly energy demand of case power plant and PV output in the summer solstice. Related to Figure 2A.

| Time | Electricity demand (kWh) | PV output (kWh) |
|------|--------------------------|-----------------|
| 0    | 19200                    | 0               |
| 1    | 19200                    | 0               |
| 2    | 19200                    | 0               |
| 3    | 19200                    | 0               |
| 4    | 14400                    | 0               |
| 5    | 19200                    | 0               |
| 6    | 19200                    | 0               |
| 7    | 14400                    | 39              |
| 8    | 24000                    | 489             |
| 9    | 24000                    | 1038            |
| 10   | 19200                    | 1614            |
| 11   | 19200                    | 2133            |
| 12   | 19200                    | 2550            |
| 13   | 19200                    | 2826            |
| 14   | 19200                    | 2961            |
| 15   | 19200                    | 2943            |
| 16   | 19200                    | 2742            |
| 17   | 19200                    | 2403            |
| 18   | 19200                    | 1938            |
| 19   | 19200                    | 1392            |
| 20   | 24000                    | 810             |
| 21   | 28800                    | 303             |
| 22   | 28800                    | 3               |
| 23   | 28800                    | 0               |
Table S4. Hourly energy demand of case power plant and PV_{pp} output in the winter solstice. Related to Figure 2B.

| Time | Electricity demand (kWh) | PV output (kWh) |
|------|--------------------------|----------------|
| 0    | 24000                    | 0              |
| 1    | 19200                    | 0              |
| 2    | 19200                    | 0              |
| 3    | 24000                    | 0              |
| 4    | 19200                    | 0              |
| 5    | 24000                    | 0              |
| 6    | 19200                    | 0              |
| 7    | 24000                    | 0              |
| 8    | 19200                    | 0              |
| 9    | 19200                    | 0              |
| 10   | 24000                    | 6              |
| 11   | 24000                    | 132            |
| 12   | 19200                    | 249            |
| 13   | 24000                    | 336            |
| 14   | 19200                    | 390            |
| 15   | 24000                    | 369            |
| 16   | 24000                    | 297            |
| 17   | 19200                    | 192            |
| 18   | 24000                    | 78             |
| 19   | 19200                    | 0              |
| 20   | 24000                    | 0              |
| 21   | 19200                    | 0              |
| 22   | 24000                    | 0              |
| 23   | 19200                    | 0              |
| Unit                        | PV$_{pp}$ | Distributed PV system | Centralized PV system | PV with storage system |
|-----------------------------|-----------|-----------------------|-----------------------|------------------------|
| PV modules                  | CNY/W     | 2                     | 2                     | 2                      |
| Supports                    | CNY/W     | 0.3                   | 0.3                   | 0.3                    |
| Inverter                    | CNY/W     | 0.3                   | 0.3                   | 0.3                    |
| Wirings                     | CNY/W     | 0.2                   | 0.2                   | 0.2                    |
| Engineering                 | CNY/W     | 0.6                   | 0.9                   | 0.9                    |
| Junction boxes              | CNY/W     | 0.1                   | 0.1                   | 0.1                    |
| Insurance cost              | CNY/W     | 0.035                 | 0.035                 | 0.035                  |
| Grid connection cost        | CNY/W     | -                     | -                     | 0.5                    |
| Battery                     | CNY/Wh    | -                     | -                     | -                      |
| O&M cost                    | CNY/W/year| 0.04                 | 0.04                  | 0.04                   |
| Rooftop rent                | CNY/m$^2$/year, | -       | 4                     | -                      |
| Land rent                   | CNY/m$^2$/year, | -       | -                     | 1.5                    |
| Interest rate               | %         | 8                     | 8                     | 8                      |
| Yearly cost for the first 5 years | CNY/W     | 0.93                  | 1.03                  | 1.16                   |
| Battery replacement for the 5th year | CNY/W     | -                     | -                     | 1.17                   |
| Yearly cost for the 6th-9th years | CNY/W     | 0.04                  | 0.06                  | 0.06                   |
| Yearly cost for the 10th years | CNY/W     | 0.34                  | 0.36                  | 0.36                   |
| Yearly cost for the 11th-14th years | CNY/W     | 0.04                  | 0.06                  | 0.06                   |
| Yearly cost for the 15th year | CNY/W     | 0.04                  | 0.06                  | 0.06                   |
| Yearly cost for the 16th-19th years | CNY/W     | 0.04                  | 0.06                  | 0.06                   |
| Yearly cost for the 20th year | CNY/W     | 0.34                  | 0.36                  | 0.36                   |
| Yearly cost for the 21st-25th years | CNY/W     | 0.04                  | 0.06                  | 0.06                   |
| Total                       |           | 6.03                  | 7.06                  | 7.66                   | 13.16                  |

