A comparison of impacts on investment behaviors in the context of grid parity photovoltaic technology by introducing renewable portfolio standards policy

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Abstract: Investments in power capacity is widely investigated in the effects of the renewable energy support policy to promote capacity expansion. However, the existing studies have not considered the impact of investment behaviors on capacity expansion under the renewable portfolio standards (RPS) policy. To address this problem, we develop a two-stage decision model to assess investment behaviors with the RPS policy. The investment behaviors are divided into three scenarios: decentralized competition (DC), cooperated planning (CP), and centralized strategy (CS). We construct the Cournot game model for the DC scenario, the cooperative game model for the CP scenario, and the portfolio investment model for the CS scenario, respectively. The three models are introduced to the two-stage decision framework to capture the characteristics of investment behaviors of generators under the RPS policy. Compared to the DC scenario, the CP scenario has the most benefits and turns the green certificates market trade into an internal business; and the CS scenario could avoid the

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price risk from trading green certificates by considering renewable power quota during the process of investing in both technologies.

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1. Introduction

Renewable energy indicates a clean way to generate electric power, and it is becoming the mainstream of power generation with almost no carbon dioxide emissions. Compared to traditional energy, the high cost of renewable energy had limited its wide application in the past decade. Nowadays, the levelized cost of the renewable energy industry in China has been reduced by 90%. Renewable power generated from solar or wind energy is able to connect to the grid at an equal price. Note that Germany is a pioneer in developing renewable power, which reached the grid parity of solar photovoltaic (PV) technology around 2012 [1]. Despite a dramatic reduction in the cost of renewable energy, the cumulated installed capacity of renewable power is smaller than traditional power. This phenomenon is a complicated issue that covers both the characteristics of renewable power [2-4] and the energy policy [5].

In Chinese power market, the renewable portfolio standards (RPS) policy is gradually replacing the feed-in tariff (FIT) policy. To spur investment enthusiasm for renewable power, the government issued an RPS policy to provide revenue compensation for renewable generators via green certificates trading. Up to now, the implementation of the RPS policy has diversified generators' investment behaviors under the government's quota requirements. As a result, the RPS policy has significantly affected generators' investment behaviors in the renewable power field. Essentially, the generators' investment behavior in power capacity is a competitive problem among generators. For the problem, most of studies focus on the two-stage decision model of investments in power capacity to stimulate the generators' decision process. Specifically, the existing two-stage decision models investigate the decentralized competition problem among generators. In this scenario, the traditional generator and the renewable generator are independent players regarding the competition of investment capacity and power production. However, they ignore the cooperation of the two independent players by maximizing the return on investment or satisfying requirements of the renewable energy support policy. For this reason, we sought to determine generators' strategic behaviors under the RPS policy and consider their implications for capacity investment and profit variance.

To analyze the two-stage decision model of investments in power capacity during decision process among generators, three different investment behaviors are assumed to facilitate this analysis: (1) decentralized competition (DC) that the traditional generator and renewable generator are independent players regarding the competition of investment capacity and power production; (2) cooperated planning (CP) that the traditional and renewable generators cooperate to maximize the return on investment profit; and (3) centralized strategy (CS) that generator simultaneously invests in traditional and PV technology based on an RPS target imposed by the policymaker. Following the decision sequence of power investment and production, we propose a new two-stage decision model to explore the capacity investment and operation affected by the investment behaviors of generators. The model of the DC and the CP scenarios follows a quadratic program with inequality constraints: In the first stage, the generator maximizes its expected profit by determining its investment capacity, and then in the second stage, each generator produces power subjected to capacity constraints. In the CS scenario, an equation constraint for the renewable power quota is added to the first stage of the model. This new mathematical program contains equality and inequality constraints and is more complicated than that of the DC and the CP scenarios. We aim to get the closed-form solutions to the model of the three scenarios and to clarify how best to fulfill renewable power quotas.

The main contribution of this paper is that we propose the two-stage decision model for three investment scenarios (DC, CP and CS). The basic concept of the two-stage decision model of investments in power capacity is that the investment and sales decisions are separated with investment in the first stage and sales in the second stage [6]. Although the conventional two-stage decision model performs well in competitive problems (e.g. the DC scenario), they ignored the two scenarios (e.g. the CP scenario and the CS scenario) when the RPS policy is interpreted. To solve the problem, an improved two-stage decision model is proposed. The game theory is adopted to construct the Cournot game model for the DC scenario, the cooperative game model for the CP scenario, and the portfolio investment model for the CS scenario, respectively. Then, the three models are introduced to the two-stage decision framework to capture the characteristics of investment behaviors of generators under the RPS policy. Compared to the conventional two-stage decision model, the proposed model firstly establishes the game structure of the DC, the CP, and the CS scenarios by considering the model parameter of the RPS policy and its restrictive conditions on capacity. Afterward, the Cournot game, cooperation game and portfolio mode are adopted to additionally consider the features of the DC, the CS and the CP scenarios in the first stage equilibrium. As a result, the model equilibrium and the profit under these three scenarios are compared. The comparison results show the CP scenario has the most benefits and turns the green certificates market trade into an internal business; and the CS scenario could avoid the price risk from trading green certificates by considering renewable power quota during the process of investing in both technologies. These findings have important implications for members of China's power supply chain as they support the alternative investment behavior to hunt profit or avoid risks.

The rest of this paper is organized as follows: Section 2 reviews the related literature on the policy and competition of the power market. Section 3 characterizes generators' investment behaviors into three scenarios and formulates a two-stage decision model to express the feature of behavior under the RPS policy. By solving the equilibrium in each scenario, we compare the profit issue caused by the investment behaviors. In Section 4, a numerical experiment is adopted to validate the effectiveness of the proposed model. Concluding remarks are given in Section 5.

2. Literature review

The renewable obligation was introduced in 2002 in England and Wales. As part of the government policy, it stipulated that licensed power generators were legislated to buy a certain percentage of renewable obligation certificates [7]. England's renewable obligation is the RPS, which is a form of quantity regulation. Specifically, the government establishes the quota or proportion of renewable power for the entire power supply, and the market determines a reasonable price for renewable power [8]. This scheme allows renewable generators to compete with fossil fuel power generators by receiving additional revenue from green certificates trading [9]. As a policy tool, the RPS policy was a cost-effective market mechanism [10]. Moreover, the effectiveness of the RPS policy was more evident in the case of the shift from the FIT to the RPS policy [11,12]. Compared to the FIT, the learning rate of the PV power generation during the RPS policy period is much higher [13]; The implementation of the RPS policy is consistent with the governmental goal of grid parity of renewable power [14].

