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The expansion of China's solar energy: Challenges and policy options

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ABSTRACT

Given that China is committed to peak its carbon dioxide emissions in or before 2030 under the Paris Agreement, promoting renewable energy to substitute coal is one critical solution to facilitate China to meet this commitment. Among various types of renewable energy, solar energy is an attractive choice that will significantly influence the future of energy supply and energy usage. We first provide an overview of the most recent development of solar energy in China, in which the changing pattern from stationary to distributive forms is highlighted. We show that the diversified prices and subsidies across regions may play an important role in the changing pattern. Furthermore, we find major challenges that might impede the future expansion of solar energy. To address these challenges, governments need to propose policies to develop technologies and meditate the benefits of stakeholders, especially grid companies and electricity end-users. Market-based policies are also expected to accelerate the learning-by-doing process through R&D investment, which will help reduce and ultimately eliminate solar subsidies.

1. Introduction

Renewable energy has received growing support owing to active global interests in climate change mitigation [1]. It is estimated that about 72% of the human-emitted greenhouse gases is CO_2,[1] and fossil fuel combustion is the largest contributor to human-made CO_2 emissions [2]. Over the last decade, in particular, since the publication of the Stern Review [3] and the 4th IPCC Assessment Report in 2007, climate change has attracted increasing attention from policy makers, researchers, and the general public.

To address the global concern on greenhouse gas emission and climate change, solar energy is supposed to be one of the optimal options. Solar energy resources are widely abundant and are becoming more competitive with conventional fossil fuels in generating electricity, with the sharp decrease in installed costs of solar photovoltaic (PV) – falling more than 80% since 2010 [4]. Accordingly, the deployment has increased dramatically, reaching 399.6 GW total installed capacity worldwide in 2017 [5]. The lifecycle of the greenhouse gas emissions of solar energy is much smaller than that of fossil energy types [6].

China is the main contributor to the sharp increase in solar capacity, accounting for one-third of global solar power to 2017. The cumulative solar capacities in China in 2010 and 2017 are provided in Fig. 1, and are compared with those in several other counties who are also leading developers of solar power. Started from less than 1 GW in 2010, China's capacity of solar power in 2017 increased to be much larger than other countries. The rapid deployment of solar power in China is the result of abundant solar resources and ambitious policy support, such as feed-in tariffs (FiTs) [7,8]. However, while such progress has been made, China's solar power still has major challenges to overcome during the energy transition process [9,10]. Identifying these opportunities and challenges is of importance to policymakers and firm decision-makers to carry out ex-ante policy assessment and operating management [11].

In the literature, there have been a large number of studies investigating renewable energy development. The mainstream of literature has been intensively focused on the following fields of renewable energy, including the renewable technology patterns [12,13], renewable structure [14,15], cost and benefit analysis [16–18], and economic returns of investment [19–21]. These studies are mainly on bioenergy,

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[1] The remainder consists of 18% methane, 8% NO_x and 2% other gases.

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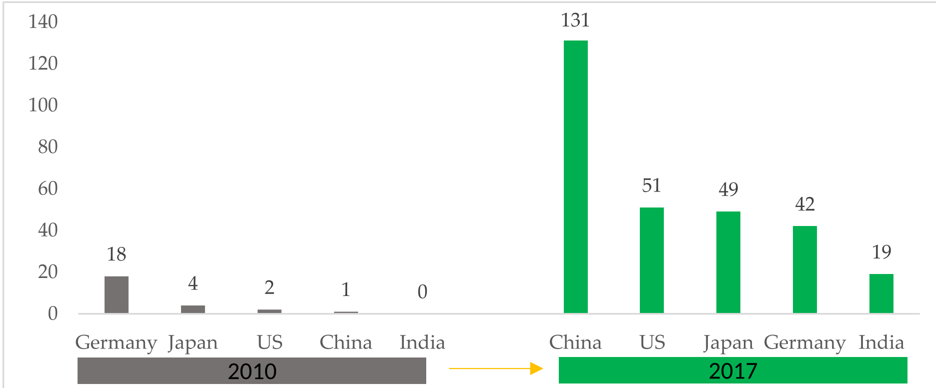


Fig. 1. A comparison of cumulative solar capacity in major solar PV countries. Note: The unit is GW.

hydro-power, wind energy, and other types of renewable energy [22,23], while there remain research gaps to explore the challenges and policy options of solar energy in China, the largest solar power market worldwide [24]. Motivated by the research gaps, this paper seeks to identify various issues, challenges, and policy options that could promote the development of China's solar energy. We also review the experiences and existing policies on solar energy enacted in the past few years to identify the gaps that can be filled to effectively support China's sustainable transition. The remaining parts are organized as follows. In Section 2, we highlight the importance of solar power in China's energy transition and the enormous potential of solar power in the future market. Section 3 describes the characteristics of China's solar power deployment, especially the changing pattern from western to eastern region and from stationary to distributive form. The financial initiatives for solar power are analyzed in Section 4. Section 5 provides the key challenges of China's solar power adoption and the optional policies to overcome these challenges. Section 6 concludes.

2. Why solar? The background of the energy transition in China

Energy consumption in China experienced explosive growth in the past decades, leading to a dramatic increase in CO_2 emissions. Since the market-oriented reform, China's primary energy consumption annually has increased from 571 million tonnes of coal equivalence (Mtce) in 1978–4490 Mtce in 2017, with an average growth rate of 5.4% lasting forty years [25]. Moreover, coal plays a dominant role in China's energy mix, aggravating international concerns on China's ability to effectively curb its CO_2 emissions [26]. According to British Petroleum [5], in 2017, 28% of global CO_2 emissions from anthropogenic activities were generated in China, following by the United States (15%), the European Union (11%), India (7.0%), the Russian Federation (4.6%) and Japan (3.5%).

In particular, coal combustion is the main source of not only CO_2 emissions but also environmental pollution such as SO_2, NO_x, and dust [27]. Thus, in recent years, China strived to reduce its coal consumption for curbing CO_2 emissions and alleviating environmental degradation at the same time. Coal substitution towards the other alternative energy types is the main part of this ambitious strategy. The future energy supply for substituting coal will need a range of options. There is little potential to substitute coal using oil because about 70% of oil consumption in China is dependent on imports in 2018, while its domestic production has peaked at around 200 million tonnes for a long period. Accordingly, China has initiated ambitious energy transition plans, including "coal-to-gas" and "coal-to-electricity".

However, similar to oil, it is not an easy task to meet the increasing natural gas demand induced by coal substitution due to China's shortage of natural gas resources. According to BP (2018), only 2.8% of proved natural gas reserves are in China. Substituting coal by natural gas, which is mainly from imported resources, would increase China's energy external dependency. This rate of external dependency exceeded 45% in 2018. Lacking reliable natural gas supplies will make it increasingly challenging to meet growing gas demands throughout the year, especially in the long term. A recent example is the severe gas shortages in the Beijing-Tianjin-Hebei region in the winter of2017[2] [28].