*a. Numbers were rounded.*

*b. The discount rate was not taken into account.*
Table S6. Provincial potential PV \( p_p \) capacity, installed PV capacity and the ratio of PV \( p_p \) capacity to installed PV capacity. Related to Figure 4A.

| Region | Province | Potential PV \( p_p \) capacity (MW) | Installed PV capacity (MW)\(^a\) | The ratio of PV \( p_p \) capacity to installed PV capacity |
|--------|----------|-------------------------------------|----------------------------------|----------------------------------------------------------|
| E      | JS       | 321                                 | 14860                            | 2.16%                                                     |
| E      | SD       | 309                                 | 16190                            | 1.91%                                                     |
| E      | IM       | 300                                 | 10810                            | 2.78%                                                     |
| E      | HE       | 196                                 | 14740                            | 1.33%                                                     |
| E      | ZJ       | 180                                 | 13390                            | 1.34%                                                     |
| E      | AH       | 159                                 | 12540                            | 1.27%                                                     |
| E      | FJ       | 109                                 | 1690                             | 6.45%                                                     |
| E      | SH       | 87                                  | 1090                             | 7.98%                                                     |
| E      | JX       | 58                                  | 6300                             | 0.92%                                                     |
| C      | HA       | 269                                 | 10540                            | 2.55%                                                     |
| C      | HB       | 105                                 | 6210                             | 1.69%                                                     |
| C      | HN       | 86                                  | 3440                             | 2.50%                                                     |
| N      | SX       | 258                                 | 10880                            | 2.37%                                                     |
| N      | TJ       | 54                                  | 1430                             | 3.78%                                                     |
| N      | BJ       | 21                                  | 510                              | 4.12%                                                     |
| S      | GD       | 290                                 | 6100                             | 4.75%                                                     |
| S      | GX       | 70                                  | 1350                             | 5.19%                                                     |
| S      | HI       | 20                                  | 1400                             | 1.43%                                                     |
| NE     | LN       | 142                                 | 3430                             | 4.14%                                                     |
| NE     | JL       | 96                                  | 2740                             | 3.50%                                                     |
| NE     | HL       | 91                                  | 2740                             | 3.32%                                                     |
| NW     | XJ       | 181                                 | 10800                            | 1.68%                                                     |
| NW     | SN       | 109                                 | 9390                             | 1.16%                                                     |
| NW     | GS       | 82                                  | 9080                             | 0.90%                                                     |
| NW     | NX       | 78                                  | 9180                             | 0.85%                                                     |
| NW     | QH       | 14                                  | 11010                            | 0.13%                                                     |
| SW     | GZ       | 99                                  | 5100                             | 1.94%                                                     |
| SW     | SC       | 65                                  | 1880                             | 3.46%                                                     |
| SW     | YN       | 54                                  | 3750                             | 1.44%                                                     |
| SW     | CQ       | 52                                  | 650                              | 8.00%                                                     |
| SW     | XZ       | 3                                   | 1100                             | 0.27%                                                     |

\(^a\) the data of 2019.
Transparent Methods
Identification and Estimation of Available Area

