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City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China

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Supplementary Note 1. About the “531 New Policy” and other critical concepts.

The “Notice on matters relevant to PV power generation in 2018 (NDRC [2018] No. 823)”—i.e. the so-called “531 New Policy”—was issued on May 31st 2018 by China’s National Development and Reform Commission (NDRC), Ministry of Finance (MOF), and National Energy Administration (NEA). It provided the following main new regulations for the PV industry in China: 1) No construction quota will be allocated in 2018 for ordinary solar PV power plants. Before further notice from the central government, local governments may not, in any way, plan the construction of ordinary solar PV power plants that require subsidies from the central government. 2) A quota of 10 GW of distributed photovoltaic projects is planned to receive support in 2018. 3) From the moment of this Notice publication, the benchmark feed-in tariff (FiT) for power plants will be uniformly lowered by 0.05 CNY/kWh to 0.5 CNY/kWh, 0.6 CNY/kWh, and 0.7 CNY/kWh (tax included), for Resource Zones I, II, and III, respectively. The benchmark for distributed solar PV projects of "self-generation of power at the users' end for self-use and utilization of surplus power in the grid" is hereby reduced by 0.05 CNY/kWh to 0.32 CNY/kWh (tax included). 4) Continue to support PV for Poverty-Alleviation projects and Front-Runner projects. 5) Encourage development of PV projects that do not require state subsidies¹.

According to the definition from “Interim measures for distributed generation management” (NDRC Energy [2013]1381) issued by NDRC, distributed power generation refers to power generation facilities or power output that are built and installed at or near the users’ site, with self-consumption and extra generation feeding into the grid, as well as power generation facilities featuring power distribution network system balance adjustment or comprehensive and stepped utilization of energy cogeneration facilities with power output².

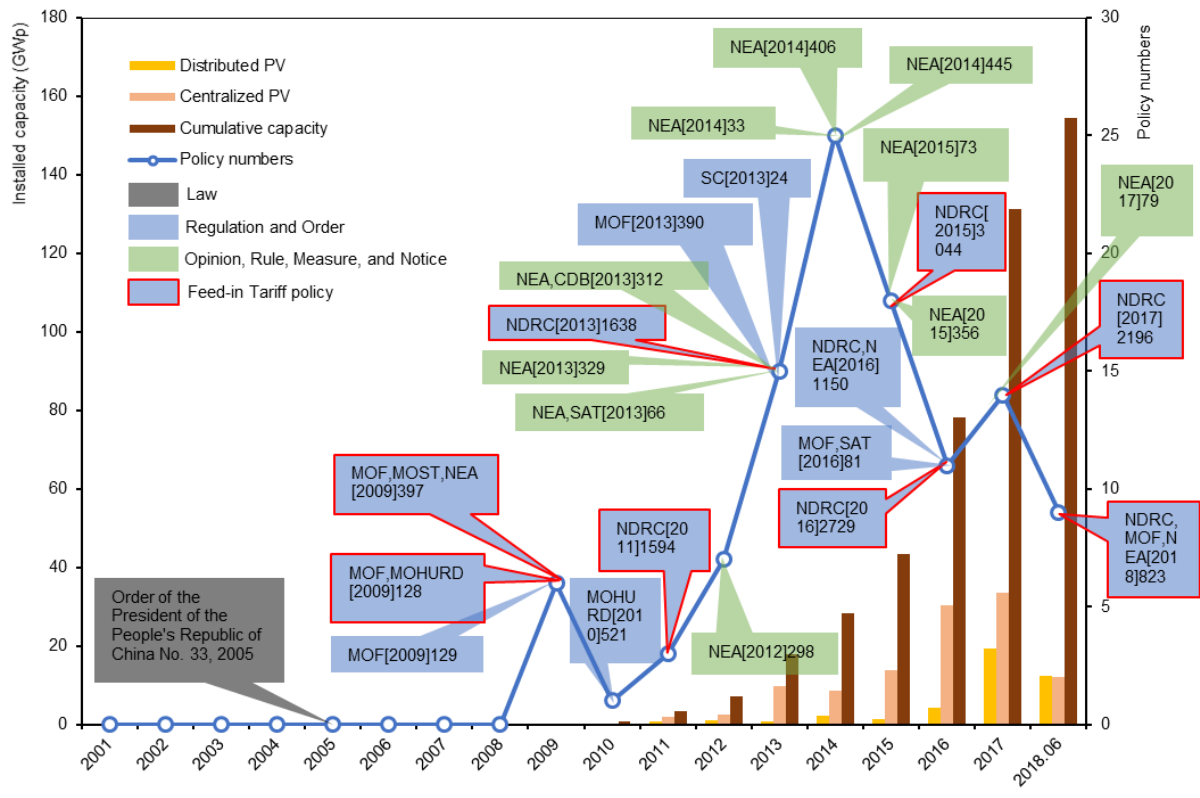
In this study, the Central government refers to National People's Congress and its Standing Committee, State Council and its Ministries, and National Bureaus³.

