A game-theory analysis of the subsidy withdrawal policy for China’s photovoltaic power generation industry

Jianliang Wang1,2 | Xu Geng1 | Hui Hu3,4 | Wanfang Xiong5 | Kelly Burns6,7

1 School of Economics and Management, China University of Petroleum, Beijing, China
2 Research Center for China’s Oil and Gas Industry Development, China University of Petroleum, Beijing, China
3 Economic Development Research Centre, Wuhan University, Hubei, China
4 School of Economics & Management, Wuhan University, Hubei, China
5 School of Economics, Hubei University of Science and Technology, Hubei, China
6 Low Carbon Economics School, Hubei University of Economics, Hubei, China
7 School of Economics, Finance and Property, Curtin University, Perth, Australia

Correspondence
Hui Hu, Economic Development Research Centre, Wuhan University, Hubei 430072, China.
Email: hui.hu@whu.edu.cn

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Abstract
Over the past decade, the feed-in-tariff (FIT) subsidy policy of China has driven rapid growth in the photovoltaic power generation (PPG) industry. China now boasts the largest installed capacity of PPG around the world. However, the policy-driven expansion of the PPG industry has not brought about a simultaneous improvement in quality. PPG costs remain high and it is difficult to sustain PPG competitiveness. Therefore, it is imperative to gradually withdraw from the implementation of photovoltaic subsidies. Using a game theory approach, this study investigates the impact of subsidy exit policy on China’s PPG industry. The results show that stimulating research and development (R&D) can be difficult under current uncertain subsidy withdrawal plan. The government should announce the plan of subsidy reduction with clear adjustment as well as corresponding effective dates. In addition, under the condition of government-controlled prices, the social welfare of the monopoly market is higher than that in the competitive market. In order to achieve the same technological progress and target output, the total cost (including enterprise cost and government expenditure) in competitive market is higher than that in monopoly market, which is caused by repeated R&D investment and technical cost. Technical cooperation could lower costs and increase profits, and is therefore recommended.

1 | INTRODUCTION

Solar photovoltaic power generation (PPG) is the direct conversion of solar light into electricity. PPG is increasingly attracting worldwide attention as a viable global response to climate change [1]. Between 2002 and 2012, the annual growth rate of the global PPG industry worldwide was approximately 50%. In China, the photovoltaic (PV) industry is growing even faster. By 2012, China’s PV industry accounted for 60% of the international PV market [2]. In terms of PV installed capacity, China overtook Germany for the first time in 2015 and became the country with world’s largest cumulative PV installed capacity [3]. By the end of 2017, the cumulative installed PV capacity in China has reached 130 gigawatts (GW) [4], and accounted for nearly one-third of world’s total PV capacity (404.5 GW) [5].

The main reason for this rapid development of the PV industry in China is the implementation of various subsidy policies in PV industry [6]. Various departments implemented policies such as “Solar Roof Plan” and “Golden Sun Demonstration Project” to support PPG projects [7, 8]. These incentives reduced PV electricity prices and promoted the development of China’s PPG industry. In addition, with the promulgation and implementation of relative supporting policies, some PPG projects were integrated into the grid-connected power system [1]. However, large-scale government subsidies can bring...
about overcapacity. In theory, subsidies could distort investment behaviour, especially when the subsidy measures are driven by government goals. This can lead to duplicate construction and, as a result, overcapacity [9, 10].

Some studies point out that the Chinese government needs to consider a subsidy withdrawal mechanism to reduce firm dependence on government [11]. In fact, the Chinese government has realized overcapacity of PV industry and has begun a process of subsidy withdrawal. It aims to resolve overcapacity and promote the healthy development of the PV industry by increasing R&D investment and technological innovation [12, 13]. However, the actual impacts may not be completely consistent with expectation of policy makers. These new policies immediately triggered a “great earthquake” in China’s new energy industry. The stock price of PV listed companies fell sharply, and many firms faced bankruptcy [14]. Furthermore, the current subsidy withdrawal policy of China is not certain and clear, for two reasons. First, there is no specific withdrawal timetable. Second, withdrawal level can be adjusted ad hoc by the government, rather than specific and fixed withdrawal levels at specified dates.

It is imperative that policymakers consider the expected effect of this uncertain subsidy withdrawal policy before implementation [15]. The paper studies uncertain long-term subsidy withdrawal policy in China and its effect on the PV power generation on the quantity of PV generation. The paper investigates three cases, monopoly, and competitive market represented by a duopoly with and without PV technology cooperation. We compare the generated quantity of PV electricity, R&D expenditures and company profits depending on the subsidy levels. We construct the game-theoretic experiment and draws quantitative results, with discussion of their implications.

This study has theoretical and practical contributions. First, this study is the first to investigate the effect of subsidy withdrawal on China’s PV industry from the perspective of game theory. The qualitative analysis is of universal significance. It constructs models under three situations and finds the monopoly market is the most effective. Technical cooperation between enterprises in competitive market could lower costs and increase profits. These conclusions are not influenced by function setting. Second, the study provides novel insights to the Chinese policy makers on the subsidy withdrawal plan. By game analysis, it finds the current subsidy withdrawal is not effective in promoting technical progress and improving enterprises’ competitiveness. The government should announce the plan of subsidy reduction with clear adjustment as well as corresponding effective dates.