With the reform of the power market, a retail market composed of power generators has developed. Independent power producers, as the central bodies of market competition, face many new pressures and challenges from both the government and the market. With policy support, there is a potential market for developing renewable technology, and investment behaviors of generators appear to be diversified. In general, they prefer to collaborate with other power producers to obtain more profit, rather than operating individually [15]. Aggregation among renewable generators is also beneficial because the coalition increases their expected profit [16]. Virtual power plants, which can be integrated with distributed energy resources, yield a surplus profit compared with individual distributed energy resources [17]. These studies have discussed the positive effect of the coalition or cooperation game in the power market alongside the penetration of renewable power. In recent years, some scholars have studied the strategic investment behavior. By postponing investments, investors in renewable power could choose the investment time and size when the optimal option value of the project was reached [18,19]. Under the renewable energy support policy, the bidding price, capacity choice, and economic feasibility of investments for investors were studied using real options analysis [20-22]. These studies indicate that the investment behaviors of generators have started attracting academic attention, but neither of them considers the effects of the RPS policy on investment behaviors.

In monopoly market structure, the market power is reflected in generators' investment or production behaviors. To theoretically explain the generators' decisions, game theory provides a distinctive perspective and has been widely applied. The classical Cournot game is commonly used to deal with the game model with complete information among generators [23]. Hafezalkotob et al. (2017) proposed a Cournot-oligopoly model for green supply chain management [24]. Zhang et al. (2020) thought the power suppliers' trading decision model in the energy supply chain was a Cournot game process [25]. Helgesen and Tomasgard (2018) investigated the economic impacts of green certificates trading on the deployment of renewable power stations by using the Nash Cournot model [26].

In this study, we consider the impact of investment behaviors on capacity expansion under the RPS policy in the monopoly power market and the generators' decision process with two stages. Generally, the investment capacity is installed in stage 1, and the power output is then optimized in stage 2. Nowadays, a two-stage decision game has gained much attention for its usage of the generators' decision process. For instance, Murphy and Smeers (2005) considered three investment models for power capacity in restructured electricity systems, where the capacity expansion game is treated as a two-stage decision game [27]. They examined the impact of the forward market on investments in oligopolistic power markets [6]. Subsequently, the two-stage decision model was applied in many problems including capacity commitment and price volatility, price volatility and market power, capacity underinvestment, and fuel cost uncertainty and capacity investment [28-31]. However, the existing work ignored the impact of investment behaviors on capacity expansion under the RPS policy. As a result, this study proposes a new two-stage decision model to study the investment behaviors of generators under the RPS policy.

3. Model

3.1 Assumptions

In this paper, the double-sided market between the demand market and generators (the supplies of traditional power and solar power) is investigated. Although the power transmission capacity affects the results, we assume a sufficient capacity in the power transmission due to the electric power infrastructure is well established. Thus, the power transmission capacity constraint is not been considered in the modeling process.

Generally, demand is affected by market and policy factors such as product price, consumer income, consumer preference, consumer expectation, and governmental policy. However, the product price is the most significant factor which has been proved by Phu and Akao (2020) [32]. In this paper, we focus on investigating the relationship between product price and demand. According to the abovementioned fact, the assumption of the linear demand function [33,34] is adopted as follows:

$$p = a - bQ \tag{1}$$

Where p and Q are respectively the price and demand of the power; a denotes the power market size; b indicates the linear relationship between power price and demand.

The power outputs from traditional technology $q^T(q^{T''})$ and PV technology q^R fully meet the market's demand. Thus, an underlying assumption is given as $Q = q^T(q^{T''}) + q^R$. The output of PV technology q^R commonly consists of the operational profit, the power price, and the green certificate price. In fact, the output of PV technology is commonly affected by the probability of the weather condition. As a result, we consider the probability of weather condition as a discrete random variable ρ. In this paper, we address the probability of the output of PV technology by using the binary probabilistic model [28].

Let ρ denotes the probability of the condition of sunny in a day. When the condition is sunny, the PV capacity is defined as x^R. Otherwise, the PV capacity is defined as 0. For identification, q^T and $q^{T"}$ denote the traditional power output under the condition of unsunny ($1-\rho$) and under the condition of sunny (ρ), respectively. According to the external expansion theory of the power industry, the generator's power output is determined by investment capacity. The generators should expand their investment capacity to enlarge production. Let x^T and x^R denote the investment capacity for traditional technology and PV technology, then $q^T(q^{T"}) \le x^T$, $q^R \le x^R$.

Under the RPS policy, the government sets a renewable power quota. The green certificates trading market, a complementary measure, aims to fulfill the policy quota for each generator. We assume that the generator is automatically granted a green certificate for each unit of renewable power. There must be a wide range of green certificates for one generator and a shortage for another. Therefore, they have become trading objects in the green certificates market. In this study, the renewable power quota and the green certificate price indicate θ and w, respectively. As the grid parity of renewable power, the sum of the operational cost v^R and investment cost k^R per unit of solar power is less than or equal to the sum of the operational cost v^T and investment cost k^T per unit of traditional power.

Referring to Tishler and Milstein (2008) [35], the total production cost of the traditional technology $C(x^T, q^T)$ or PV technology $C(x^R, q^R)$ is

$$\begin{cases} C(x^T, q^T) = k^T x^T + v^T q^T \\ C(x^R, q^R) = k^R x^R + v^R q^R \end{cases} \tag{2}$$

Actually, the power production and investment is a two-stage decision problem. In the first stage, the generator decides the investment capacity to maximize net profit. Given the investment capacity, it needs to determine its power output in the second stage. We solve this two-stage problem using backward induction.