According to the policy “Notice on exerting price leverage to promote the healthy development of the solar PV industry (NDRC[2013] No.1638),” the country is divided into three types of solar energy Resource Zones based on local solar energy resource conditions and construction costs. Moreover, the corresponding grid-connected electricity tariff is formulated accordingly⁴.

Supplementary Note 2. Stunning performance and driving factors.

Solar PV is one of the more rapidly growing industries in China. In 2011, the total PV installed capacity of China was only 2.5 GW⁵, while in the same year, total installed capacity of Germany (the world's photovoltaic leader) was 24.82 GW⁶. In just six years, by the end of 2017, the cumulative PV installed capacity of China had reached 131.25 GW⁷, a fifty-fold increase over the 2011 level, and a threefold increase over the 43 GW of Germany in 2017⁸. Newly installed capacity is 53.6 GW: PV power plants account for 33.62 GW (an 11% increase) and distributed PV accounts for 19.44 GW (a 3.7-fold increase compared with 2016)⁷. These facts have confirmed the strength of growth in China, which in 2017 accounted for 32% of global installed capacity and 54% of the PV market⁹. In 2018, China's PV installation continued its global expansion, reaching 154.51 GW of cumulative installation by the end of June, including 112.6 GW of PV plants and 41.9 GW of distributed PV¹⁰. Furthermore, China's PV power output reached 118.2 TWh in 2017, a 78.6% year-to-year increase⁷.

Policy support—including grid support, operation specification, and operation supervision from central and local governments—is an important policy instrument available to governments for supporting renewable energy industries. Policy has played a critical role in China's stunning achievements in the fiercely competitive PV markets. There are, in total, over 300 renewable energy and PV industry policies that have been implemented from 1994 to June 2018, both nationally and regionally¹¹. Among them, there have been 109 policies from the central government that specifically target the PV industry. Early on, policies focused on renewable energy Research & Development (R&D) through the 863 Program, the 973 Program, and the Key Technologies programs^{12 13}. In 2009, China rolled out two national solar subsidy programs: the “Building Integrated with Photovoltaics (BiPV) subsidy program” (also known as the “Solar Roofs Program”)^{14 15}, and the “Golden Sun Demonstration Program”¹⁶. These programs clearly demonstrated China's determination to support the adoption of PV. As the first solar subsidy program, the BiPV subsidy offered 20 CNY/W_p upfront for BiPV systems, which covered 30%–50% of PV system costs. Four months after the effective Solar Roofs Program (July 2009), the media reported that 111 rooftop-based and BiPV projects nationwide, with a combined capacity of 91 MW, had been allocated subsidies totaling nearly 1.3 billion CNY^{17 18}. The Golden Sun Demonstration Program, in order to facilitate growth and to expand the scale of the PV power generation industry, offered a 50% investment for solar power projects and relevant power transmission and distribution systems that connect to grid networks. In addition, the nationwide solar PV FiT scheme was first introduced shortly after these two programs in July 2011, with the on-grid benchmark price of 1.15 CNY/kWh¹⁹. The financial incentives represented by FiT have been active for almost ten years to date, playing a significant role in stimulating and attracting solar PV industry investment. In August 2013, the NDRC issued the “Notice on exerting price leverage to promote the healthy development of the PV industry” to categorize PV power generation into either distributed or centralized systems⁴. Distributed solar PV systems became a distinct type of solar PV system, and gained popularity. Programmatically, the Strategy of Energy Production and Consumption (2016–2030) affirmatively aimed to “Coordinate the construction of distributed systems, solar PV generation, and the application of heating...” in 2016²⁰. At the end of November 2017, the NDRC and the National Energy Agency (NEA) issued the “Notice of Market-based Transaction Pilots for Distributed Generation”²¹. The participation of distributed energy in the electricity market marked a milestone in the reform of the electric power industry. Policy incentives have been introduced continuously to motivate the development of China's solar PV industry (Supplementary Figure 1).