The remainder of the paper is organized as follows. Section 2 reviews the existing literature. Section 3 presents the methodology and hypotheses. The game equilibrium in different situations is analysed in Section 4. The simulation of decision sequence under different circumstances is presented in Section 5. Section 6 presents a discussion of the results and recommendations for further research. Finally, Section 7 offers the conclusion.

2 LITERATURE REVIEW

Since 2007, many policies supporting the development of PV industry has been implemented. In January 2007, the National Development and Reform Commission [16] issued the “Interim Measures for the Administration of Renewable Energy Subsidies”, which stipulated the scope of subsidies and standard rates for solar PPG. In March 2009, the Chinese Ministry of Finance (2009) promulgated the “Interim Measures on the Management of Financial funds for Solar Energy Construction” [17]. The scheme prescribes a solar energy construction subsidy, which is adjusted annually based on actual cost. In July 2011, the National Development and Reform Commission [18] issued the “Improving the Online Tariff Policy for Solar PPG” which became the first feed-in-tariff (FIT) scheme for solar power generation. These policies not only promote the development of PV industry, but also cause overcapacity in PV industry.

Many studies point out that there has already been overcapacity in China’s PV industry [19, 20]. Due to the lack of independent R&D abilities and core technologies, upstream PV enterprises generate profits by repeating the low-end manufacturing and processing. This results in inferior competition as well as overcapacity in China [19]. Meanwhile, the global financial crises and European debt crisis saw the market shrink sharply (including a large number of firms terminating production or shutting down) because of substantial industry dependence on foreign demand [21]. Furthermore, the European Union and the United States conducted anti-subsidy investigations on China’s PV industry in 2012, and foreign demand declined rapidly.

Despite this, many domestic enterprises increased production in order to obtain more subsidies, which exacerbated overcapacity in China’s PV industry [22–24]. In the downstream PV industry, the distortive effects of the subsidies are more obvious and serious. To obtain more subsidies, PV power plants have expanded at an accelerated rate [25]. However, due to the intermittent and poor predictability of PPG, the current power grid operation control technology does not meet the requirements for large-scale photovoltaics connection to the grid [26, 27]. At the same time, China’s PV resource-rich regions have relatively lagging economic development and limited local consumption capacity [28]. In this case, rapid expansion in PV power plants may result in an abundance of discarded PV power [29]. In 2017, the national curtailment rate was 6.2%, whereas several provinces such as Gansu province and Xinjiang province reported a much higher rate of 20% (although the Chinese government steps up efforts to reduce the curtailment rate in recent years) [4].

A review of the existing literature reveals there are already some studies focusing on PV subsidy policies. However, most of these studies focus on the impact of introducing subsidy policies on the PV industry instead of subsidy withdrawal policies. For example, Carley [30] uses system dynamics and econometric models to evaluate empirically the effectiveness of US state renewable energy power policies, affirming the role of renewable portfolio standard (RPS) policies and competitive markets. Yun et al. [31] reviewed the implementation of different
solar policies. They considered FIT and RPS to be the most favourable renewable energy policies implemented in many countries around the world [32–35]. In terms of policy design and implementation, FIT and RPS are increasingly being combined to achieve quality results [36, 37]. The reason is both policies have their distinct advantages. For instance, Altenburg and Engelmeier [38] study rent management policies in India and find that the “green rent” policy can promote investment in the photovoltaic industry through lower subsidy expenditure. Crago and Chernyakhovskiy’s study [39] show that rebates impact financial incentives for PPG in the northeastern United States.

In fact, the government has considered the subsidy exit to resolve overcapacity in China’s PV industry. In December 2018, the National Development and Reform Commission [40] issued the “The Price Policy for PPG Projects” to reduce the subsidy standards of PPG. In May 2018, the NDRC, the Ministry of Finance, and the National Energy Administration [41] jointly issued the “Notice on Matters Related to Photovoltaic Power Generation in 2018”, where the government decided to further reduce subsidy coverage. However, there are few studies analyzing the impact of subsidy withdrawal policies on the PV industry, especially for China. As such, there is great need for empirical studies into the impact of subsidy withdrawal policies on China’s PPG industry. In this study, we use a game theory framework to analyse the impact of China’s PV subsidy withdrawal policy on the PPG industry. The study provides a great reference for policymakers in formulating and revising PV industry policies.