Accordingly, "coal-to-electricity" becomes a promising choice. In terms of curbing global warming, the electricity used to substitute coal must be generated from renewable energy (and nuclear) rather than from coal-fired power. Although the latter one is also beneficial for mitigating environmental pollutants, it is still hard to capture CO_2 emissions [29].

China has pledged that the share of non-fossil energy consumption will account for at least 20% in primary energy consumption by 2030. For many decades, the majority of non-fossil energy consumed in China has been provided by hydropower, which accounts for about 20% of electricity or 9% of primary energy. Yet, it is hard for hydro-power to substantially increase in the future because hydro-power in China is nearing the upper limit [30]. The installed capacity of hydropower was 341 GW in 2017, while the economic exploitable capacity is about 400 GW. Another widely used non-fossil energy in the globe is nuclear energy. In China, nuclear power only meets 2% of primary energy demand until 2017 with 248 billion kWh, while the production is growing fast with a growth of 16.5% over 2016. China was planning to equip 58 GW of installed capacity by 2020 with an additional 30 GW under construction. It is a hard choice for China, although nuclear power may be relatively stable and less expensive. Safety is a major concern. For cooling by seawater, most nuclear power plants in China are located in the coastal regions. It means many of its nuclear plants have to be placed near large cities, leading to a major concern that tens of millions of people could be exposed to radiation in the event of an accident. For example, the surroundings of Lingao nuclear plants in Guangdong province have around 28 million people within a 75-km radius, which covers Hong Kong as well [31].

As a result, the capacities of wind and solar power need to be substantially increased in the future decades, although they currently provide relatively small energy shares. The technical potentials of renewable energy, especially wind and solar, are theoretically able to substitute fossil fuels [20]. Yet, power from wind and solar is generated disproportionately over time [32]. Compared with wind power, which generates more electricity at night hours, the favorable timing of solar power production during high demand makes it match energy demand better [33]. Especially in distributive form, solar power can be generated at the location of the end-user and therefore can reduce the costs of transmission and distribution investments [34]. It is great merit to

[2] Another reason comes from the limitation of natural gas storage.

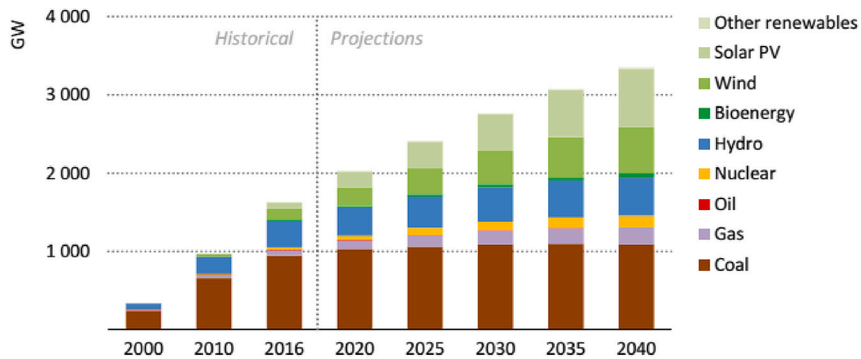


Fig. 2. The projected trends of installed capacity by energy sources, **Source**: IEA (2017).

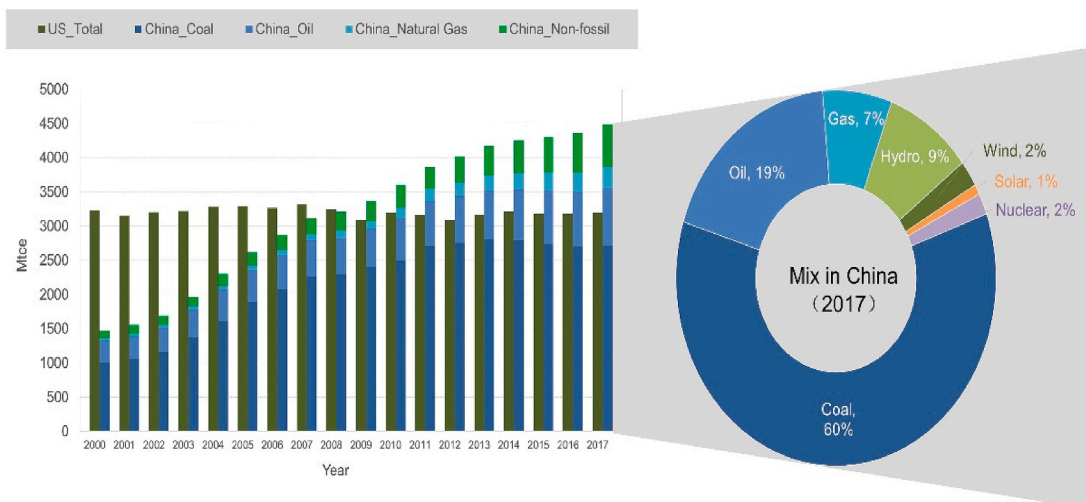


Fig. 3. China's structure change in energy consumption.

alleviate the geographic imbalance in China's energy endowment. According to the prediction of IEA [35], Fig. 2 shows that by 2040, the installed capacity of solar photovoltaics is expected to exceed wind, accounting for 22% of China's total electricity capacities. It indicates the great potential of China's solar power market.

3. Changing pattern of solar power: from stationary to distributive forms

Primarily for the high demand for energy, a small change in energy mix indicates a large adjustment for individual energy types, especially for those types with small initial shares such as solar power. As shown in Fig. 3, with the share of solar in primary energy mix increasing from almost 0% several years ago to 1% in 2017, China became the largest solar installer worldwide accounting for 33% of the world's cumulative capacity of solar power in the form of photovoltaics (PV). In 2017, it provided 118 billion kWh electricity from 130 GW capacity, which is equivalent to nearly the entire national electricity generation in the Netherlands or Venezuela [5].

Among China's solar capacity at the end of 2017, stationary solar capacity was 100 GW, while distributive solar capacity was only 30 GW [36]. It is controversial to the original policy target of the Chinese central government. We find that despite strong political interest in promoting distributed solar power, it was substantially below the government targets. Contrarily, stationary solar power experienced such explosive growth that the central government has to increase the policy targets of solar capacity several times for matching the boom in stationary solar. According to *the* 13th *Five-year Plan for Electricity* [37], the central government planned to cumulatively install solar capacity of 110 GW by 2020, among which distributed solar power would reach 60 GW, and the remaining 50 GW is stationary solar power. In reality, China's stationary solar capacity by 2017 (100 GW) was double compared to the planned targets by 2020, while distributive solar capacity (30 GW) was much less than the expectation. Accordingly, the Chinese central government has made the plan to adjust the targets for solar power by 2020 [38] and restrict the rapid increase in stationary solar power [39].