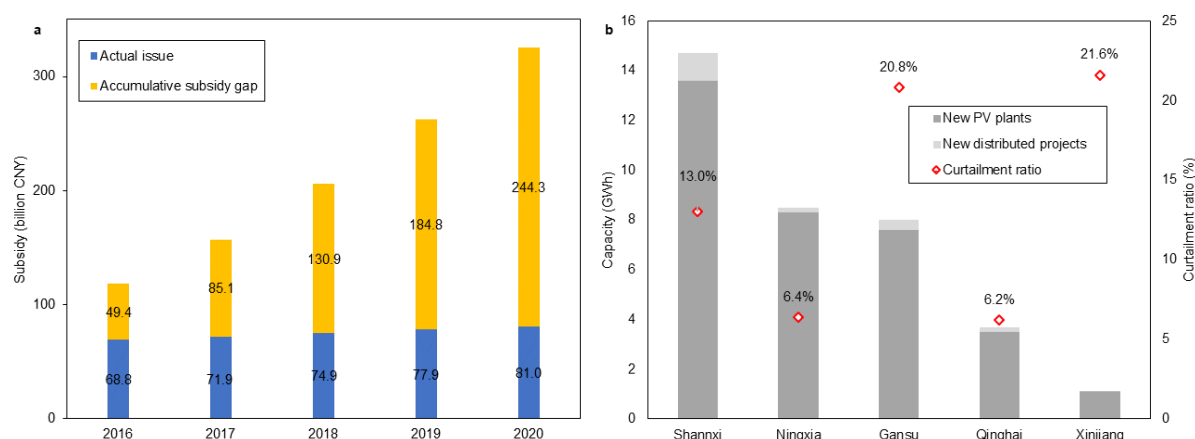


Supplementary Figure 1 | Historical policies of the solar PV industry in China and installed capacity. Box colors represent the policy-issuing body and its administrative ranking: grey represents the National People's Congress and its Standing Committee (Laws); blue represents the State Council and its Ministries (Regulations and Orders); and green represents the National Bureaus (Opinions, Rules, Measures, and Notices). The policies above are shown as “issuing body + issuing year + policy number.” The full policy title to each abbreviation can be found in Supplementary Tables 1 and 2. The blue line shows the historical trend in policy quantity. Among the policies, the national FiT is the main support measure that defines a fixed and guaranteed payout for a unit of electricity generated by solar PV systems. FiT policies are indicated by boxes with red frames. Additionally, the clustered columns represent centralized and distributed solar PV yearly installed capacity, and cumulative installed capacity. Collected data up to June 2018 are included.

Supplementary Note 3. Overcapacity, curtailment, and state financial burden.

China's 13th Five Year Plan for Renewable Energy Development (2016–2020) set a 105-GW target for new solar PV capacity by 2020⁴. This target was met almost three years earlier, at the end of 2017. However, high installation rate has led to overcapacity, high rates of power generation curtailment, and state financial burden. Over 70% of China's large-scale solar projects have been installed in the resource-rich northern regions, which have low electricity demands and low export capacity, thus resulting in a national average curtailment ratio as high as 20% in 2016 for solar electricity²³ due to the record increase (43.18 GW²⁴) in solar capacity built in 2015. In Xinjiang and Gansu provinces, solar curtailment surged to 30% and 32%, respectively²⁵. In contrast, the curtailment rates in Germany and the US state of Texas were approximately 1% and 0.5%, respectively²⁶. Moreover, China's state-run renewable energy fund, financed by a surcharge on the energy bills of users, is in deficit by 85.1 billion CNY, of which the PV subsidy gap was 45.5 billion CNY as of the end of 2017 (Supplementary Figure 2)²⁷, and this is expanding yearly, according to statistics from the Ministry of Finance (MOF). Many projects have not received due payments since 2015. The installation of a 10-GW PV project equates to a 4-billion CNY annual increase, and 80 billion CNY over 20 years, based on 2017 distributed solar PV subsidies. If this extraordinary growth continues, the financial subsidy gap will continue to expand, which will adversely affect the development of the industry.