3.2 Scenario analysis

As observed, generator investment behaviors are classified into three scenarios based on the impact of the RPS policy and technology differences. Then, the DC, the CP, and the CS scenarios are described as follows:

3.2.1 DC scenario

In this scenario, each generator adopts only one of the two technologies: traditional technology or PV technology. Here, the traditional generator invests in coal-fired technology, while the renewable generator adopts PV technology. In terms of weather conditions, the power output of PV technology is intermittent, so the conditions of sunny and unsunny were considered. The renewable generator is a competitor to the traditional generator in the power supply market. Under the RPS policy, each generator must also keep to the proportion of the renewable power limit, so green certificates trading appears between the generators.

The generators' decision processes can be considered a two-stage Cournot game in which the generators invest in power turbines and trade on the spot market. By backward induction, the Cournot game model for the DC scenario is given as follows:

Stage 2:

PV turbines cannot work under the condition of unsunny, so only the traditional generator can continue its operations. Under the RPS policy, there should be θ percent of all power output from renewable energy. To achieve this goal, traditional generators have to purchase the corresponding quantity of green certificates. Assuming the price of the green certificate is w for each unit, the operational profit for the traditional generator under the condition of unsunny is

$$\pi(q^T) = (a - bq^T - v^T)q^T - \theta q^T w$$
$$s.t. \quad \begin{cases} q^T \le x^T & (\vartheta_1) \\ q^T \ge 0 & (\mu_1) \end{cases} \tag{3}$$

Equation (3) has two constraints which are the boundaries of the power output. ϑ_1 and μ_1 are the dual variables of constraints $q^T \le x^T$ and $q^T \ge 0$, respectively.

Under the condition of sunny, traditional and PV turbines are both working simultaneously. Under the RPS policy, there should be θ percent of all power output from renewable energy, and the traditional generator should purchase the corresponding quantity of green certificates based on its power output. Thus, the operational profit for a traditional generator under the condition of sunny is

$$\pi(q^{T''}) = (a - bq^{T''} - bq^R - v^T)q^{T''} - \theta q^{T''} w$$
$$s.t. \quad \begin{cases} q^{T''} \le x^T & (\vartheta_2) \\ q^{T''} \ge 0 & (\mu_2) \end{cases} \tag{4}$$

where ϑ_2 and μ_2 are the dual variables of the constraints $q^{T''} \le x^T$ and $q^{T''} \ge 0$, respectively.

Affected by weather conditions, PV turbines only operate under the condition of sunny. Under the RPS policy, a solar power generator can profit from trading in power and green certificates, which is reflected in the first two items for the operational profit of the renewable generator (equation 5). Similarly, the renewable generator also needs to meet the renewable power quota in the government regulation. The third item is renewable power that cannot be traded in the green certificates market. The operational profit of the renewable generator is expressed as follows:

$$\pi(q^R) = (a - bq^{T''} - bq^R - v^R)q^R + q^R w - \theta q^R w$$
$$s.t. \quad \begin{cases} q^R \le x^R & (\vartheta_3) \\ q^R \ge 0 & (\mu_3) \end{cases} \tag{5}$$

where ϑ_3 and μ_3 are the dual variables of the constraints $q^R \le x^R$ and $q^R \ge 0$, respectively.

Stage 1:

In stage 1, the generator's expected net profit is its operational profit minus the investment cost. The model of stage 1 attains the investment capacity to maximize the expected net profit, as affected by the probability of the condition of sunny in a day.

The renewable and traditional generators decide on their optimal investment capacity separately. Their expected net profit functions are

$$\begin{cases} E\{\pi^{Rdc}(x^R)\} = \rho\pi(q^R) - k^R x^R \\ E\{\pi^{Tdc}(x^T)\} = (1-\rho)\pi(q^T) + \rho\pi(q^{T''}) - k^T x^T \end{cases} \tag{6}$$

Using the Lagrange multiplier method, the equilibrium solution of the Cournot game is obtained when the Kuhn-Tucker conditions of the two-stage decision model are satisfied simultaneously. Throughout the equilibrium analysis in the DC scenario, we limit the equilibrium satisfying $0 < q^T \le x^T$; $0 < q^{T''} \le x^T$; $0 < q^R \le x^R$. That is, the traditional and renewable generators are active in equilibrium. Additionally, the equilibrium of the two-stage decision model satisfies one of the three following conditions:

Condition (i) $\vartheta_1 = 0,\ \ \vartheta_2 = 0,\ \ \vartheta_3 > 0;$

Condition (ii) $\vartheta_1 > 0,\ \ \vartheta_2 = 0,\ \ \vartheta_3 > 0;$

Condition (iii) $\vartheta_1 > 0,\ \ \vartheta_2 > 0,\ \ \vartheta_3 > 0.$

In stage 1, the expected net profit of the renewable generator is a monotone decreasing function of x^R. The optimal value of x^R is q^R, that is, $\vartheta_3 > 0$. For this reason, we do not consider the condition of $\vartheta_3 = 0$ corresponding to $q^R < x^R$. When (i) $\vartheta_1 = 0,\ \vartheta_2 = 0,\ \vartheta_3 > 0$, the power output of the generators in stage 2 satisfies $q^T < x^T$, $q^{T''} < x^T$, $q^R = x^R$. In stage 1, the expected net profit of the traditional generator is a monotone decreasing function of x^T. The rational generator is bound to reduce the value of x^T until the investment capacity is equal to the required power output-Condition (ii) or (iii). Condition (ii) indicates that the traditional generator operates at full load under the condition of unsunny and sets an optimal power output lower than the investment capacity under the condition of sunny. Condition (iii) indicates that the traditional generator operates at full load regardless of the weather condition.