Building stationary solar plants in large-scales leads to challenges for the power grid in transmitting and distributing the solar generation, especially considering the regional heterogeneities across China in solar endowment and utilization [7]. In Fig. 4, we summarize the solar capacities by region. Substantial parts of solar capacities are concentrated in the northwestern region, while the demand centers in eastern coastal areas are far away from these solar capacities. It is still hard to store electricity economically on a large scale [40], and therefore, the solar generation that cannot be consumed instantaneously has to be curtailed [41]. As a result, China's solar power curtailment in the northwestern region reached 6.7 billion kWh in 2017, with the curtailment rate of 14.1% in northwest China [42].

However, the geographic pattern of solar power was changing. Fig. 4 also demonstrates that the increases in stationary solar power in the northwestern region have declined since 2016. As a result, the solar power curtailment rate in the northwestern region declined from 19.8% in 2016 to 14.1% in 2017. Correspondingly, stationary solar power capacities in central, southern, and eastern regions accelerated after 2015. In particular, distributive solar power in these regions also increased

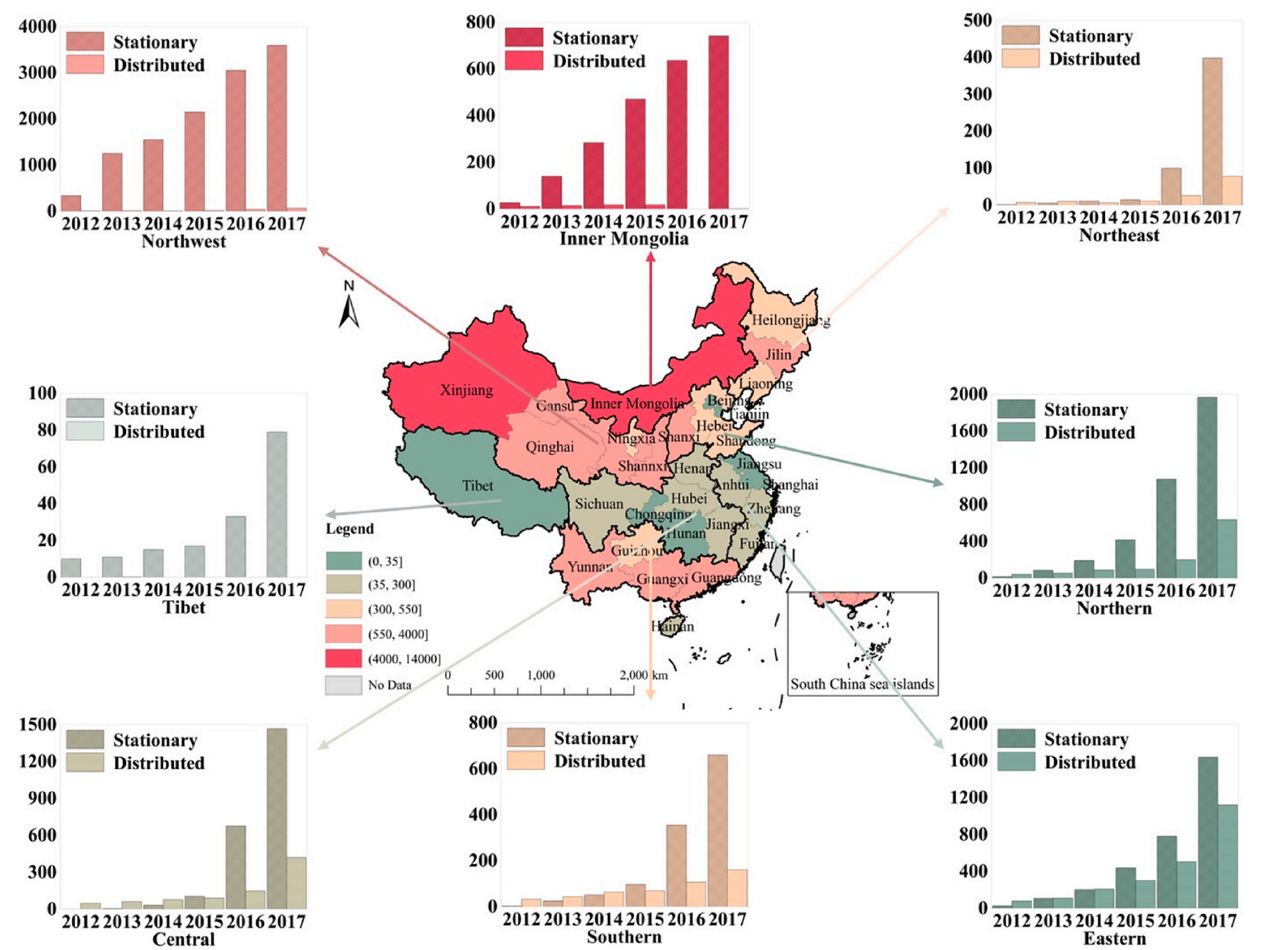


Fig. 4. Historic solar capacities in China's different regions. Notes: There are eight regions of power grids, including six greater regions and two independent regions (Tibet and Inner-Mongolia). These regions are classified by China's regional power grids. Inner-Mongolia is particularly separated from the northern gird region because of its large installed capacity and extraordinary solar endowment.

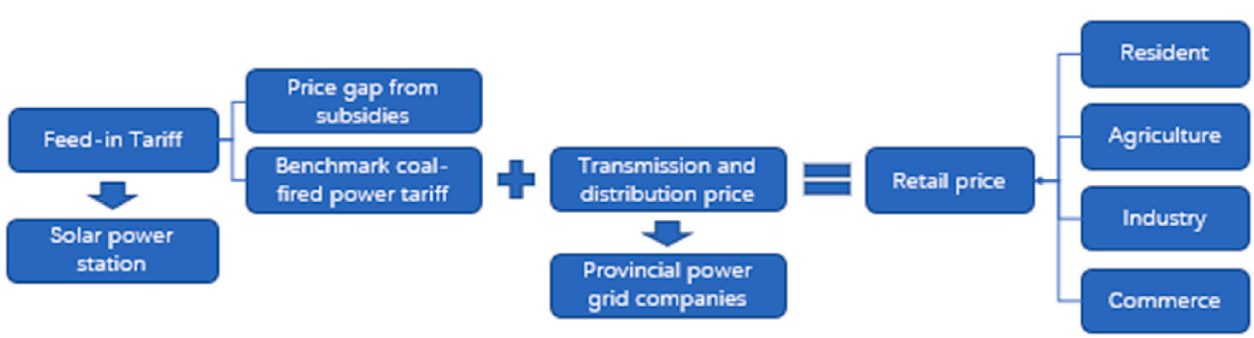


Fig. 5. Pricing mechanism for electricity from stationary solar power.

substantially during 2015–2017. The changing pattern matters a lot for the balanced development of solar power in China because it enables the supply of solar power to match the electricity demand in space. In the next section, we provide an explanation for the changing pattern of solar power in China.