Researchers have pointed out that subsidies are an important tool that the government uses to intervene in specific industries, and that this was one of the main factors that led to Chinese solar PV growth and overcapacity^{28 29 30}. They have also suggested prudent reform of subsidy policy for solar energy enterprises.

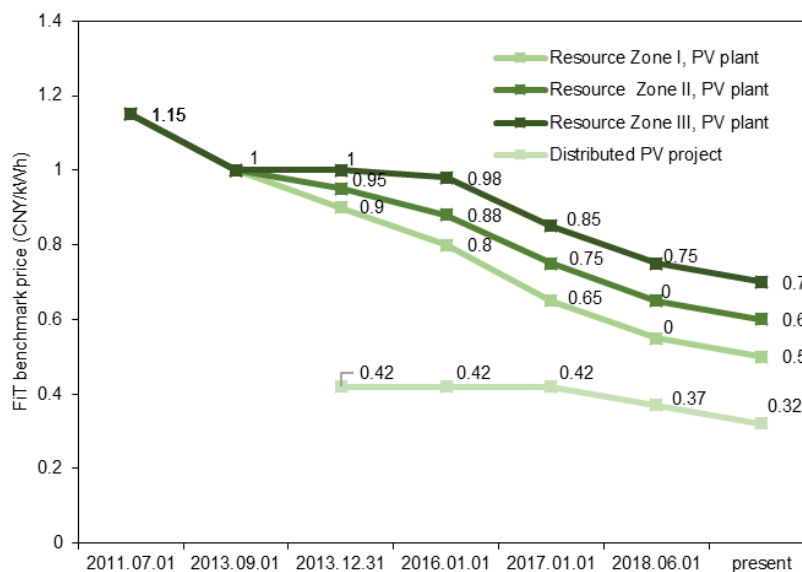


Supplementary Figure 2| China's renewable energy subsidy funding gap and solar PV construction. **a.** Existing renewable energy funding in China comes from a surcharge on electricity bills that is collected from customers by energy suppliers. The figure shows the annual subsidy requirements, the actual issuing amounts, and the subsidy gaps in the solar PV sector. In 2017, this funding faced an 85 billion CNY shortfall, approximately 50% of which was from the solar PV sector. **b.** The figure shows the growing capacity in the Northwest provinces of Shanxi, Ningxia, Gansu, Qinghai, and Xinjiang in 2017 under the promised subsidies. The triangle-marked points show the power curtailment ratio from solar PV generation in these provinces in 2017.

Supplementary Note 4. Increasingly tightened policies and the “531 New Policy”.

In light of issues related to overcapacity, efforts undertaken in recent years for capacity constraints have been mainly focused on reducing financial subsidies. On May 31st, 2018, the NDRC, MOF, and NEA released new guidelines that were made effective on June 1st, i.e. “Notice on matters relevant to PV power generation in 2018”¹, which instructed to 1) terminate any approvals of new subsidized utility-scale PV power plants in 2018 until further notice; and 2) slash the FiT by 0.05 CNY/kWh, with 0.5-, 0.6- and 0.7-CNY/kWh cuts to PV plant projects in Resource Zones I, II, and III, respectively, and a 0.32-CNY/kWh cut for distributed PV projects. Any projects without subsidy support are welcome as long as the grid can handle the power generation. The above guidelines are the so-called “531 New Policy”.

This is not the first policy that the government used to abate the FiT in China. In 2011, just after the Chinese PV subsidy policy was introduced, the on-grid price was 1.15 CNY/kWh. In 2017, it fell to 0.65 CNY/kWh, a drop of 44% in five years. Through the policies of the PV industry, the Chinese authorities aimed to continuously lower the FiT’s benchmark price (Supplementary Figure 3).