The properties of the equilibrium solution in the DC scenario are summarized as follows:

Proposition 1. The equilibrium in the DC scenario satisfied Condition (ii) is

$$\begin{cases} q^{T"1*} = \dfrac{2(a-v^T-\theta w)-[a-v^R-k^R/\rho+(1-\theta)w]}{3b} \\ q^{T1*} = x^{T1*} = \dfrac{a-v^T-k^T/(1-\rho)-\theta w}{2b} \\ q^{R1*} = x^{R1*} = \dfrac{2[a-v^R-k^R/\rho+(1-\theta)w]-(a-v^T-\theta w)}{3b} \end{cases} \tag{7}$$

The equilibrium in the DC scenario satisfied Condition (iii) is

$$\begin{cases} q^{T*} = q^{T"*} = x^{T*} = \dfrac{2(a-v^T-k^T-\theta w)-\rho[a-v^R-k^R/\rho+(1-\theta)w]}{(4-\rho)b} \\ q^{R*} = x^{R*} = \dfrac{2[a-v^R-k^R/\rho+(1-\theta)w]-(a-v^T-k^T-\theta w)}{(4-\rho)b} \end{cases} \tag{8}$$

Proof: In the DC scenario, there are two local equilibrium solutions. If weather permits (ρ probability), the renewable generator will always produce power at full capacity. The traditional generator has two options: producing power at full capacity all the time or producing less than full capacity during sunny hours and producing power at full capacity under the condition of unsunny. The traditional generator's operation decision in stage 2 determines the equilibrium solution. By comparing the expected net profit of the traditional generator in these two options, producing power at full capacity all the time is its optimal solution (see Appendix). Equation (8) is the optimal solution of the DC scenario.

3.2.2 CP scenario

In the CP scenario, the traditional generator cooperates with a renewable generator. Regulated by the RPS policy, the traditional generator cooperates with the renewable generator to fulfill its renewable power quota. As in the supply chain, establishing contracts or agreements between the traditional and renewable generator can realize their share of the net profit. Based on this cooperation, generators' operation and investment problems are formulated in the cooperation game model for the CP scenario.

Stage 2:

Under the condition of unsunny, the traditional generator maintains the operation to satisfy the power demand. The operational profit of the traditional generator in the CP scenario is the same as that in the DC scenario. Accordingly, the operational profit of the generator under the condition of unsunny is

$$\pi(q^T) = (a - bq^T - v^T)q^T - \theta q^T w \\ s.t. \quad \begin{cases} q^T \le x^T & (\vartheta_1) \\ q^T \ge 0 & (\mu_1) \end{cases} \tag{9}$$

Under the condition of sunny, traditional and PV turbines work normally in sunny hours. The operational profit of the two generators is given as follows:

$$\pi(q^{T"}, q^R) = (a - bq^{T"} - bq^R - v^T)q^T - \theta q^{T"} w + (a - bq^{T"} - bq^R - v^R)q^R + q^R w - \theta q^R w \\ s.t. \quad \begin{cases} q^{T"} \le x^T & (\vartheta_2) \\ q^{T"} \ge 0 & (\mu_2) \\ q^R \le x^R & (\vartheta_3) \\ q^R \ge 0 & (\mu_3) \end{cases} \tag{10}$$

Stage 1:

Generator cooperation is conceived, as a whole, to determine the investment capacity for traditional and renewable technology. The expected net profit for the generators in the CS scenario is

$$E\{\pi^{cp}(x^T, x^R)\} = (1-\rho)\pi(q^T) + \rho\pi(q^{T"}, q^R) - k^T x^T - k^R x^R \tag{11}$$

Applying the same evolution method from the DC scenario to solve the two-stage game in the CP scenario, we derived the equilibrium solution when the traditional generator cooperates with the renewable generator. The properties of this equilibrium solution are summarized in Proposition 2.

Proposition 2. Equilibrium does not exist when Condition (i) $\vartheta_1 = 0$, $\vartheta_2 = 0$, $\vartheta_3 > 0$ or Condition (ii) $\vartheta_1 > 0$, $\vartheta_2 = 0$, $\vartheta_3 > 0$ holds. The equilibrium solution of the CP scenario satisfied Condition (iii) $\vartheta_1 > 0$, $\vartheta_2 > 0$, $\vartheta_3 > 0$ is

$$\begin{cases} q^{T**} = q^{T'**} = x^{T**} = \dfrac{(a - v^T - k^T - \theta w) - \rho[a - v^R - k^R / \rho + (1-\theta)w]}{2(1-\rho)b} \\ q^{R**} = x^{R**} = \dfrac{[w - v^R - k^R / \rho] + (v^T + k^T)}{2(1-\rho)b} \end{cases} \tag{12}$$

Proof: The infeasibility of Condition (i) in the CP scenario is identical to that under Condition (i) in the DC scenario. The equilibrium does not exist when Condition (ii) holds, and there is a unique equilibrium solution for the CP scenario when Condition (iii) holds (see Appendix).

When traditional and renewable generators cooperate to fulfill their policy target under the RPS policy, operating at full capacity is their optimal solution in stage 2. Because of the two generators' cooperation, their object functions become one. Then, an optimal solution is achieved by solving the Kuhn-Tucker conditions corresponding to the model of the CP scenario. Under the interior optimal solution in this scenario, ceteris paribus, an increase of θ results in no change in the optimal investment capacity of the renewable generator but a decrease in the optimal investment capacity of the traditional generator.

3.2.3 CS scenario

Under the RPS policy, a large public or private generator can choose to invest in both the traditional and the PV technologies simultaneously to reduce the green certificates trading. This section considers the CS scenario in which the generator simultaneously invests in both technologies in terms of the renewable power quota. As the generator’s operation and investment decision is a two-stage process, the determination in stage 1 directly influences the power output in stage 2. Affected by the RPS policy and weather conditions, the power and green certificates trading are also limited by the determination of investment capacity in stage 1. A portfolio investment model for this scenario is formulated to capture the features of the generator's investment behavior. Although the model of stage 2 is the same as that in the CP scenario, the generator's optimal investment capacity is additionally subject to an equation of the renewable power quota in stage 1. The detailed target expressions of the portfolio investment model for the CS scenario are shown as follows:

Stage 2:

Under the condition of unsunny, the operational profit of the generator investing in both technologies is

$$\pi(q^T) = (a - bq^T - v^T)q^T - \theta q^T w$$
$$s.t. \quad \begin{cases} q^T \le x^T & (\vartheta_1) \\ q^T \ge 0 & (\mu_1) \end{cases} \tag{13}$$