This study used Google Earth\textsuperscript{TM} software (version 7.3.3.7786) to obtain satellite images of power plants and to measure the available area of suitable rooftops. The authors collaborated with experienced experts from China Energy Investment Corporation to set criteria to identify the suitable rooftops for PV deployment. We divided the rooftops of the power plants into two types, i.e., suitable rooftops and unsuitable rooftops, based on roof structure, building function and safety concerns. Additionally, it is easy to observe that there are many structures and pieces of functional equipment on some rooftops; hence, the rooftops that are not obstacle-free are also excluded from the suitable rooftop group. The material that the rooftop is constructed from also affects whether PV panels can be installed or not. Concrete and steel are two common materials for rooftops. We exclude steel rooftops from the suitable rooftop group because it may not be strong enough to hold PV panels. In China, most steel roofs are blue or red. Therefore, all blue rooftops and red rooftops are excluded from the available area measurement process. Although PV panels cannot be directly deployed on coal storage yards, coal-fired power plants are installing coal sheds and enclosures to meet environmental protection requirements, which is believed to increase the available area for PV deployment. Therefore, the area of coal storage yards was also taken into account to estimate the maximum PV\textsubscript{pp} potential in the discussion section.

Power plant information was collected from the annual compilation of statistics of the power industry (CEC, 2014). There are more than 3000 power plants with capacity values between 6 MW and 4800 MW in the dataset. However, the units with capacity values below 50 MW and the units with capacity values below 100 MW that have been operating for 20 years face shutdown plans (NDRC, 2007), which indicates that most of the small power plants will not continue to operate in the future. The typical lifetime of a PV system is approximately 20 to 30 years. As a result, we studied only the PV\textsubscript{pp} potential of the 1082 power plants with capacity values over 100 MW in this work.

Measuring the available areas in all 1082 Chinese coal-fired power plants can be time consuming. Therefore, this study adopted a linear regression approach to estimate the available area. Fifty-six power plants (5\% of the total population) were randomly chosen as samples, and their available area was measured manually. A prediction model was developed to identify the relationship between the capacity of power plants (predictor variable) and the available area for PV deployment (response variable). Data from 56 sample power plants were used to train the regression model (see Figure S2 and Figure S3). The model was used to predict the available area based on the power plants’ capacity. We performed a regression analysis using Microsoft Excel. The equations for the available area estimation are as follows:

\begin{align}
  \text{area}_{\text{roof}} &= 13.181x + 12746 \\
  \text{area}_{\text{coal yard}} &= 33.855x + 14012
\end{align}

where \(x\) is the capacity of the coal-fired power plant, \(\text{area}_{\text{roof}}\) is the available rooftop area of the power plant site, and \(\text{area}_{\text{coal yard}}\) is the coal storage yard area of the power plant.
**PV Generation Model**

A monocrystalline 72-cell module from a Chinese solar photovoltaic manufacturer was chosen to build the PV generation model. The specification of the PV module listed in Table S1 was used for the PV generation modeling.

Following existing instances and Hong et al.’s work, we assumed that PV modules are installed horizontally on the roofs (Hong et al., 2017). We used the packing factor $\eta$ to calculate the effective panel area. The packing factor refers to the ratio of the array area to the actual land or rooftop area (SBH, 2020). When installing PV panels, we need to leave space between the PV arrays for maintenance and operation purposes. Therefore, the actual space a PV array needs is larger than its actual size. With regard to real cases, it is common to see PV panels deployed 1- to 4-rows into an array on industrial roofs. The spaces between the PV arrays enable workers to walk between them. We found that the width of the fiber-reinforced plastic grating used to pave the PV maintenance channel is 400 mm (http://gxblbggs.com/showproducts.asp?id=168), so we assumed that the width of the space between the PV arrays is 500 mm, and the PV array is assumed to have 3 rows of PV modules (see Figure S1).