3 | METHODOLOGY AND HYPOTHESES

Game theory is the study of strategic behaviour and decision making by rival players [42]. Under the maximization of their respective interests, stakeholders can reach an equilibrium solution from different strategies, which can help formulate guidelines for policymakers. This study adopts the game theory method to research the impact of subsidy withdrawal policy in China’s PPG industry. The government and PPG enterprises are the two players in the subsidy exit game of the PPG industry. The decision sequence is as follows: First, the government declares a subsidy level as a future subsidy policy. Second, the PPG enterprise chooses its R&D investment and production strategy according to the subsidy level set by the government. The sum of the production scale of all enterprises is the total production scale on the market. Next, the government re-adjusts its subsidy strategy and sets a new subsidy level according to the production scale and technical level in the market. Finally, when achieving the Nash equilibrium of the game [42, 43], neither side has the motivation to change its strategy. The strategic choice of both players is the equilibrium solution of this decision sequence. This is a sequential game and players are perfectly informed.

In the above game, government utility is a function of subsidy expenditure and the government maximizes its utility by minimizing its subsidy expenditure. We convert the minimization problem into a maximization problem by multiplying subsidy expenditure by -1. The government’s utility constraint is the industrial production scale. This infers the government aims to minimize its subsidy expenditure without impairing the scale of industrial development. The phenomenon of production scale constraint is common and important in China due to its planned development mode in many sectors. For example, in the “13th Five-Year Plan”, the government set a target of achieving cumulative installed solar capacity of PPG to 105 GW by 2020 (although this target has already been achieved in 2017) [44]. At the same time, the annual use of solar energy was in excess of 140 million tons of coal. This means that the government needs to maintain the scale of PPG above a certain level. In this study, we set \( Q \) to indicate the minimum production scale of government acceptable photovoltaic power. It is important to note that actual output cannot be lower than the target output of the government. The government’s one-stage utility function and constraint is expressed as:

\[
\text{MAX} \ U (T) = -T Q,
\]

subject to \( Q \geq Q_t \)

where \( T \) is the level of subsidy, \( Q \) is the output of PPG, and \( Q_t \) is the minimum output scale of the government acceptable photovoltaic power.

For the PPG enterprise, the utility function is the profit function, which is formulated as:

\[
U (Q, W) = P_t Q - C (Q) + f (W) Q - W^*,
\]

where \( Q \) is the power generation of electricity generated by the PPG enterprise; \( W \) is the technological R&D investment of the enterprise; \( P_t \) is the price of PPG; \( C \) is the total cost which is a function of the output of PPG; and \( f (W) \) indicates benefits that can be brought by the technological R&D investment. In addition to complete information, we apply the following assumptions for the above variables and functional relationships:

**Assumption 1**: The price of PPG is exogenous. The reason is the current FIT price in China is regulated by the government and there is consistent pricing for different types of power generation. Further, the subsidy level (i.e. \( T \)) in this paper can be seen as the part of the PV on-grid price that exceeds the on-grid price of traditional thermal power (\( P \) represents the price of traditional thermal power), in this case, \( P_t = P + T \). To obtain a solution, we set \( P_t = T \) (yuan RMB). In the decision sequence, \( P_t \) is treated as a constant parameter and the assignment does not affect the conclusions of this study.

**Assumption 2**: There exists Harrold-neutral technology [45, 46]. After technological progress, the ratio of factors of production remains unchanged. Harrold-neutral technology is widely used in research of economic growth. This assumption means that the utility function of the enterprise is comparable before and after technological progress. In other words,
between different stages of the game, the utility function of the enterprise is comparable.

Assumption 3: The enterprise is in a stage of decreasing return to scale. Under this hypothesis, the cost function meets the following requirements: $C''(Q) > 0$, $C''(Q) > 0$, which means: 1) costs will increase as the amount of PPG increases; 2) marginal cost will also increase as the amount of PPG increases. For convenience, we set $C(Q) = \frac{2}{3} aQ^2$ [47]. Other cost functions that satisfy the decreasing return to scale assumption do not affect the conclusion.

Assumption 4: The benefit of additional technological R&D investment is expressed in terms of a decrease in unit production costs. This study does not trace how technological progress affects corporate profits. We use a decline in unit production costs brought by technological progress to simplify the path of influence. The benefit of technological R&D investment exhibits diminishing returns. The profit function is based on the following assumption: $f(W) > 0$, $f'(W) > 0$, $f''(W) < 0$, $\lim_{W \to \infty} f(W) = c$ represents unit cost, $c = C(Q)/Q$, which means: 1) additional technological R&D in investment can decrease unit production costs; 2) the reduction of unit production cost increases with additional technological R&D investment; 3) the marginal effect of technological progress decreases with additional R&D investment; 4) The effect of additional technological R&D investment will not increase indefinitely. The reduction of unit production costs brought by additional technological R&D investment will always be less than a fixed value, which is the current unit production cost (i.e. $c$). We set $f(W) = 1 - \frac{1}{W+1}$ $(W > 0)$ [48], and this setting does not affect the conclusion.

4. GAME EQUILIBRIUM IN DIFFERENT SITUATIONS

The Section 4 considers the impact of subsidy withdrawal on China’s PPG industry in three cases: monopoly market, fully competitive market without technology cooperation and a fully competitive market with technical cooperation. The details of the three cases are described in Sections 4.1, 4.2, and 4.3.