Supplementary Figure 3| 2011–2018 Chinese solar PV FiT benchmark policies. The FiT scheme was first issued in 2011, followed by a decreasing trend year after year. China was categorized into three Resource Zones in 2013 according to solar resource availability. The green lines represent the respective FiTs of the Resource Zones. The higher the Resource Zone number, the lower the available solar resources and the higher the subsidy.

According to the NEA, the “531 New Policy” aims at “promoting the solar energy sector’s sustainable development, enhancing its development quality, and speeding up the reduction of subsidies”³¹. Reducing the sales of new construction that requires subsidies will ease the financial burden on the government, avoid system risks, and benefit the long-term industrial development. Slowing the pace of development will help reduce the abandonment of solar power generation and thus solve the curtailment problem. Becoming less dependent on subsidies will force the industry to phase out outdated and subsidy-dependent enterprises, and encourage enterprises to innovate in ways that are sensitive to market demand, thus cultivating world-class manufacturers. In addition, adopting this policy will urge local governments to adopt incentive policies, thus reducing excessive fees, taxes, and other non-technical costs of the solar PV industry.

From an industry perspective, interviews of marketing directors, suppliers, and company heads showed a pessimistic or gloomy outlook on the post-subsidy era. A letter by eleven Chinese solar PV industry representatives was sent to the Xinhua news agency on June 4th 2018. The letter stated that the surprise move to withdraw support had come far too soon. The representatives urged the

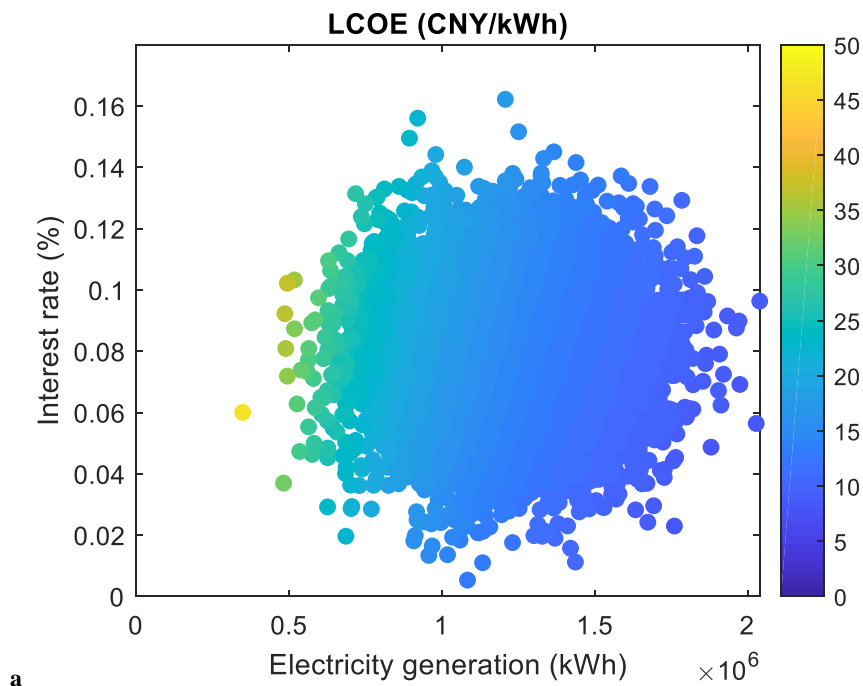
government to provide a grace period for approved projects, reduce the scale of the cut, carry out medium- and long-term planning, and discuss with the industry before executing the policy³². However, auctions for the Front-Runner projects had already yielded developer bids well below the FiT in Qinghai Province in 2018. The lowest bids came in at 0.31 CNY/kWh, far below the 0.55-CNY/kWh tariff, and lower than the regular on-grid electricity tariff and desulfurization coal benchmark electricity price³³.

Supplementary Note 5. Variables input and output in Monte Carlo analysis.