Under the condition of sunny, the operational profit of the generator investing in both technologies is

$$\pi(q^{T"}, q^R) = (a - bq^{T"} - bq^R - v^T)q^{T"} - \theta q^{T"} w + (a - bq^{T"} - bq^R - v^R)q^R + q^R w - \theta q^R w$$
$$s.t. \begin{cases} q^{T"} \le x^T & (\vartheta_2) \\ q^{T"} \ge 0 & (\mu_2) \\ q^R \le x^R & (\vartheta_3) \\ q^R \ge 0 & (\mu_3) \end{cases}$$

(14)

Stage 1:

To reduce green certificates trading, the generator invests in the traditional and the PV technologies in terms of the renewable power quota in stage 1. The expected net profit from investing in both technologies (same as the CP scenario) is represented as an objective function. The investment capacity for the traditional and the PV technologies is designated as a constraint in terms of the renewable power quota. Thus, the portfolio investment model for the CS scenario in stage 1 is

$$E\{\pi^{cs}(x^T, x^R)\} = (1-\rho)\pi(q^T) + \rho\pi(q^{T''}, q^R) - k^T x^T - k^R x^R$$
$$s.t. \quad \theta(x^T + \rho x^R) = \rho x^R \quad (\vartheta_2) \tag{15}$$

Investing in both technologies described by Milstein and Tishler (2015) is the cooperation in the CP scenario [28]. In the CS scenario, the generator's investment behavior considers the renewable energy quota in stage 1. The constraint of equation (15) indicates that the power capacity is invested in terms of the renewable power quota. Considering the power output affected by weather conditions, ρx^R represents the average accessible investment capacity for the PV technology.

The equilibrium of the CS scenario must also satisfy one of the three possible conditions: Condition (i), Condition (ii) and Condition (iii). When Condition (i) or (ii) holds, there are no equilibrium solutions. When Condition (iii) holds, we get Proposition 3 which is the equilibrium of the CS scenario by using the Lagrange multiplier method.

Proposition 3. There exists a unique equilibrium solution of the portfolio investment model for the CS scenario. The equilibrium solution is

$$\begin{cases} q^{T***} = q^{T''***} = x^{T***} = \dfrac{\rho(1-\theta)\{(1-\theta)(a-v^T-k^T)+\theta[a-v^R-k^R/\rho]\}}{2b(\rho+\theta^2-\rho\theta^2)} \\ q^{R***} = x^{R***} = \dfrac{\theta\{(1-\theta)(a-v^T-k^T)+\theta[a-v^R-k^R/\rho]\}}{2b(\rho+\theta^2-\rho\theta^2)} \end{cases} \tag{16}$$

The proof of Proposition 3 is the same as that of Proposition 2, so we omit it.

The power output at equilibrium state is equal to the investment capacity, which is unaffected by w. The green certificate price does not threaten the generator in the CS scenario. The generator can effectively ignore the potential price risks in the green certificates market, so the regulatory agency does not work by adding this market.

Comprehensively, if the equilibriums of the DC, the CP, and the CS scenarios exist and are unique, we obtain $q^T = q^{T''} = x^T; q^R = x^R$. The power market reaches equilibrium under the RPS policy when generators operate at full capacity. Otherwise, the market should be considered to deviate from the equilibrium.

3.3 Comparative study of the three scenarios

In this section, the generator's expected net profits under the DC, the CP, and the CS scenarios will be compared. In the DC scenario, the generator only invests in one technology and decides its investment capacity based on its expected net profit. Compared to the CS scenario, the sum expected net profit of traditional and renewable generators for the DC and the CP scenarios is conceived as a whole. The power generator can obtain the optimal profit with the power output and the investment capacity satisfied Condition (iii). Set $A = a - v^T - k^T - \theta w$, $B = a - v^R - k^R / \rho + (1-\theta)w$, $C = \rho + \theta^2 - \rho\theta^2$, and $D = \rho + \theta^2 + \rho\theta^2 - 2\rho\theta$, the comparative results of this research are listed as follows.

Lemma 1 For a given RPS policy, the expected net profit in the CP scenario is higher than that in the DC scenario: $E\{\pi^{cp}(x^{T**}, x^{R**})\} - E\{\pi^{dc}\} > 0$.

Proof: Substitute equilibrium solution (8) into expected net profit function (6), the sum expected net profit of the DC scenario is

$$E\{\pi^{dc}\} = E\{\pi^{Tdc}(x^{T*})\} + E\{\pi^{Rdc}(x^{R*})\} = \rho b[\frac{2B-A}{(4-\rho)b}]^2 + b[\frac{2A-\rho B}{(4-\rho)b}]^2 \quad (17)$$

Substitute equilibrium solution (12) into expected net profit function (11), the expected net profit of the CP scenario is

$$E\{\pi^{cp}(x^{T**}, x^{R**})\} = \frac{A^2 - 2\rho AB + \rho B^2}{4(1-\rho)b} \quad (18)$$

Subtracting equation (17) from equation (18), we get

$$E\{\pi^{cp}(x^{T**}, x^{R**})\} - E\{\pi^{dc}\} = \frac{(4\rho + 5\rho^2)A^2 - (8\rho + \rho^2)(2\rho AB) + (4\rho + 5\rho^2)\rho B^2}{4b(1-\rho)(4-\rho)^2} \quad (19)$$

On the right side of equation (19), the numerator can be seen as a quadratic function of A, where $\Delta = 4\rho^3 B^2(\rho-1)(\rho-4)^2 < 0$. Given $0 < \rho < 1$, $(4\rho + 5\rho^2) > 0$ and $(4\rho + 5\rho^2)A^2 - (8\rho + \rho^2)(2\rho AB) + (4\rho + 5\rho^2)\rho B^2 > 0$ always hold. Then $E\{\pi^{cp}(x^{T**}, x^{R**})\} - E\{\pi^{dc}\} > 0$, Lemma 1 is proved.

Lemma 2 For a given RPS policy, the expected net profit in the CP scenario is higher than that in the CS scenario: $E\{\pi^{cs}(x^{T***}, x^{R***})\} < E\{\pi^{cp}(x^{T**}, x^{R**})\}$.