4. Reasons for the changing pattern: diversified prices and subsidies

Besides the resourceful endowment, the rapid increase in solar capacity is also the result of generous policy supports [1,43,44]. Even though the costs of solar energy generation have dramatically decreased worldwide in recent years [11], the cost of solar energy is still less competitive compared with conventional energy sources [45]. For public policymakers, solar energy can be valuable to diversify the energy mix and reduce pollutants and greenhouse gas emissions; but for investors, what matters more in the decision-making process is whether, where, and how it is worth investing in solar generation. In particular, given policies, is there a profitable return on their investment? Thus, there is a gap between social benefit and private benefit because of

Table 1
LCOE of stationary solar power and the corresponding FiTs across regions.

Year	LCOE			FiTs		
	I	II	III	I	II	III
2013	0.70	0.81	0.95	1.00	1.00	1.00
2014	0.59	0.68	0.80	0.90	0.95	1.00
2015	0.55	0.64	0.75	0.90	0.95	1.00
2016	0.53	0.62	0.73	0.90	0.95	1.00
2017	0.52	0.60	0.71	0.65	0.75	0.85
2018				0.50	0.60	0.70

Note: The unit is Yuan/kWh.

positive externality [46]. As a result, policymakers need to design effective supports to encourage solar energy deployment.

Accordingly, China initiates several financial support policies for solar power, which are mainly implemented by subsidizing initial investment and generation subsidies through pricing policies [47]. Policies on subsidizing initial investment have not been consistently adopted in China as the *Golden Sun Demonstration Project* being abandoned since 2013 because of cheating. Thus, in this section, we pay particular attention to China's pricing initiatives for solar power, which may provide an explanation for the rapid development and changing pattern of solar power.

FiTs may be the most important pricing policy in China to encourage the deployment of solar technologies [48]. FiTs program guarantees that the owners of solar generation facilities, such as solar plants, can receive a set price from all the electricity they provide to the grid [49]. Thus, the advantage is that FiTs anchor the revenue of power generation throughout the entire life cycle [50]. It has been adopted for stationary solar plants in China since 2011.

In Fig. 5, we illustrate the pricing policy for electricity generated from stationary solar power. The supply chain of solar electricity includes two key stakeholders: solar generators and the power grid. Under FiTs, solar generators receive a fixed price set by the National Development and Reform Commission (NDRC), a key department in the charging of energy and development of the Chinese central government. The FiTs are usually higher than the tariff for coal-fired electricity, but the latter is the actual price of the grid company that paid for solar power. The gap between FiTs for solar power and coal-fired power tariff is undertaken by renewable energy surcharge (RES) embodied in retail electricity prices, and thus it is ultimately undertaken by electricity consumers. Adopting RES can guarantee that power grids do not have to pay a higher FiTs to solar generators than coal-fired power [50], and thus encourage power grids to provide penetration for solar electricity. With the upward trends of adopting renewable energy over several years, the rate of RES has been increased from 0.001 Yuan/kWh in 2006 to 0.019 Yuan/kWh since 2016. Moreover, the retail prices of electricity are also highly regulated by the NDRC. The difference between retail price and the coal-fired power tariff is the revenue of grid companies for providing transmission and distribution services for solar power.

With the learning-by-doing process, the installed cost of solar power declined dramatically due to the plummeting costs of modules and batteries [47,51]. Accordingly, the FiTs are decreasing with the dramatic reduction in installed cost as it accounts for the most part of the total cost [50]. Partly because of the mismatch between solar supply and energy demand across space, FiTs evolved from national uniformed price to diversified prices across regions to encourage the solar capacity in central and eastern regions [8].

We calculate the levelized cost of electricity (LCOE) of solar power in different regions across China, and compare it with FiTs set by the Chinese government. The results are shown in Table 1. The technical details and parameter values of the calculation can be seen in the *Appendix*. Based on solar resource abundance, the whole country is divided into three regions,[3] which are denoted as I, II, and III, respectively, in this paper. The annual equivalent utilization hours of these three regions are: I > II > III, and the FiTs in three regions are different. The geographic distribution of these three regions can be seen in Ye et al. (2017) [8]. Regions with better solar irradiation and longer generating hours are predicted to have lower LCOE as they can generate more electricity given the same capacity. Even though the government sets diversified and dynamically reduced FiTs for different regions, the adjustment of FiTs usually lags behind the technology-induced cost reduction. As a result, the sluggish adjustment of FiTs leads to the burgeoning growth of stationary solar power in recent years, especially in regions with larger LCOE-FiTs gaps.

Fig. 6 shows the gaps between LCOE and FiTs across regions. Continuously, the reduction in LCOE in the region I proceeds the decline in FiTs during 2013 and 2016, suggesting that the gap increases from 0.30 Yuan/kWh to 0.37 Yuan/kWh. Meanwhile, although the gaps in regions II and III were positive, they were much smaller than those in the region I. This may explain why increasingly stationary solar power was concentrated in northwestern China (mainly belongs to the region I) before 2016.

In 2017, the Chinese government substantially lowered the FiTs overall the country, especially in the region I, from 0.9 Yuan/kWh to 0.65 Yuan/kWh. FiTs in the region III (II) were also decreased from 1.0 Yuan/kWh (0.95) to 0.85 Yuan/kWh (0.75), but the adjustment was just moderate comparing with that in region I. Accordingly, the magnitudes of gaps reversed across regions, inducing investors to build stationary solar power plants in the region III. This explains why the capacity of stationary solar power in region III accelerated from then on. In May 2018, the Chinese government further adjusted the FiTs to be 0.5, 0.6, and 0.7 Yuan/kWh in regions I, II, and III, respectively. We find that the recent FiTs were quite close to the LCOE in 2017. Thus, the newly installed stationary capacity can only make profits through technological progress. Inferring from FiTs, the stationary solar power in the region I after 2018 are becoming competitive with conventional generation sources, especially coal-fired power.

As for distributed solar power, there are two utilization models: (A) self-consumption and selling surplus to the grid; and (B) selling all solar generations to the grid. To reduce the costs of transmission and distribution (such as transmission loss), model A is more encouraged by the Chinese government. Fig. 7 displays these two pricing models for distributed solar power. The benefits of generators by adopting model A include: (i) the decreased expenditure for purchasing electricity from the grid at a retail price; (ii) subsidies from the government; and (iii) gains from selling surplus to the grid at coal-fired power tariff. For generators who adopt model B, the benefits include: (i) subsidies from the government, and (ii) gains from selling all generations to grid at coal-fired power tariff.