4.1 Monopoly market

In a monopoly market, there is only one company whose amount of PPG is the total amount of the market power generation. Both players’ income functions are continuously steerable in the game process. The game equilibrium can be solved by the inverse induction method. The monopolist faces the following decision:

$$\begin{align*}
\text{MAX } U (Q, W) &= (P + T) Q - \frac{2}{3} aQ^2 \\
&\quad + \left(1 - \frac{1}{W+1}\right) Q - W^* \tag{3}
\end{align*}$$

s.t. $(P + T) Q - \frac{2}{3} aQ^2 + \left(1 - \frac{1}{W+1}\right) Q - W^* \geq 0$.

The subsidy is exogenous. We assume that a certain subsidy level accounts for $\bar{T}$, and the PPG enterprise (i.e. the monopolist) has the only R&D investment level corresponding to the production level, $W^* = W^*$, $Q = Q^*$ (the detailed solving process is shown in Appendix A), separately. The response function of the company to the level of government subsidy is:

$$W^* = 2a^{-1} \left[2 + T + \left(2 + T\right)^2 - 4a\right]^{1/2} - 1, \tag{4}$$

$$Q = (2a)^{-2} \left[2(T + 2)^2 - 4a + 2(2 + T) \left(2 + T\right)^2 - 4a\right]^{1/2}. \tag{5}$$

According to the response function above, the firms R&D investment and power generation increases with an increase in government subsidies. Both the optimal R&D level $W^*$ and the optimal production level $Q^*$ are proportional to the subsidy level $T$. Therefore, when the subsidy level increases, R&D investment and power generation also increase, and vice versa. Correspondingly, once the government changes its subsidy level at the first round of decision-making, the company will adjust its R&D investment and power generation according to the response function.

Next, we substitute $Q = Q^*$ into the primary stage of government decision-making. The government faces the following decision:

$$\text{MAX } U (T) = -T Q^*, \tag{6}$$

s.t. $Q^* \geq Q_t$.

The government’s optimal strategy under production constraints depends on $Q^*$ and $Q_t$. This study uses the underline method to solve the Nash equilibrium of the game (see Table 1) [42, 43]. By classification, the decision sets of both sides of the game are divided into three categories to obtain a 3 × 3 strategy space, where $W^*_L < W^*_S < W^*_H$, $Q^*_L < Q^*_S < Q^*_H$, $T^*_L < T^*_S < T^*_H$. Thus, we can find the Nash equilibrium points through the scribing solution in the strategy space.

If $Q^* > Q_t$, then $Q = Q^*_H$, there are three strategic spaces for the government, $-T_L Q^*_H, -T^*_S Q^*_H$ and $-T^*_H Q^*_H$, separately. The current power generation is greater than the government’s expected target. The government’s utility maximization function is the minimization of subsidy expenditure. The government has the ability to not abide by the promise of subsidy given as $T$, but to continue to reduce the subsidy level. Therefore, the government’s dominant strategy is point $-T_H Q^*_H$. However, in this case, the enterprise will suffer additional losses due to lower subsidy level.

If $Q^* < Q_t$, then $Q = Q^*_L$, and current power generation is less than the government’s expected target. Under the
than the initial subsidy. Government’s optimal production quantity in equilibrium, rather than the initial subsidy.

If \( Q^* = Q \), then \( Q = Q^* \), and a Nash equilibrium arises. The government has no intention to change the subsidy level \( T \). In this case, this level \( T \) given by the government is the optimal level, that is, \( T = T^* \). If the government changes the subsidy level, the PPG enterprises will also change the level of power generation.

This study assumes that the PPG enterprise is rational. It can expect the optimal subsidy level \( T^* \) according to the government target output \( Q \). In the second stage of the game, the enterprise will also adjust the level of additional technological R&D investment to \( W^* \) according to the expected subsidy level \( T^* \), and in this case, the amount of power generation is \( Q = Q^* = Q \). Thus, in the primary stage, the government will also have to subsidize according to the subsidy level of \( T^* \). The equilibrium solution of the market is unique without external forces. For each given quantity of government production \( Q \), there is a unique equilibrium solution. In other words, the amount of additional R&D in PPG firms is determined by the government’s optimal production quantity in equilibrium, rather than the initial subsidy.

4.2 Fully competitive market without technical cooperation

We consider two homogeneous firms to simulate the competitive case. Their power generations and R&D investment are \( Q_1 \) and \( W^*_1 \), and \( Q_2 \) and \( W^*_2 \), respectively. When using the backward induction method to solve the game equilibrium [49], it is necessary to solve the strategies of both enterprises in the second stage separately. In the competition case, the strategy of the two enterprises follows the rules of the sub-game. By analyzing and solving the sub-game (see Appendix B), this study finds the two enterprises will have the same decisions when they make their decisions at the same time. Therefore, we can combine these two enterprises’ utility function into a single new enterprise.