Proof: Substitute equilibrium solution (16) into expected net profit function (15) in the CS scenario, the expected net profit of the generator is

$$E\{\pi^{cs}(x^{T***}, x^{R***})\} = \frac{\rho[(1-\theta)A + \theta B]^2}{4bC} \tag{20}$$

Subtracting equation (18) from equation (20), we get

$$E\{\pi^{cs}(x^{T***}, x^{R***})\} - E\{\pi^{cp}(x^{T**}, x^{R**})\} = \frac{-[(\rho + \theta - \rho\theta)A - \rho B]^2}{4b(1-\rho)C} \tag{21}$$

When $0 < \rho < 1$, $E\{\pi^{cs}(x^{T***}, x^{R***})\} - E\{\pi^{cp}(x^{T**}, x^{R**})\} < 0$ holds. The CP scenario brings more profit than the CS scenario.

Lemma 3 For a given RPS policy, the CS scenario does not always provide more gains than the DC scenario.

Proof: Subtracting equation (17) from equation (20), we get

$$E\{\pi^{cs}(x^{T***}, x^{R***})\} - E\{\pi^{dc}\} = \frac{[\rho(4-\rho)^2(1-\theta)^2 - 4(\rho+4)C]A^2 + 2\rho AB[\theta(1-\theta)(4-\rho)^2 + 16C] + [(4-\rho)^2\theta^2 - 4(\rho+4)C]\rho B^2}{4b(4-\rho)^2 C} \tag{22}$$

Take the numerator of the right side of equation (22) as a quadratic function of *B*. Given $0 < \rho < 1$, the quadratic coefficient is $(4-\rho)^2\theta^2 - 4(\rho+4)C < 0$. The quadratic function of *B* is a parabola pointing downward. Based on $\Delta = 16\rho^2 A^2 (4-\rho)^2 C(\theta^2 + \rho(\theta-1)^2) > 0$, the profitable scenario is hard to determine.

When $\frac{\theta(1-\theta)(4-\rho)^2+16C-2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A < B < \frac{\theta(1-\theta)(4-\rho)^2+16C+2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$, $E\{\pi^{cs}(x^{T**},x^{R**})\} > E\{\pi^{dc}\}$; When $B < \frac{\theta(1-\theta)(4-\rho)^2+16C-2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$ or $B > \frac{\theta(1-\theta)(4-\rho)^2+16C+2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$, $E\{\pi^{cs}(x^{T**},x^{R**})\} < E\{\pi^{dc}\}$. The size of $E\{\pi^{cs}(x^{T**},x^{R**})\}$ and $E\{\pi^{dc}\}$ is uncertain and depends on the values of the relevant parameters.

As a corollary of the abovementioned lemmas, we can conclude that the comparison result of expected net profits during these three scenarios, and we refer to the following proposition.

Proposition 4 For a given RPS policy, the expected net profit in the CP scenario is higher than that in the CS scenario which is higher than that in the DC scenario: $E\{\pi^{cp}(x^{T**},x^{R**})\} > E\{\pi^{cs}(x^{T***},x^{R***})\} > E\{\pi^{dc}\}$, when $\frac{\theta(1-\theta)(4-\rho)^2+16C-2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A < B < \frac{\theta(1-\theta)(4-\rho)^2+16C+2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$; And the expected net profit in the CP scenario is higher than that in the DC scenario which is higher than that in the CS scenario: $E\{\pi^{cp}(x^{T**},x^{R**})\} > E\{\pi^{dc}\} > E\{\pi^{cs}(x^{T***},x^{R***})\}$, when $B < \frac{\theta(1-\theta)(4-\rho)^2+16C-2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$ or $B > \frac{\theta(1-\theta)(4-\rho)^2+16C+2(4-\rho)\sqrt{CD}}{4(\rho+4)C-(4-\rho)^2\theta^2}A$.

Among the three kinds of investment behaviors, the CP scenario makes more profit than the DC or the CS scenario. The traditional generator should do its best to facilitate cooperation with the renewable generator. However, when the generator does not want to cooperate or it is difficult to find a partner, the generator can invest in both technologies based on the cooperation equilibrium. Otherwise, profits from investment in both technologies to satisfy the quota requirements may be lower than investment in only one technology.

4. Numerical experiment

The research on the generator investment behaviors in this study is based on a linear demand function for power generation. The estimation of parameters (i.e. *a* and *b*) is the premise of the computation of investment capacity. First, we give the power demand function the following parameter values: *a*=980, *b*=0.8. The traditional technology and renewable technologies we researched in this study are coal-fired technology and PV technology. The cost data are reported from US Energy Information Administration for electric generating facilities entering service in 2023. According to the levelized cost of electricity, the levelized capital cost is the capacity cost, while the operation cost includes the levelized fixed and variable operation and maintenance costs and the transmission costs. The cost parameters are estimated as $v^T = 48.32$, $k^T = 50.2$, $v^R = 47.8$ and $k^R = 12.3$. For parameters of the RPS policy, it is assumed that the mandatory renewable power quota θ is 15%, and the price of the green certificate for solar power is 10 $/MWh (international rate). We set $\rho = 0.6$ based on the evidence that, in North Jiangsu Province, the probability of sunny days in a year is about 0.6. During these days, the sun appears fully or partially in the daytime, otherwise, it does not appear at all. These estimated parameter values are used in the later experiment without a special request.

Figs. 1 and 2 present the variation in investment capacity and expected net profit as functions of ρ in the three scenarios (DC, CP, and CS). The probability ρ represents the number of sunny days in a year in a certain area. The corresponding regions for different weather conditions are marked with varying values of ρ. Although the PV technology reaches grid parity, the existence of ρ results in raising the investment cost of the PV technology. Additionally, the profit from solar resources is increasing with $\rho = [0.6,\ 0.85]$. It can be seen from Fig. 1 that, in the DC and the CP scenarios, the increase of ρ causes a significant decrease and a modest increase in the investment capacity for traditional technology and PV technology, respectively. Fig. 2 shows that the generators' expected net profit in the CP scenario is more than that in the CS scenario which is more than that in the DC scenario with different solar resources.