Based on the assumptions, the packing factor is calculated as follows:

$$\eta = \frac{2976 \times 1960}{(2976 + 500) \times 1960} \approx 0.856 \quad (3)$$

In this case study section, we assume that the centralized PV and PV with battery systems are tilted-mounted. There should be enough distance between the PV arrays to ensure that the PV arrays do not shade the adjacent array from 9:00 am to 3:00 pm on the winter solstice (MOHURD and AQSIQ, 2012). The packing factor of tilted PV panels is calculated as follows:

$$D = W \times \cos \beta + W \times \sin \beta \times \frac{0.707 \tan \phi + 0.4338}{0.707 - 0.4338 \tan \phi} \quad (4)$$

$$\eta_t = \frac{W}{D} \quad (5)$$

where $D$ is the distance between the PV arrays (m), $W$ is the width of a PV pane (m), which is 0.992 m, $\phi$ is the latitude of the site, which is $42^\circ$ and $\beta$ is the tilt angle, which is equal to $\phi$ (Mondol et al., 2007). $\eta_t$ is the packing factor of the tilted PV arrays.

The potential PV capacity is calculated as follows:

$$\text{capacity} = \frac{\text{area}_{\text{available}}}{\text{area}_{\text{PV}}} \times P_{\text{max}} \times \eta \quad (6)$$

where $\text{capacity}$ is the potential capacity of the PV system (kW), $\text{area}_{\text{available}}$ is the available area for PV deployment (m²), $\text{area}_{\text{PV}}$ is the area of the PV panel (m²), $P_{\text{max}}$ is the peak power
of the PV module (kW), and $\eta$ is the packing factor of PV arrays.

The solar radiation used to predict the annual generation potential in this study was from WorldClim, which provides average monthly climate data from 1970 to 2000 (Fick and Hijmans, 2017). The spatial resolution of the solar radiation data was 2.5 minutes. We extracted the radiation data for each power plant using the ESRI ArcGIS® software (version 10.2). The solar radiation used to predict the hourly generation in the case study section was from the Meteonorm database. We compared the two datasets and found that the annual solar radiation data for the case power plant in the two datasets were very similar. In addition to the PV modules, a PV system also consists of equipment such as inverters and cables. The efficiency of all the equipment will also affect the overall performance of the PV system. The overall performance coefficient of PV systems is usually between 0.75 and 0.85. This study used 0.78 for the calculation (Verso et al., 2015; Ito et al., 2010). We did not take the effects of shade into account for two reasons. First, it can be highly challenging to consider the effect of shade on the PV output of 1082 power plants. Second, the buildings of power plants are typically widely spaced, so they do not typically shade each other. According to GB 50797-2012, the annual PV generation is calculated as follows (MOHURD and AQSIQ, 2012):

$$E_{p,h} = H_h \times \frac{\text{capacity}}{E_S} \times K$$ \hspace{1cm} (7)

$$E_{p,i} = H_A \times \frac{\text{capacity}}{E_S} \times K \times (1 - D)^i$$ \hspace{1cm} (8)

$$E_{p,\text{total}} = \sum_{i=1}^{25} H_A \times \frac{\text{capacity}}{E_S} \times K \times (1 - D)^i$$ \hspace{1cm} (9)

where $E_{p,h}$ is the PV output (kWh) of the $h$th hour of a day, $H_h$ is the global horizontal irradiance (kWh/m²) of the $h$th hour of a day, and $K$ is the overall performance coefficient, which is 0.78. $E_{p,i}$ is the annual PV (kWh) output in year $i$, $H_A$ is the annual local horizontal irradiance (kWh/m²), $E_S$ is the standard PV test condition (1000 W/m²), capacity is the potential capacity of the PV system (kW). $D$ is the annual degradation rate of PV panels, which is 0.01 (Azizi et al., 2018); $E_{p,\text{total}}$ is the total PV output over the lifetime of the PV system (kWh), and the lifetime of the PV system is set to 25 years.