For the utility function of this new enterprise, we use \( Q_{11} \) and \( W^*_{11} \) to represent the total output of PPG and total R&D investment of the market, respectively. Thus, we have: \( Q_{11} = Q_1 + Q_2 \) and \( W^*_{11} = W^*_1 + W^*_2 \). Furthermore, the R&D investment of the enterprises is independent and there is no technical cooperation between them. Technical cooperation refers as that enterprises cooperate in technology R&D. It can avoid repeated R&D investment and improve R&D efficiency [50]. In this case, the reduction of unit production costs in the competitive market will be lower than that in the monopoly market. Therefore, the R&D utility function for the new enterprise is \( f (W^*_{11}) = 1 - \frac{2}{W^*_{11} + 2} \). The new enterprise faces the following decision:

\[
\begin{align*}
\text{MAX } U(Q_{11}, W^*_{11}) &= (P + T) Q_{11} - \frac{2}{3} a Q_{11}^\frac{3}{2} + \left(1 - \frac{2}{W^*_{11} + 2}\right) Q_{11} - W^*_{11} \quad (8) \\
\text{s.t. } (1 + T) Q_{11} - \frac{2}{3} a Q_{11}^\frac{3}{2} + \left(1 - \frac{2}{W^*_{11} + 2}\right) Q_{11} - W^*_{11} &\geq 0.
\end{align*}
\]

Consistent with the solution to Equation (3) (which is shown in Appendix A), the reaction function under competition is:

\[
W^*_{11} = \left(\sqrt{2a} \right)^{-1} \left( 2 + T + \left(2 + T\right)^2 - 4\sqrt{2a} \right)^{\frac{1}{2}} - 2, \quad (9)
\]

\[
Q^*_{11} = (2a)^{-\frac{2}{3}} \left( 2(T + 2)^2 - 4\sqrt{2a} + 2(2 + T) \right) \left( (2 + T)^2 - 4\sqrt{2a} \right)^{\frac{1}{3}}. \quad (10)
\]

Comparing the reaction function in this scenario with the monopoly market outcomes, we find the following.

First, in the competitive situation, the government needs to pay greater subsidies to achieve the same total power generation target. Comparing Equations (10) and (5), we obtain \( Q^*_{11} < Q^* \). Then, if we substitute \( Q_1 = Q^*_{11} \) into the government decision at the primary stage, we find that the optimal decision strategy of the government depends on \( Q^*_{11} \) and \( Q_1 \), which is similar with the case in the monopoly situation. When \( Q^*_{11} = Q_1 \), a Nash equilibrium arises and the government has no incentive to change the subsidy level. Correspondingly, the subsidy level

| Company | \( W = W^{*}_{1} \) | \( Q = Q_1 \) | \( T = T_{L} \) | \( T = T^* (Q^* = Q_1) \) | \( T = T_{H} \) |
|---------|-----------------|--------------|-------------|-----------------|-------------|
| \( W = W^* \) | \( Q = Q^* \) | \( -T_{L} Q^{*}_{L}, U_{T_{L}}(Q^{*}_{L}, W^{*}) \) | \( T_{H} Q^{*}_{H}, U_{T_{H}}(Q^{*}_{H}, W^{*}) \) | \( T_{H} Q^{*}_{H}, U_{T_{H}}(Q^{*}_{H}, W^{*}) \) |
| \( W = W^{*}_{H} \) | \( Q = Q^{*}_{H} \) | \( T_{H} Q^{*}_{H}, U_{T_{H}}(Q^{*}_{H}, W^{*}_{H}) \) | \( T_{H} Q^{*}_{H}, U_{T_{H}}(Q^{*}_{H}, W^{*}_{H}) \) | \( T_{H} Q^{*}_{H}, U_{T_{H}}(Q^{*}_{H}, W^{*}_{H}) \) |

Note: If \( W = W^* \), then \( Q = Q^* = Q_1 \); if \( W = W^{*}_{1} \), then \( Q = Q_{1} < Q_1 \); if \( W^* = W^{*}_{H} \), then \( Q = Q^{*}_{H} > Q_1 \).
is $T = T^*$. As shown in Section 3.1, since $Q^*_1 < Q^*$, then we have $T^*_1 \geq T^*$, which shows that to obtain the same amount of output target of PPG, the government needs to provide a higher subsidy level in the competitive market scenario than that in the monopoly market.

Second, as technology caused by competition is not interoperable, this leads to higher levels of R&D spending. Comparing Equations (9) and (4), we have $W^*_s > W^*$, which means that compared with the monopoly market, firms in a competitive market have higher R&D expenditure.