Particularly, solar generators adopting both models can receive national and local subsidies based on the amount of generation. The national subsidy is uniform across the entire country, which was 0.42 Yuan/kWh in 2013 and decreased to 0.37 Yuan/kWh in 2017 and then 0.32 Yuan/kWh in the middle of 2018. Yet, subsidies being offered by local governments vary in different cities, e.g., from zero to 0.55 Yuan/kWh in Shanghai. As for power grid companies, note that there is no difference in purchasing costs for power grid companies to integrate distributed solar electricity or coal-fired power, which is similar to the case on stationary solar plants.

Comparing with continuously decreasing FiTs for stationary solar power, generation-based subsidies for distributed solar from the central government were quite stable. Besides, most of the local subsidies were in central and eastern China. Therefore, distributed solar with stable national and extra local subsidies became more profitable comparing

[3] Tibet is an exception which is not included in FiTs regions.

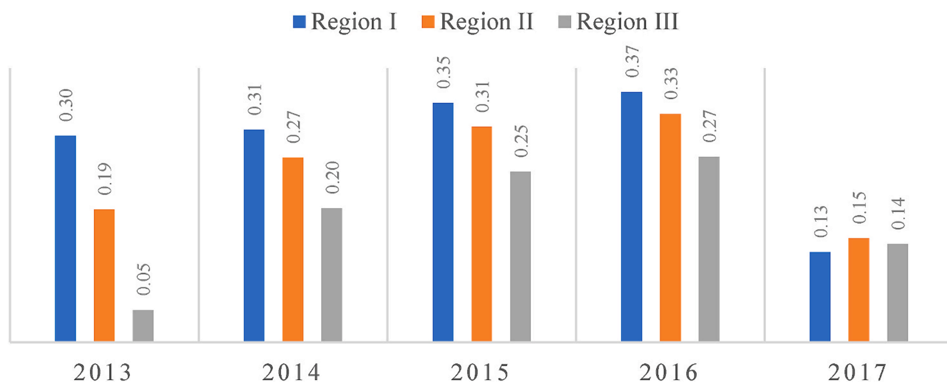


Fig. 6. The gaps between FiTs and LCOE across regions.

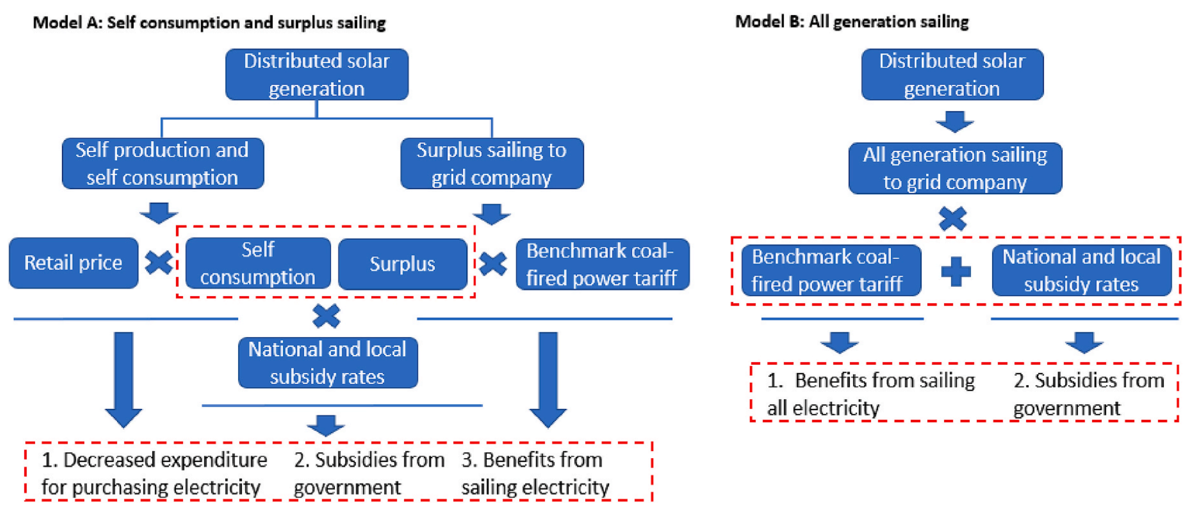


Fig. 7. Pricing mechanism for electricity from distributed solar power.

with stationary solar power, especially in central and eastern regions whose electricity retail price and coal-fired power tariff were usually higher. Accordingly, with continuously and substantially decreasing in FiTs for stationary solar power, investments switched to distributed solar in central and eastern regions. As shown in Fig. 4 above, distributed solar capacity in central and eastern regions increased substantially in 2017.

5. Challenges and policy options

With a range of supporting policies, especially pricing initiatives for generators, the installed capacity of solar power has experienced a steep upward trend in China over the last several years. However, as China aims to install a further multi-gigawatts of solar power capacity in the next decade, it is vital to incentivize and manage the balanced and sustainable expansion of solar power. Except for generators, the policymaking process needs to consider the incentives of other stakeholders, especially those of grid companies and energy end-users.

This section highlights the key challenges that may constrain the potential of China's solar power adoption. As such, policy options to overcome these challenges have been proposed to stimulate the balanced and sustainable expansion of solar power.

5.1. Grid penetration of solar power

One challenge is the negative impact of high shares of solar power on grid companies.[4] The pricing policies discussed above in Section 4 indicate that, for grid companies, the purchasing cost of solar power is indifferent from coal-fired electricity because FiTs exceeding coal-fired power tariff would be made up through RES. However, the costs for grid connection and dispatch are much higher than those of coal-fired electricity due to the hardly predicted variability of solar power [50]. In many countries, the costs of generation, transmission, and distribution are all recovered through retail tariffs levied on the volumetric basis [43,52]. In China, much more attention has been paid to dealing with the additional costs of solar energy through RES, while the increased costs of transmission and distribution for delivering solar generation have been largely ignored [50]. In such cases, grid companies who integrate more solar power would also have to undertake more costs of connection and dispatch. As a result, grid companies are disincentivized to penetrate solar power, which may be even more acute with higher shares of solar generation.

The command-and-control regulation policy was first implemented to address the grid penetration issue: it is mandatory to make solar energy (and other renewable energy types) connected to the grid, which was enacted by the 2005 *Renewable Energy Law* (amended in 2009). The problem is that it is difficult for the government to fully regulate the

[4] There are two main grid companies providing electricity transmission and distribution services for the entire country: State Grid and Southern Grid. Both of them are state-owned enterprises.

mandates because of asymmetric information, especially information on load balancing. As such, with the soaring development of solar power (especially in a stationary form) in the regions far away from demand centers, curtailment was becoming a tough issue along with the expansion of solar power.