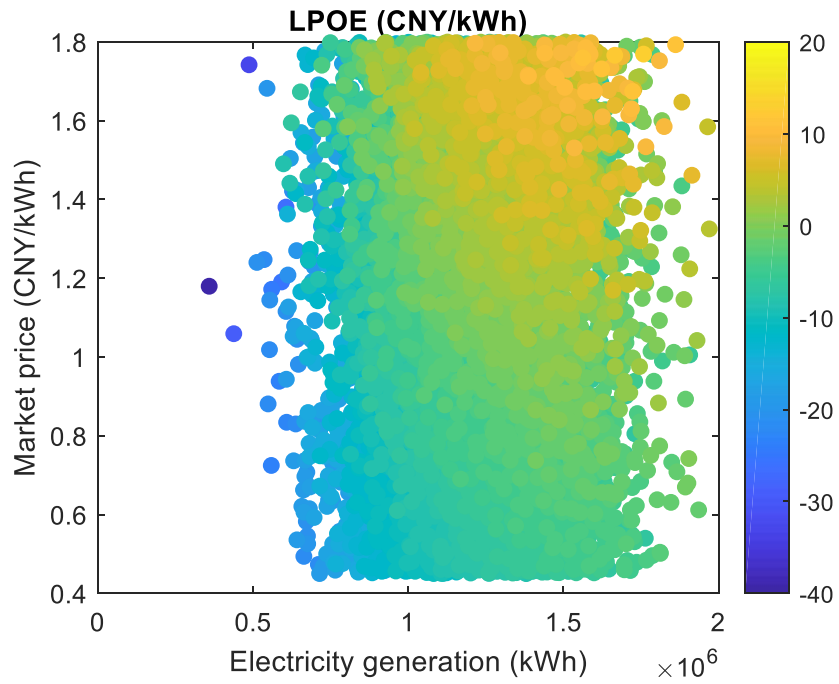
Supplementary Table 5. The sensitivity analysis inputs and their distributions.

Risk variables	LCOE	LPOE	Distribution	Parameters
Bank interest rate	0.23	-0.18	Normal Distribution	Mean is 0.08, Standard Deviation is 0.02
PV module cost	0.02	-0.01	Uniform Distribution	Minimum value is 2, maximum value is 5
Rooftop rent	0.07	-0.05	Uniform Distribution	Minimum value is 3, maximum value is 8
Electricity generation	-0.93	0.72	Normal Distribution	Mean is 1,220,000, Standard Deviation is 220,000
Self-consumption ratio	0.01	0.54	Uniform Distribution	Minimum value is 0, maximum value is 1
Desulfurized coal benchmark price	-	0.12	Uniform Distribution	Minimum value is 0.25, maximum value is 0.5
Electricity market price	-	0.63	Uniform Distribution	Minimum value is 0.45, maximum value is 1.8

The sensitivity analyses results are shown in the Supplementary Figure 4.



a



Supplementary Figure 4| Sensitivity analysis results on LCOE and LPOE. This is the color gradient maps of Monte Carlo analysis for **a.** the LCOE (CNY/kWh), electricity generation (kWh), and interest rate (%) and **b.** LPOE (CNY/kWh), electricity generation (kWh), and market price (CNY/kWh).

Supplementary Table 1. Government support types and their policy items.

Support types	Policy items
National Feed-in Tariff (FiT) scheme	<p>Notice on improving the on-grid electricity price policy for solar PV power generation. NDRC[2011]1594.</p> <p>Notice on the implementation of related issues such as the power subsidy policy for distributed solar PV power generation. MOF[2013]390.</p> <p>Notice on exerting price leverage to promote the healthy development of the solar PV industry. NDRC[2013]1638.</p> <p>Notice on improving the on-grid electricity price policy of onshore wind power and solar PV power generation. NDRC[2015]3044.</p> <p>Notice on adjusting the on-grid electricity price of solar PV power and onshore wind power generation. NDRC[2016]2729.</p> <p>Notice on the price policy of solar PV power generation projects in 2018. NDRC[2017]2196.</p> <p>Notice on matters relevant to PV power generation in 2018. NDRC,MOF,NEA[2018]823.</p> <p>Notice on actively promoting the work related to subsidy-free wind power and photovoltaic power generation for grid parity. NDRC,NEA[2019]19.</p>
Regulation for market access	<p>Implementation opinions on accelerating the applications of Building Integrated with Photovoltaics. MOF,MOHURD[2009]128.</p> <p>Announcement on the release of the industry standard "Technical Specifications for the Application of Solar PV Systems for Civil Buildings". MOHURD[2010]521.</p> <p>Notice on printing and distributing the interim measures for the management of solar PV power plant projects. NEA[2013]329.</p> <p>Notice on further strengthening the construction and operation management of solar PV power stations. NEA[2014]445.</p> <p>Notice on establishing market-environment monitoring and evaluation mechanism to guide the healthy and orderly development of solar PV Industry. NEA[2017]79.</p>
Financial funds and services	<p>Interim measures for the administration of financial assistance funds for Building Integrated with Photovoltaics applications. MOF[2009]129.</p> <p>Opinions on financial services supporting distributed solar PV generation. NEA,CDB[2013]312.</p>