**PV system costs**

The equipment costs (PV module cost, support cost, inverter, wirings, combiner box, battery cost) and soft costs (engineering cost, insurance cost, grid connection cost, O&M cost, rooftop rent, land rent, interest) make up the total PV system cost. The lifetime of a PV system is assumed to be 25 years in this work. Batteries and inverters need to be replaced every 5 and 10 years, respectively (Kaabeche et al., 2011; Shabani et al., 2020; Yan et al., 2019). We used a PV to battery ratio of 1.50 to size the battery capacity (Boeckl and Kienberger, 2019). The
interest rate was 8%, and the loan term was 5 years (Yan et al., 2019). The cost breakdown of PV systems is shown in Table S5.

Economic metrics

The lifetime cost is calculated as follows:

\[
LC = \sum_{i=1}^{25} \left( \left( C_{\text{equipment},i} + C_{\text{O&M},i} \right) \times \text{capacity} \right) \times 1.05^i
\]

where \( LC \) is the lifetime cost (CNY), \( C_{\text{equipment},i} \) is the unit equipment investment and equipment replacement cost for year \( i \) (CNY), \( C_{\text{O&M},i} \) is the unit O&M cost for year \( i \) (CNY), and the discounted value is set to 5%.

The lifetime revenue can be generated from selling electricity, and it can be calculated using the following equation:

\[
Revenue_k = \sum_{i=1}^{25} E_{p,i} \times \left( P_k + S_{PV,i,k} \right) 
\]

where \( Revenue_k \) is the lifetime revenue in scenario \( k \) (CNY), \( E_{p,i} \) is the PV output in year \( i \) (kWh), \( P_k \) is the electricity selling price in scenario \( k \) (CNY/kWh), and \( S_{PV,i,k} \) represents the PV system subsidy for year \( i \) in scenario \( k \) (CNY/kWh).

Another metric to evaluate economic performance is the return on investment (ROI), which reflects the efficiency of investment and is calculated as follows:

\[
ROI = \frac{NI}{LC} \times 100\%
\]

where \( NI \) is the lifetime net income (CNY).

The discounted payback period (DPBP) refers to the amount of time the PV_pp system takes to reach the break-even point. The payback period is calculated as follows based on the yearly net cash flow:

\[
\sum_{i=1}^{\text{DPBP}} \frac{R_i}{1.05^i} = 0
\]

where \( R_i \) is the yearly net cash flow in year \( i \) (CNY/kWh).

This study uses the levelized cost of electricity (LCOE) to calculate the generation cost, which is calculated as follows:
\[
LCOE = \frac{\sum_{j=1}^{25} (C_{equipment,j} + C_{O&M,j}) \times \text{capacity}}{\left(\sum_{j=1}^{25} E_{p,j}\right)(1.05)^i}
\]

The variables in the equation have been defined above.

The grid parity indicators from Yan et al.’s work are applied to demonstrate the grid parity ability of each PV system (Yan et al., 2019). They are calculated as follows:

\[
GPI = \frac{LCOE}{CP}
\]

Here, \(CP\) is the desulfurized coal benchmark price (CNY/kWh).

\[
GPI_{iu} = \frac{LCOE}{MP_{iu}}
\]

Here, \(MP_{iu}\) is the electricity market price for industrial and commercial (I&C) users (CNY/kWh).

\[
GPI_{ru} = \frac{LCOE}{MP_{ru}}
\]

Here, \(MP_{ru}\) is the electricity market price for residential users (CNY/kWh).

**Scenarios considered in the study**

The revenues are mainly from selling electricity. In addition to feeding electricity into the power grid, we also assume that electricity can be sold directly to end-users. We created five scenarios to comprehensively investigate the economic performance of the PV systems according to China’s PV pricing and subsidy policy. The subsidy and business model of each scenario are detailed in Table S2. In Scenario I, half of the system output is sold to I&C users and the other half is fed into the grid. In Scenario II, half of the system output is sold to residential users and the other half is fed into the grid. In Scenario III, the output is sold to I&C users. In Scenario IV, the output is sold to residential users. In Scenario V, the output is fed into the power grid. The subsidies for PV system last for 20 years.
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