To alleviate the curtailment of solar power, since 2016, the Chinese central government enforced minimal generating hours of solar power for those provinces with large solar capacities [53]. This is another kind of command-and-control regulation. But after implementing this policy, it still could not fully solve the problem, especially for those provinces that have large gaps, e.g., Xinjiang, Gansu, and Ningxia, where many solar panels are located in.

Market-based initiatives are alternatives to the command-and-control regulations in changing the incentives of grid companies. Different from mandates, market-based policy instruments aim to modify the behaviors of economic entities by changing the financial incentives they face [54]. Market-based policies try to incorporate the cost associated with but not reflected in market prices into grid companies' decision-making process. A wide range of market-based policies can be considered, such as a two-part tariff with a fixed charge for grid services according to the scale of renewables [55], the imposition or elimination of taxes, fees, or subsidies associated with renewable energy for grid companies [54]. However, by far, few market-based policies have been implemented in China to incentivize gird companies to provide fully solar integration.

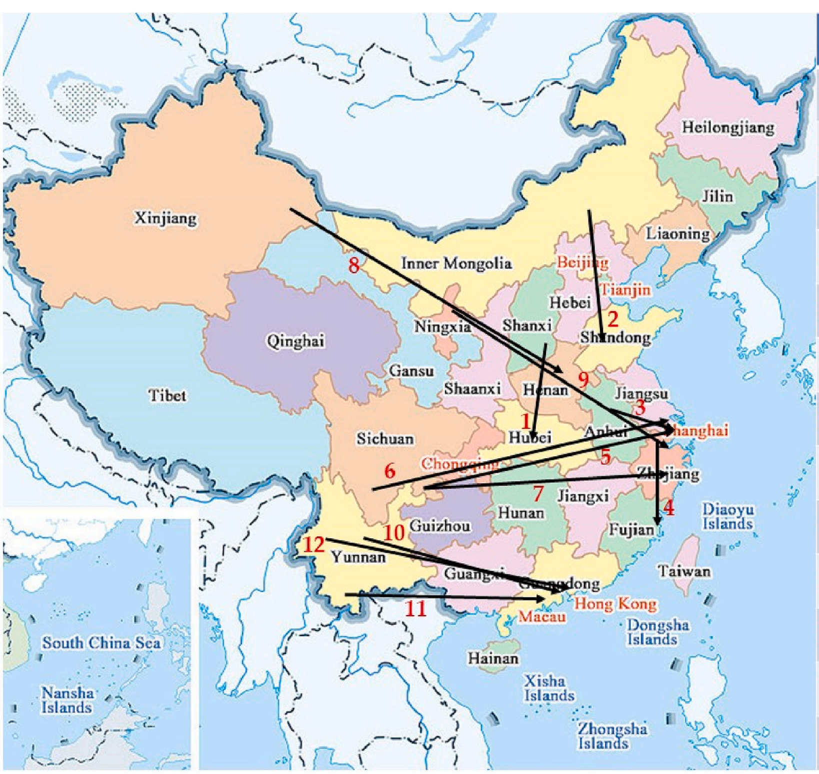
5.2. Matching demand and supply in space: reaching demand and/or relocating supply

The large positive gaps between FiTs for stationary power plants and LCOE (as discussed in Section 4) also incentivize solar power concentrating in regions with the best solar resources that are far away from the electricity demand centers. As a result, electricity demand and solar energy get separated in space.

Matching electricity supply and demand by relocating renewable resources highlights the importance of ultra-high-voltage inter-regional electricity transmission (UHV-IRET). Fig. 8 displays the UHV-IRET lines operating in 2017. In general, these lines are transmitting electricity thousands of miles from the windy and sunny north and northwest, and hydropower-rich south of the country to the load centers in the south-east and along the east coasts. The amount of transmission in 2017 was 301 billion kWh in total, among which renewables contributed to 190 billion kWh. Compared with the total electricity demand, the scale of transmission is still limited. China currently has only transmitted 4.6% of electricity and 10.3% of renewable energy through UHV-IRET.

One concern is that without UHV-IRET to relocate solar (and other renewable) power to demand centers, it is hard to keep electricity balance in northwestern China given their limited self-demand and lacking enough back-up capacity. However, the further development of UHV-IRET has been under intensive debates, especially in terms of security, economy, and monopoly issues [27]. In particular, powering UHV-IRET lines only with renewable energy can be technically challenging and economically unfavorable (Peng et al., 2017). Solar generation is intermittent and variable and can only work during daylight hours, indicating that transmission lines cannot operate at full capacity all the time. Accordingly, the low utilization rate means less electricity is transmitted and sold to end-users, producing less revenue for grid investors seeking to recoup their investment costs [41]. A more promising strategy may be transmitting a mix of solar, wind, and coal-fired power, which allows for a high utilization rate and provides the flexibility to increase the share of renewable transmission in the future [41]. This kind of "hybrid-by-wire" strategy is feasible in China because in some regions, such as Xinjiang and Inner-Mongolia, various energy sources like solar, wind, and coal-fired power are all affluent and thus can be transmitted together to increase the utilization rate of UHV-IRET lines. One specific example is the UHV-IRET line from Hami (in Xinjiang) to Zhengzhou (in Henan).

For a balanced and sustainable expansion of solar power, it is critical to relocate the supply and develop distributed solar power [33]. Transmitting electricity from western China to eastern China involves



Order	Total	Renewable
1	6.55	3.7
2	6.48	0
3	59.45	0
4	4.02	0
5	32.4	32.03
6	38.71	38.46
7	38.96	38.96
8	35.97	15.26
9	20.13	3.44
10	28.22	28.22
11	29.75	29.75
12	0.14	0.14
Sum	**300.75**	**189.96**

Fig. 8. UHV-IRET across China in 2017 (Unit: billion kWh).

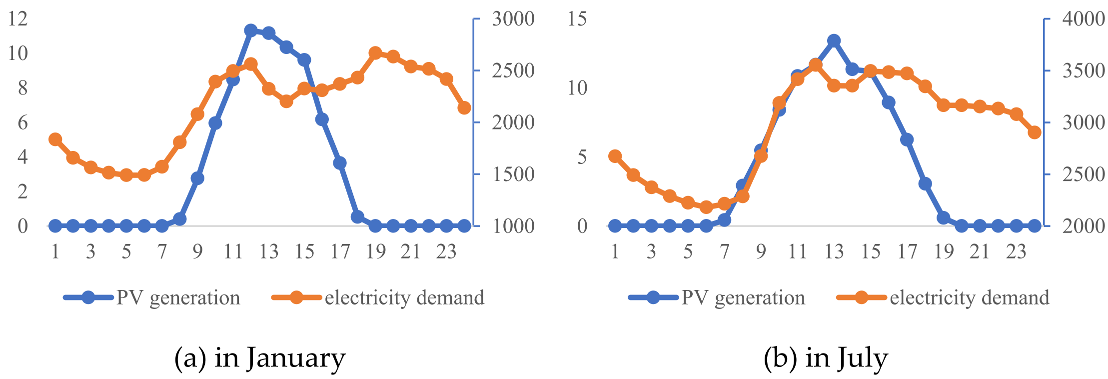


Fig. 9. Hourly average electricity demand and solar PV production in January and July. Note: The data is daily averaged within the month.