Demonstration projects	<p>Notice on the implementation of the Golden Sun Demonstration Project. MOF,MOST,NEA[2009]397.</p> <p>Notice on declaring distributed scale solar PV power generation application demonstration zone. NEA[2012]298.</p>
Grid support	<p>Notice on the management of full guarantee acquisition of wind power and solar PV power generation. NDRC,NEA[2016]1150.</p>
Construction plan	<p>Renewable Energy Law of the People's Republic of China. Order of the President of the People's Republic of China No. 33(2005).</p> <p>Several opinions on promoting the healthy development of solar PV industry. SC[2013]24.</p> <p>Notice on further implementing relevant policies on distributed solar PV power generation. NEA[2014]406.</p> <p>Notice on the issuance of new construction scale for solar PV power generation in 2014.NEA[2014]33.</p> <p>Notice on the implementation plan for the construction of solar PV power generation in 2015. NEA[2015]73.</p> <p>Notice on increasing the scale of 2015 solar PV power plant construction in some areas. NEA[2015]356.</p> <p>Notice on the implementation plan for the construction of solar PV power generation in 2016. NEA[2016]166.</p> <p>Notice on printing and distributing the 13th Five-Year-Plan for solar energy development. NEA[2016]354.</p>
Favorable taxation and other exemption	<p>Notice of the Value-Added Tax policy for PV power generation. NEA,SAT[2013]66.</p> <p>Notice on issues concerning the exemption of government funds for self-consumption of distributed solar PV power. MOF[2013]103.</p> <p>Notice on the continuation of the Value-Added Tax policy for PV power generation. MOF,SAT[2016]81.</p>

Supplementary Table 2. Selected policies from 2005 to present.

Policy	Policy title
Order of the President of the People's Republic of China No. 33(2005).	Renewable Energy Law of the People's Republic of China.
MOF,MOHURD[2009]128	Implementation opinions on accelerating the applications of Building Integrated with Photovoltaics.
MOF[2009]129	Interim measures for the administration of financial assistance funds for Building Integrated with Photovoltaics applications.
MOF,MOST,NEA[2009]397	Notice on the implementation of the Golden Sun Demonstration Project.
MOHURD[2010]521	Announcement on the release of the industry standard "Technical Specifications for the Application of Solar PV Systems for Civil Buildings".
NDRC[2011]1594	Notice on improving the on-grid electricity price policy for solar PV power generation.
NEA[2012]298	Notice on declaring distributed scale solar PV power generation application demonstration zone.
SC[2013]24	Several opinions on promoting the healthy development of solar PV industry.
MOF[2013]390	Notice on the implementation of related issues such as the power subsidy policy for distributed solar PV power generation.
NEA,CDB[2013]312	Opinions on financial services supporting distributed solar PV generation.
NDRC[2013]1638	Notice on exerting price leverage to promote the healthy development of the solar PV industry.
NEA[2013]329	Notice on printing and distributing the interim measures for the management of solar PV power plant projects.
NEA,SAT[2013]66	Notice of the Value-Added Tax policy for PV power generation.