Table 1 and Fig. 3 present the generators' investment capacity and expected net profit as functions of θ in the three scenarios. In China, the initial renewable power quota is set to 15%. The quota will be large along with the development of the renewable energy industry. The renewable power quota is on the rise when $\theta = [0.15,\ \ 0.45]$. In the DC scenario, the traditional and renewable generators will reduce their investment capacity with increases in the renewable power quota. In the CP scenario, the investment capacity for traditional technology will also decrease, but the investment capacity for PV technology will not be affected. In the CS scenario, the investment capacity is more sensitive to the renewable power quota, which brings a significant increase and decrease in the investment capacity for PV technology and traditional technology, respectively. Fig. 3 shows that, when $\theta = [0.15,\ \ 0.45]$, the generators' expected net profit in the CP scenario is more than that in the CS scenario which is more than that in the DC scenario. The generator's expected net profit in the CS scenario is very sensitive to any changes in the renewable power quota. The fall in the expected net profit is substantial along with the increase in the renewable power quota.

Table 2 and Fig. 4 present the generators' investment capacity and expected net profit as functions of w in the three scenarios. The green certificate price changes from the international rate to a higher level (a reasonable price of green certificates within this range) when $w = [10,\ \ 45]$. Fig. 4 shows that the CP scenario is sensitive to changes in the green certificate price. The increase in the green certificate price causes a marked decrease and increase in the investment capacity for traditional technology and PV technology, respectively. In the CS scenario, green certificates trading becomes an internal transaction as the generator considers the renewable power quota during the process of investing in both technologies. The investment capacity for PV and traditional technology is not affected by the green certificate price. As shown in Fig. 4, the expected net profit for the generator in the CP scenario is larger than that in the CS scenario which is more than that in the DC scenario, along with the changes in the green certificate price. In addition, the expected net profit in the CS scenario is constant as the green certificate price changes.

Comprehensively, Figs. 2, 3, and 4 show that the CP scenario makes the most expected net profit, followed by the CS scenario and the DC scenario makes the least expected net profit. In the CP scenario, generator cooperation allows the investment capacity for PV technology to bypass the regulation of the renewable power quota under the RPS policy. In the CS scenario, the generator internalizes the green certificates trading by considering the renewable power quota during the process of investing in both technologies. The investment capacity for the traditional and the PV technologies is thus irrelevant to the price of the green certificate, which helps the generator avoid price risks from the green certificates trading market. However, the investment capacity and expected net profit in the CS scenario are very sensitive to changes in the renewable power quota. In particular, the generator's expected net profit in the CS scenario obviously falls along with the increase in the renewable power quota. Compared with the CP scenario, the generator investing in both technologies in the CS scenario sacrifices profits to avoid the price risk in green certificates trading. The higher the renewable power quota regulated; the more profit will disappear.

5. Conclusion

This study analyzed the impact of investment behaviors on capacity expansion with the RPS policy. Under the RPS policy, we developed a two-stage decision model to explore the capacity investment and operation affected by the investment behaviors of generators. Based on the generators' investment behaviors, we establish the game structures of the DC, the CP, and the CS scenarios and discuss the equilibrium solution and profit under the three scenarios. In this study, there are some findings are summarized as follows:

(1) Based on the analytical solutions, we found that the CP scenario is the most profitable among the three scenarios. (2) Based on the numerical solutions, we found that the profit ranking of the three scenarios is the CP> the CS> the DC. (3) The investment capacity for the PV technology is unaffected by the renewable power quota in the CP scenario. (4) The investment capacity for the traditional and PV technologies is unaffected by the green certificate price in the CS scenario.

The limitation of our paper is that the traditional and the PV technologies were discussed only. As a result, the transaction details (i.e. the suppliers and purchasers of green certificates) will not be fully identified. Future study will look at integrating a trading platform into the power market to help the generators in the trading of green certificates under the RPS policy.