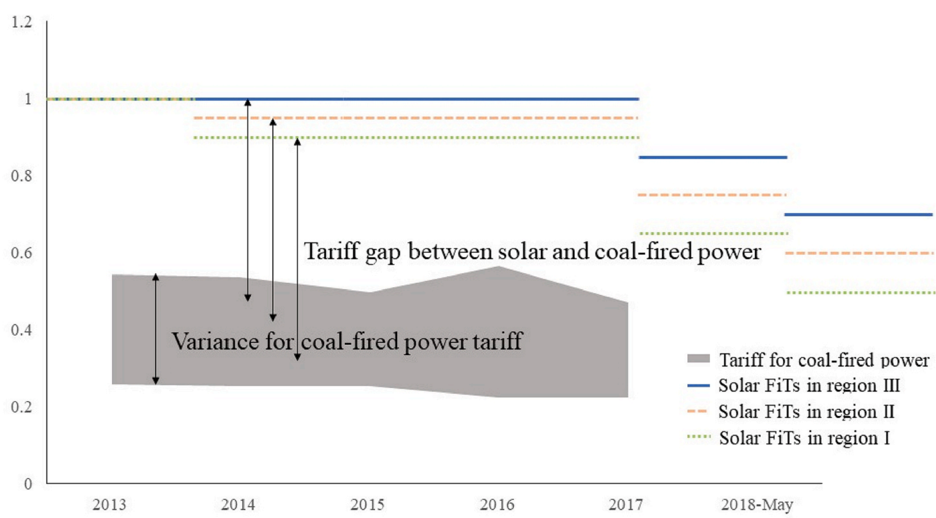


Fig. 10. Comparison of tariffs for solar and coal-fired power (Unit: Yuan/kWh).

hundreds of billions of investments (in Chinese Yuan). If we could relocate the supply, it reduces the electricity losses. On average, 6.5% of generated electricity is lost during transmission and distribution process, and the number is higher during daylight hours when demand peaks. Fig. 9 displays the simulation results of distributed solar power output in Xiamen, a coastal city in China. We particularly compare the output curve with the corresponding electricity demand curve in this city. As shown, in both January and July, solar power output and electricity demand are highly positively correlated over time. Thus, distributed solar power can be deployed in demand centers to reduce electricity transmission and distribution during peak time. The synergy between the locational and timing advantages of distributed PV allows for deploying renewable energy at a lower system cost.

5.3. *Energy storage: setting priority for electricity quality rather than just quantity*

Because of the diurnal variation in solar output, energy storage is urgently needed to smooth the variability and shift the solar generations from demand valley to demand peak. Lacking cost-effective energy storage, solar power can hardly be primary energy sources for the whole society, even if the challenges from uneven interests of stakeholders and mismatch across space were solved [56]. Currently, the subsidies for solar power are based on the quantity of solar generation, rather than quality. With a larger share of solar power, its shocks to the electricity system would be even more severe [57]. Thus, for further development, subsidies should be designed in such a way to prioritize its electricity quality rather than only quantity [50]. As such, businesses and investors would be incentivized to improve energy storage technologies. In 2017, the Chinese government launched a range of pilot projects to encourage advances in energy storage technology, such as pumped hydro storage, compressed air energy storage, superconducting magnetic energy storage and bulk storage with batteries using substances like lead-acid lithium-ion [58].

5.4. *End-users' participation: Renewable Portfolio Standards and tradable green certificates*

To promote the demand for renewable energy, Renewable Portfolio Standards (RPS) have been implemented beginning from 2019 [59]. Through RPS, the minimal shares of renewable energy in the portfolio of electricity consumption in each province become mandates and will be examined by the central government. Provinces that cannot achieve the mandates or have surplus can trade the allowance with other provinces.[5] The grid companies at the provincial level are the executives to achieve the portfolio targets.

Electricity is ultimately consumed by end-users, and therefore, it might be necessary to establish green certificates and trading markets for consumers as interacting policies for RPS. For power generators and

[5] The RPS is calculated by: (self-consumed renewable energy generation in province i + imported renewable energy generation from other provinces)/(overall electricity consumption in province i).

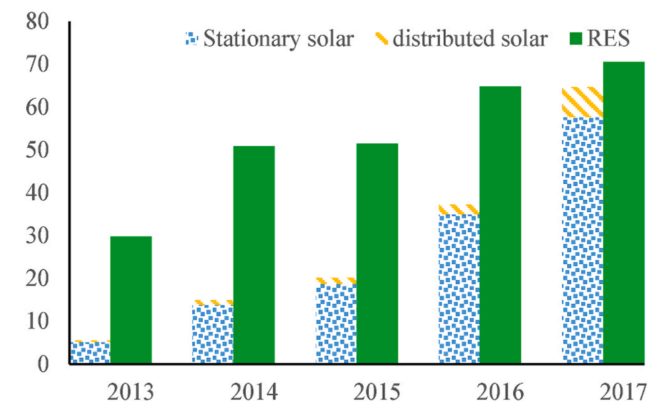


Fig. 11. The actual needs for solar subsidies and the total scale of RES. Note: The data on the actual RES scale are collected from China's Ministry of Finance. The unit is a billion Chinese Yuan.

grids, electricity from different sources and in different periods is heterogeneous with different costs and varying needs for load balancing [20]. Yet, for end-users, electricity is just homogeneous in physics with constant frequency and voltage. For example, there is no difference to power air conditioners using the electricity generated from coal-fired power or solar energy. Thus, in the short run, a tradable obligation among end-users (such as green certificates) may be needed to promote the consumers participating in solar energy adoption. In the medium and long run, transparency can be a relevant attribute in RPS and tradable obligation. For example, providing end-users with clear information about the kind of electricity they consume and its corresponding environmental impacts may help to provide enough knowledge to motivate their voluntary usage for renewable energy.

5.5. Financial challenge of subsidizing through renewable energy surcharge (RES)

Although solar power has experienced a dramatic cost reduction, there are tariff gaps between solar and coal-fired power. Fig. 10 compares the tariffs for stationary solar and coal-fired power. In China, the tariff gaps for stationary solar, and the national subsidy for distributed solar are both paid through RES, which is levied on end-users in retail electricity prices. The rate of RES embodied in the retail electricity price was firstly 0.001 Yuan/kWh since 2006. With the upward trend in renewable generations, the RES encounters challenges from a deficit. To fill the deficit, the rate of RES was increased to 0.008 yuan/kWh after 2012, 0.015 yuan/kWh after 2013, and then 0.019 yuan/kWh after 2016.