MOF[2013]103	Notice on issues concerning the exemption of government funds for self-consumption of distributed solar PV power.
NEA[2014]33	Notice on the issuance of new construction scale for solar PV power generation in 2014.
NEA[2014]406	Notice on further implementing relevant policies on distributed solar PV power generation.
NEA[2014]445	Notice on further strengthening the construction and operation management of solar PV power plants.
NEA[2015]73	Notice on the implementation plan for the construction of solar PV power generation in 2015.
NEA[2015]356	Notice on increasing the scale of 2015 solar PV power plant construction in some areas.
NDRC[2015]3044	Notice on improving the on-grid electricity price policy of onshore wind power and solar PV power generation.
NDRC,NEA[2016]1150	Notice on the management of full guarantee acquisition of wind power and solar PV power generation.
NEA[2016]166	Notice on the implementation plan for the construction of solar PV power generation in 2016.
MOF,SAT[2016]81	Notice on the continuation of the Value-Added Tax policy for PV power generation.
NEA[2016]354	Notice on printing and distributing the 13 th Five-Year-Plan for solar energy development.
NDRC[2016]2729	Notice on adjusting the on-grid electricity price of solar PV power and onshore wind power generation.
NDRC[2017]2196	Notice on the price policy of solar PV power generation projects in 2018.
NEA[2017]79	Notice on establishing market-environment monitoring and evaluation mechanism to guide the healthy and orderly development of solar PV Industry.
NDRC,MOF,NEA[2018]823	Notice on matters relevant to PV power generation in 2018.
NDRC,NEA[2019]19	Notice on actively promoting the work related to subsidy-free wind power and photovoltaic power generation for grid parity.

Supplementary Table 3. The historical Levelised Cost of Electricity (LCOE) of solar PV power generation in China.

Year	China C-SI module price (CNY/W_p)	China system price (CNY/W_p) grid-connected	LCOE high (CNY/W_p)	LCOE low (CNY/W_p)
2000	47.5	90.0	15.10	5.59
2001	47.5	75.0	12.58	4.66
2002	37.5	75.0	12.20	4.52
2003	37.5	60.0	9.76	3.62
2004	37.5	55.0	9.09	3.38
2005	32.5	55.0	9.09	3.37
2006	32.5	55.0	9.38	3.48
2007	32.5	55.0	10.11	3.75
2008	32.5	55.0	8.95	3.32
2009	14.0	25.0	4.08	1.51
2010	11.0	17.5	2.95	1.09
2011	9.0	14.5	2.55	0.95
2012	4.5	11.0	1.88	0.70
2013	4.0	9.0	1.54	0.57
2014	3.8	8.0	1.34	0.50
2015	3.6	7.5	1.17	0.43
2016	3.2	7.2	1.12	0.42
2017	3.0	7.0	1.09	0.40
2018	2.0	5.0	0.79	0.29

Supplementary Table 4. Investment, operation and maintenance costs of a 1-MW I&C distributed photovoltaic system in China.

	Component	Value	Unit	Total cost (CNY)
Investment cost	PV modules	3.00	CNY/W _p	3,000,000.00
	Supporting structure	0.30	CNY/W _p	300,000.00
	Inverter	0.30	CNY/W _p	300,000.00
	Wirings	0.20	CNY/W _p	200,000.00
	Insurance cost	0.04	CNY/W _p	35,000.00
	Engineering (design, transport and assembly, installation)	0.60	CNY/W _p	600,000.00
	Junction boxes	0.10	CNY/W _p	100,000.00
	Grid connection fee	0.00	CNY/W _p	0.00
	Gross investment cost	-	CNY	4,535,000.00
Inverter replacement cost	Inverter	0.30	CNY/W _p , replacement at the 10 th year	600,000.00
Yearly cost	O&M cost	1.00%	of system investment, CNY/year	30,000.00
	Rooftop rent	4.00	CNY/m ² /year (10,000 m ² in total)	40,000.00
	Loan duration	5.00	years	-
	Interest rate	8.00%	-	-
	Annuity	-	CNY/year	1,185,911.31
	Yearly cost for the first 5 years	-	CNY/year	1,215,911.31
	Yearly cost for the 6 th -20 th years	-	-	70,000.00
	Discount rate	5.00%	-	-
Average price per Watt	-	-	CNY/W _p	8.43

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