4.3 Fully competitive market with technical cooperation

In this scenario, we assume there is a technological cooperation platform in the perfectly competitive market, and firms can obtain R&D results directly via this platform. The decision sequence is as follows:

Suppose there are two completely homogeneous firms facing technological cooperation costs $D_1$ and $D_2$, and $D_1 = D_2$ (hereafter $D$). By combing the utility functions of the two enterprises, total PPG and R&D investment in the market are $Q_2 = Q_1 + Q_2$ and $W_2 = W_1 + W_2$, respectively. The new utility function and decision facing the firm is:

$$\max U (Q_2, W_2) = (1 + T) Q_2 - \frac{2}{3} a Q_2^2 + \left(1 - \frac{1}{W_2 + 1}\right) Q_2 - W_2 - 2D \tag{11}$$

subject to:

$$(1 + T) Q_2 - \frac{2}{3} a Q_2^2 + \left(1 - \frac{1}{W_2 + 1}\right) Q_2 - W_2 - 2D \geq 0. \tag{12}$$

Consistent with the solution to Equation (3), the reaction functions for this race condition are:

$$W^*_s = 2a^{-1} \left(2 + T + \left(2 + T\right)^2 - 4a\right)^{\frac{1}{2}} - 1. \tag{13}$$

$$Q_2^* = (2a)^{-2} \left(2(T + 2)^2 - 4a + 2(2 + T) \left((2 + T)^2 - 4a\right)^{\frac{1}{2}}\right). \tag{14}$$

Compared to the monopoly case, we find the following.

First, the additional R&D investment and power generation in a competitive market with technical cooperation are consistent with the monopoly case. Thus we have $W^*_s = W^*$, $Q^*_2 = Q^*$, $T_2^* = T^*$. Furthermore, the amount of R&D investment of PPG enterprises in a competitive market with technical cooperation is determined by the government target output of PPG. For each target output $Q_t$, there is a unique set of equilibrium solutions and this corresponds to the solution in a monopoly market.

Second, total cost in the competitive market with technical cooperation is higher than that in the monopoly market (where technical cooperation cost is zero). Furthermore, this extra cost is borne by the enterprise itself, which means the profit of enterprise in the competitive market with technical cooperation will be lower than that in the monopoly market.

Third, the motivation for enterprises to pay extra technical cooperation cost is that they will pay more on R&D investment in a competitive market without technical cooperation. Hence, firm profits in a competitive market with technical cooperation are higher than that in a competitive market without technical cooperation. In addition, if there are a large number of enterprises in the market or the technical cooperation cost is very high, then the total technical cooperation cost (i.e. $D$) may be very high, which may result in $(P + T) Q_2 - C(Q_2) + f(W_2) Q_2 - W_2 - aD < 0$. In this case, the technical cooperation between enterprises will be invalid, and the enterprise will transfer to the process of independent technological R&D investment as described in Section 4.2.

5 SIMULATION OF DECISION SEQUENCE UNDER DIFFERENT CIRCUMSTANCES

In Section 5, we use the Python toolkit to simulate the decision sequence presented in Section 5.

5.1 The monopoly case

Based on the iterated elimination of strictly dominated strategies, we simulate the decision sequence in the monopoly case as follows: Since the game begins with government decision-making to determine a subsidy level, the simulation operation is also started by the government’s strategy. First, the government decides a subsidy level and target output. The initial value of subsidy level $T$ is unaffected by the equilibrium outcomes. According to China’s relevant standards, the subsidy policy for distributed PPG has been subsidized mainly based on power generation since 2013 [51, 52]. The subsidy standard is 0.42 yuan/kWh [53, 54]. According to the announcement issued by the National Bureau of Statistics in 2018, China’s solar power generation in 2017 reached 96.7 billion kWh [55, 56]. Therefore, we set the initial subsidy level at $T = 0.4$ yuan/kWh and the target output $Q_t = 96.7$ billion kWh. We then solve the optimal generating capacity and the optimal level of R&D investment by maximizing the enterprise’s utility function subject to its constraint.

Moreover, Section 4.1 measures whether the government will change the subsidy level. In changing the subsidy level, we assume the government must adhere to the following rule: the subsidy level changes only in proportion to the difference between the market’s power generation and the government’s expected power generation. It should be noted that the assumed rules for the change would not affect the final equilibrium point.
We obtain the final equilibrium point by iterating the above process. During the decision sequence, the value of the parameter $a$ will affect the final equilibrium point but it will not affect the conclusion. In order to fit reality, this study set the parameter $a = 0.08$ in the simulation after the parameter adjustment.

The simulation result in the monopoly market is shown in Figure 1. We find that the amount of power generated and R&D investment in the market will stabilize as the number of iterations increases. The equilibrium point is that the government’s target output and enterprise’s R&D expenditure are around 96.7 billion kWh and 3.01 billion yuan, respectively. R&D investment exhibits the same trend as power generation. The results show that when the government target production is determined, the decision sequence has a unique equilibrium solution. The enterprises will produce 96.7 billion kWh of photovoltaics and invest 3.01 billion yuan in R&D. This is the Nash equilibrium production strategy in the case of known government targeted output.

In Figure 1, we set the subsidy level $T = 0.4$ yuan/kWh. Figure 2 shows the impact of changes in the initial subsidy level on the final power generation and final subsidy levels. As shown in Figure 2, when we set the initial subsidy level $= 0.3$ yuan/kWh, the decision sequence will change, but the final equilibrium result remains the same. According to the simulation results, regardless if the initial subsidy level is of 0.4 yuan/kWh or 0.3 yuan/kWh, the final subsidy level will be stable at around 0.52 yuan/kWh in the case of the target power generation of 96.7 billion kWh.