Nevertheless, the deficit between actual needs and RES is widening as more and more solar and other renewables being deployed. It is not financially sustainable to keep the rate of RES increasing in retail electricity prices. We calculated the solar subsidies, including both stationary and distributed solar power, and compared them with the total scale of RES, as shown in Fig. 11. Note that the RES covers the subsidies for all renewable types, such as wind power, biomass, etc. Although the FiTs for solar declined in recent years, the subsidies needed for solar power still increased substantially with soaring solar generations. In 2017, the subsidies needed for solar energy had accounted for 92% of the total RES. With the ever-increasing in solar and other renewable capacities, the sustainability of renewable energy subsidies through RES might be challenged further. Therefore, one caution is to avoid overly generous FiTs for stationary solar and generation-based subsidies for distributive solar, which are too costly to the government and ultimately to consumers through RES [60].

Renewable energy policies should aim at maximizing social welfare [45]. Except for the possible positive environmental externality, another reason supporting solar subsidy is the market failure due to learning-by-doing [51], which means a lot to the future economies of solar power [43]. By providing generation-based remuneration, subsidy policies currently can stimulate newly installed capacities and thus help reduce the future LCOE of solar power through learning-by-doing. Therefore, a promising future is that with the rapid accumulation in solar capacity, the learning-by-doing process would make solar power gradually become more cost-competitive than coal-fired power. With the cost advantage, the subsidy on solar energy for generators can be decreased and eventually removed. Accordingly, it will be welfare trade-offs over time. The speed of cost decline depends on the magnitude of the learning rate, which can be promoted by substantial R&D investment in technology [61].

6. Policy implications

To address global warming and environmental degradation simultaneously, China has implemented an ambitious energy transition strategy since the last decade. With the transition, China became the largest solar power installer worldwide, accounting for about 30% of cumulative installed solar capacities in the globe by the end of 2018. It is expected that China will keep rapid growth in solar power, given that solar power currently only plays a minor role in China's energy mix, and solar capacity per capita is still moderate.

For the further expansion of China's solar energy, political and industrial efforts would be needed to address the mismatch between solar generation and electricity demand across regions, to overcome the variability of sunshine over time, and to reduce the financial burden from renewable energy subsidies. In recent years, some efforts have been made to solve these challenges, but barriers to the practice still exist. To remove these barriers, we think policy stability is of particular importance because it can facilitate the installation of solar capacity and avoid possible market disruption.

First, although the curtailment rate of solar power has declined a lot, it is still severe in some regions that billions of electricity are being wasted. To resolve this problem, one practical and effective solution is to develop more energy storage system [62]. For example, the construction of energy storage stations in northwest regions, that have resourceful solar endowment but could not match its energy demand and supply, could be a critical option. The energy storage system could not only reduce the waste of solar power, but also enable the stable transmission of power over a long distance through the power grid. Thus, investment in developing more advanced energy storage technologies and installing energy storage systems should be made.

Second, there are political barriers among provincial power grids to dispatch solar power on a larger scale to overcome variability over time. Because of the organization of China's power grids, their dispatch and management are largely organized at the provincial level. It implies that most of the provincial grids are locally balanced with little electricity interconnection. Further, the local protectionism indicates that more solar generation in one province would crowd out its electricity imports from other provinces. This kind of beggar-thy-neighbor policy might lead to larger segmentation of the electricity market in China. Thus, promoting collaboration among different cities across provinces and putting renewable energy into a larger power grid might be a choice.

Third, the financial burden on solar power needs to be abated. One solution is to increase the rate of RES, like the case in Germany. For example, if the rate of RES was increased from 1.9 cents/kWh to 3.0 cents/kWh, the RES scale could have been raised by 77 billion Chinese Yuan in 2018. However, this solution might be unfavorable in policy-making because of public pressure. An alternative way is to issue a green bond, the interest of which is covered by the central government.

In addition, China has focused more on product popularization and application stages, while adequate investment in R&D of solar power has been largely neglected [10,47]. It is expected that the accelerated learning-by-doing process through R&D investment along with market-based policies (such as nationwide carbon cap-and-trade market) will help achieve the goal of further reducing and ultimately eliminating the solar subsidies in the future.

When extending to international perspectives, solar energy is also promising in global energy transition and expected to be the primary source of future energy supply. The policy implications proposed in this paper in the context of the largest solar energy market may be partly applicable for other countries, especially for the European Union in which solar resources and electricity demand are not evenly distributed across countries, and the cross-country electricity trade is also limited by borders.

Credit author statement

Jianglong Li: Conceptualization, Data curation, Methodology, Writing - original draft, Reviewing and Editing. Jiashun Huang: Conceptualization, Writing - original draft, Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

According to Zhao et al. (2017) [63], LCOE is defined as the value that equals the cost of power generation and income of generating electricity. Suppose that there is a salvage value (S) of the solar equipment after the predicted lifetime N, the LCOE can be calculated by:

$$-S_N(1+\pi)^N(1+r)^{-N}+\sum_{n=0}^{N}C_n(1+r)^{-n}=\sum_{n=0}^{N}(E_n\times LCOE)(1+r)^{-n} \tag{A1}$$

where C_n and E_n are the total cost and annual electricity production in year n, respectively; r and π are the discount rate and inflation rate, respectively.

Due to system efficiency attenuation u, electricity production per unit capacity (kW) in year n is $E_n = T_n(1-u)^n$, given the generating hour T_n. The costs include the several parts: (i) initial investment at year 0 for the equipment, land, installation, civil works, etc.; (ii) operating and maintenance (O&M) cost each year; (iii) inverter replacement cost for a certain period, which is five years according to Refs. [64].

Table A1 lists the parameter values and sources used in calculating LCOE.

Table A1
Parameters for calculating LCOE

Parameter	Notation	Value	Source
Initial investment (Yuan/W)	C	12.21 (in 2013) 10.24 (in 2014) 9.54 (in 2015) 9.24 (in 2016) 8.95 (in 2017)	Data manual of renewable energy (2015) [30]; LBNL (2017) [65]
Generating hours (hours/year)	T	1500 (Region I) 1300 (Region II) 1100 (Region III)	Energy Research Institute of NDRC (2019) [66]
Efficiency attenuation	u	0.9%	Lin and Li (2015) [50]
Discount rate	r	7%	van Benthem et al. (2008) [51]
Inflation rate	π	2%	NBS (2018) [25]
Predicted lifetime (year)	N	25	Lin and Li (2015) [50]
Inverter replacement cost (Yuan/W)	C_{inv}	0.15	LBNL (2017) [65]
Lifetime of inverter (year)	N_{inv}	5	Harder and Gibson (2011) [64]
Salvage value	S	10% of initial investment	Harder and Gibson (2011) [64]
O&M (Yuan/W/year)	OM	0.0064	Zhang (2015) [67]

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