### 5.2 The competition case

In order to compare with the simulation results in the monopoly market, this section uses the same simulation parameters as under the monopoly market. The simulation of decision sequence in the competitive market is the same as the monopoly market.

The simulation results in the competitive market without technical cooperation are shown in Figure 3. We find that when reaching the equilibrium state, the R&D expenditure reaches 4.2 billion yuan which is much higher than in the monopoly market. This is consistent with the theoretical derivation in Section 3.2. Since the technologies cannot be shared between enterprises in the competitive market, there is a duplication of R&D activities as well as declining returns. The enterprises need to pay higher R&D costs to achieve the same amount of power generation under the monopoly case.

Figure 4 shows the changes in the final subsidy level under monopoly case and competition case without technical cooperation. It shows that the level of subsidies in the competitive market is higher than the monopoly market in the equilibrium state. According to the simulation results, the subsidy level in the
Section 4.3. One important issue in the competition case with technical cooperation is firm profits. Figure 5 shows the impact of the total technical cooperation cost \( (nD) \) on firm profits in the scenario of perfect competition with technical cooperation and compares the results with those in other two cases. From Figure 5, we can see that total firm profits of the monopoly case are about 77.18 billion yuan. While in the competition case without technical cooperation, the total profits decrease to about 75.99 billion yuan due to repeated R&D investment.

In the competition case with technical cooperation, total profits are generally lower than that in the monopoly case but higher than that in the competition case without technical cooperation. If the \( nD \) is too high, technical cooperation among enterprises is invalid and enterprises will undertake independent technological R&D investment. In this case, total firm profits are the same as perfect competition without technical cooperation. In addition, we can also see from Figure 5 that higher \( D \) means the lower total profits. All the above simulation results are consistent with our analyses in Section 4.3.

6 | DISCUSSIONS

Section 6 has several important findings drawn from our results. First, under the current scenario of uncertain subsidy withdrawal policy, R&D investment by firms is only determined by the government target production of PPG instead of the initial subsidy level and firms choose their level of R&D investment and power generation according to the known government target output. Therefore, the current uncertain subsidy withdrawal policy will be ineffective in stimulating R&D investment.

Second, total cost in the monopoly market is lower than that in the competitive market for the same target output of PPG and technological progress. The main reason is that in the monopoly market of China, the price is fixed under control of Chinese government, which means it is exogenous and determined by the government rather than the market [58]. Hence, the monopolist cannot make monopoly profits through price setting. Meanwhile, compared with competitive market, the monopoly market can avoid technical cooperation cost of enterprises or repeated R&D investment [59]. All the facts above explain why the cost of monopoly market is lower. Once the price is deregulated, the monopolist is given more independent pricing power. The new price is likely to be higher than an equilibrium price and lead to decrease in market efficiency. Under such circumstances, the conclusion should be reconsidered. This study recommends further research on the impact of a freely determined market price on R&D investment and technological progress.

Third, in both competitive market scenarios, we observe that firms face higher costs than the monopolist. However, when individual firm technical cooperation cost \( (D) \) is low and/or the number of enterprise \( (n) \) is low, the total profits of enterprises in the competitive case with technical cooperation are higher than that in the competitive case without technical cooperation. Therefore, we recommend national or regional technical cooperation platforms (e.g. technology trading centre) be established in China to lower the technical cooperation cost and make technical cooperation valid [60].

The assumption of complete information is an important caveat to our findings. Under complete information, enterprises can predict the government target production of PPG and make decisions on power generation and R&D investment. However, in the real market, enterprises may not predict the government’s target power generation exactly due to a variety of factors. Under a scenario of incomplete information, decision-making in enterprises will change. The present study does not consider the general impact of government-assisted implementation of other PPG industry promotion policies in the process of policy withdrawal. This requires further study.

7 | CONCLUSIONS

This study applies game theory and system simulation techniques to analyse and validate the impact of subsidy withdrawal policy on China’s PPG industry. The results show that target PV production of government drives R&D investment and production under the complete information. Meanwhile, it indicates that total costs of the same PV production in monopoly market are lower than that in a market with more than one firm. This means that the competitive market is less efficient than the monopoly market given that PV price is exogenous. The main
reason is that the PV price is controlled by the government in our simulation. The repeated R&D investment and technical cooperation costs are avoidable in this scenario. Importantly, where technical cooperation costs are sufficient low, total profits are higher than the scenario without technical cooperation (but lower than the monopoly case).

Furthermore, this study confines the analysis to certain special cases with complete information, where enterprises can predict the target PV production of government. As a result, the enterprises make decisions of R&D investment and power generation based on their anticipation. However, in the real market environment, there are always more unforeseeable circumstances than merely government target production. Whether the decisions of enterprises change under such condition of incomplete information requires further research.

The study has some policy implications. First, stimulating research and development (R&D) can be difficult under current uncertain subsidy withdrawal plan. The government should announce the plan of subsidy reduction with clear adjustment as well as corresponding effective dates. Second, Technical cooperation in competitive market could lower costs and increase profits. Enterprises in PV industry should cooperate in technical R&D. It can avoid repeated R&D investment and improve the production efficiency.

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PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES
None.

ORCID
Jianliang Wang https://orcid.org/0000-0001-7037-9368

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APPENDIX A

The solution process of maximizing enterprise utility under the monopoly situation in the second stage

First, the government set a subsidy level $T$, and $T$ is exogenous. This study solves the extremum of the utility function employing partial bias. Deviate $Q$ and $W'$ separately to get,

$$\frac{\partial U}{\partial Q} = 2 + T - aQ^2 - \frac{1}{W' + 1}, \quad (A1)$$

$$\frac{\partial U}{\partial W'} = \frac{1}{(W' + 1)^2} Q - 1. \quad (A2)$$

By setting $\frac{\partial U}{\partial Q}$ and $\frac{\partial U}{\partial W'}$ equal to 0, we can obtain the two stagnation points of the function. One of the points is close to zero, which is rounded off according to the actual situation. This study takes the larger one only as follows:

$$W' = 2a^{-1} \left(2 + T + \left((2 + T)^2 - 4a\right)^{\frac{1}{2}}\right) - 1, \quad (A3)$$

$$Q = (2a)^{-2} \left(2(T + 2)^2 - 4a + 2(2 + T)\left((2 + T)^2 - 4a\right)^{\frac{1}{2}}\right). \quad (A4)$$

Then, this study verifies whether the stagnation point is the extreme point of the profit maximization function. By performing a second derivation on the profit function, we can obtain:

$$A = \frac{\partial^2 U}{\partial Q^2} = -C''(Q) = -\frac{1}{2} aQ^{-\frac{3}{2}}, \quad (A5)$$

$$C = \frac{\partial^2 U}{\partial W'^2} = j''(W')Q = -2(W' + 1)^{-3}Q, \quad (A6)$$

$$B = \frac{\partial^2 U}{\partial Q \partial W'} = j'(W') = (W' + 1)^{-2}. \quad (A7)$$

By substituting the solved stagnation point into the extreme value discriminant, $B^2 - AC = (W' + 1)^{-4} (1 - aQ)$. When
the output is high, \((1 - aQ) < 0\), then \(B^2 - AC < 0\). The stagnation point establishes the extreme point, and that is, the enterprise’s utility maximization function has a unique extreme point.

**APPENDIX B**

**Subgame solving process of homogeneous enterprises**

The decision sequence can be described briefly as follows. There are only two homogeneous enterprises 1 and 2 in the market. First, the government declares a subsidy level \(T\). Then, the two enterprises decide the production and technological R&D investment simultaneously. As the analysis in Section 3, when the output in the market is less than the expected output of the government, that is, \(Q^* < Q_t\), the government has the incentive to increase subsidies, vice versa. Competitive markets are the same. For calculation convenience, this study assumes the functional relationship between subsidy level \(T\) and the market yield as follows:

\[
T = z(Q_t - Q) + c, \quad T \geq 0.
\]

When the market output does not match the government’s expected output, the government will change the subsidy based on the difference and \(z\) is the adjustment factor. The profit function of the two companies is:

\[
U_i(Q_1, Q_2) = \left( z(Q_t - Q_i - Q_2) + \epsilon \right) Q_i - \frac{2}{3} a Q_i^\frac{3}{2} + \left( 1 - \frac{1}{W_i + 1} \right) Q_i - W_i, \quad i = 1, 2. \tag{B1}
\]

By deriving \(Q_1\) and \(Q_2\) and making them equal to zero, we can get the mutual reaction function between the two enterprises:

\[
Q_2 = z^{-1} \left( zQ_t - 2zQ_1 - aQ_1^\frac{1}{2} - \frac{1}{W_1 + 1} + \epsilon + 1 \right), \tag{B2}
\]

\[
Q_1 = z^{-1} \left( zQ_t - 2zQ_2 - aQ_2^\frac{1}{2} - \frac{1}{W_2 + 1} + \epsilon + 1 \right). \tag{B3}
\]

These two reaction functions indicate that when the output of firm 1 increases, the output of firm 2 will decrease, and vice versa. Solving these two reaction functions, this study obtains \(W_1 = W_2\). By setting \(W = W_1 = W_2\), this paper can obtain the Nash equilibrium solution:

\[
Q_1 = Q_2 = 36z^{-2} \left( 2a^2 - 12z \left( \frac{1}{W + 1} - zQ_t - \epsilon - 1 \right) \right.
- 2a \left( a^2 - 12z \left( \frac{1}{W + 1} - zQ_t - \epsilon - 1 \right) \right)^{\frac{1}{2}}. \tag{B4}
\]

This means that if there are two homogeneous companies with the same level of subsidy \(T\), they will make the same production decisions and R&D investment. The production and R&D investment are determined by Nash equilibrium.