Acknowledgments

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Tables and figures：

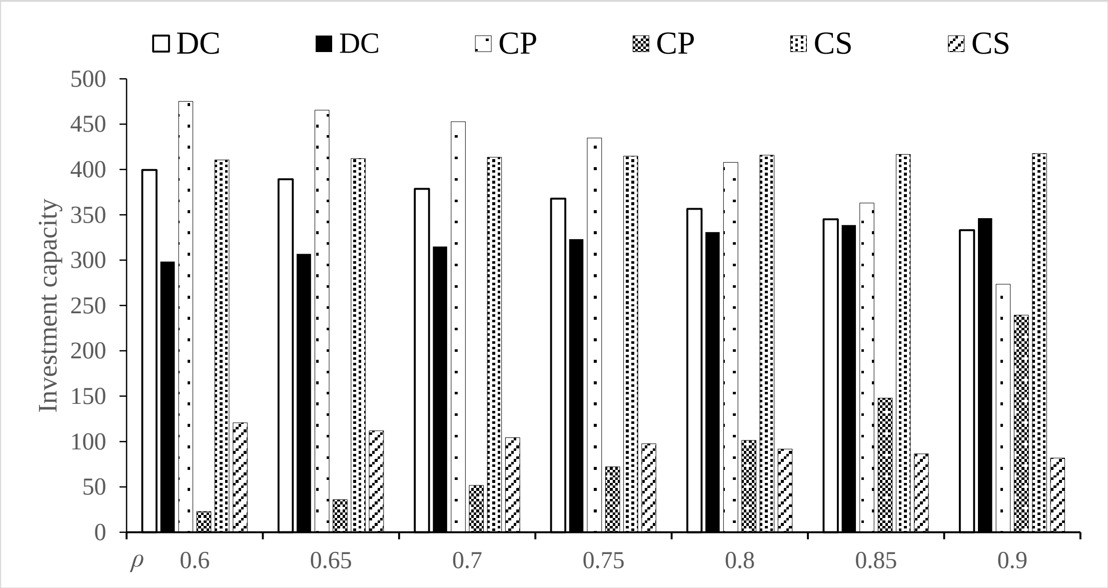

Fig. 1 Investment capacity as the function of ρ

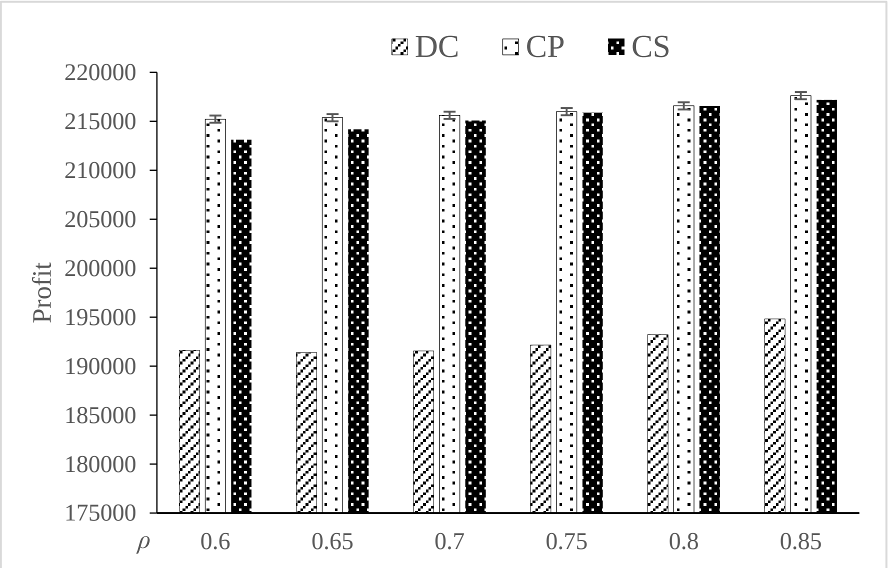

Fig. 2 Profit comparison with the change in ρ

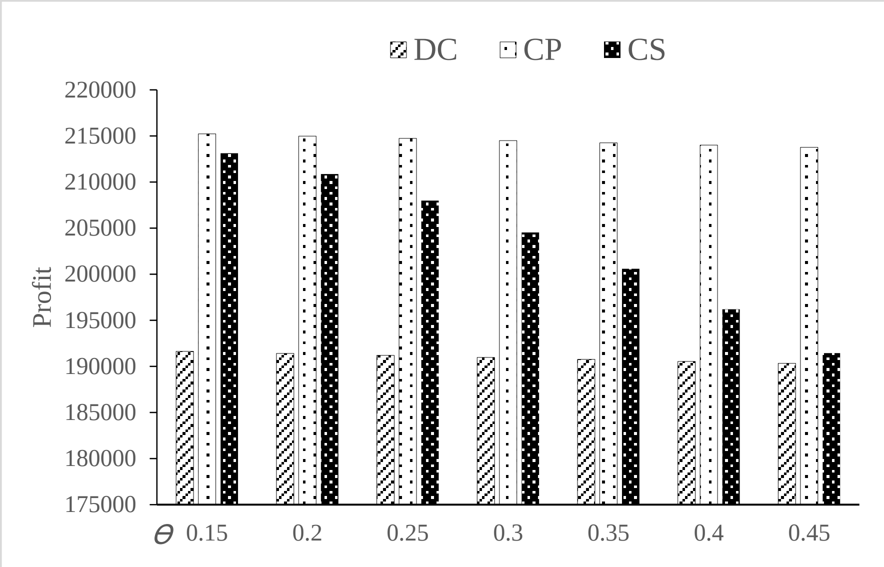

Fig. 3 Profit comparison with the change of θ

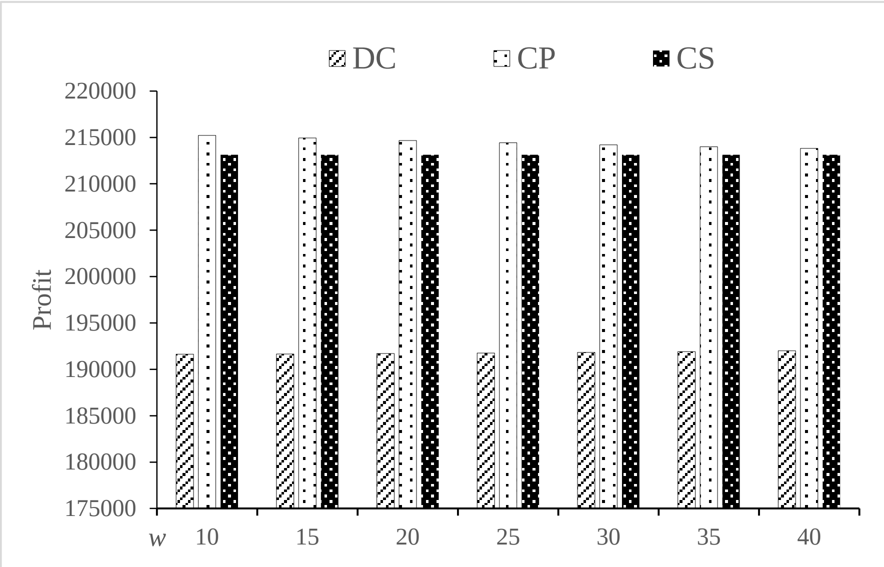

Fig. 4 Profit comparison with the change of w

Table 1 Investment capacity as the function of θ

θ	DC		CP		CS	
	Coal	PV	Coal	PV	Coal	PV
0.15	399.373	298.388	475.111	22.963	410.568	120.755
0.2	399.144	298.224	474.833	22.963	382.167	159.236
0.25	398.915	298.061	474.556	22.963	353.253	196.252
0.3	398.686	297.898	474.278	22.963	324.121	231.515
0.35	398.458	297.734	474.000	22.963	295.049	264.788
0.4	398.229	297.571	473.722	22.963	266.299	295.888
0.45	398.000	297.407	473.444	22.963	238.102	324.684

Table 2 Investment capacity as the function of w

w	DC		CP		CS	
	Coal	PV	Coal	PV	Coal	PV
10	399.373	298.388	475.111	22.963	410.568	120.755
15	398.049	301.411	470.528	29.907	410.568	120.755
20	396.725	304.434	465.944	36.852	410.568	120.755
25	395.402	307.456	461.361	43.796	410.568	120.755
30	394.078	310.479	456.778	50.741	410.568	120.755
35	392.755	313.502	452.194	57.685	410.568	120.755
40	391.431	316.525	447.611	64.630	410.568	120.755

Appendix

1. The equilibrium solution of the DC scenario

Under the condition of unsunny, the expected net profit of the traditional generator is

$$E\left\{\pi^{Tdc}\left(q^{T''} < x^T\right)\right\} = b\left(1-\rho\right)(x^{T1*})^2 + \rho b(q^{T''1*})^2 = \frac{\left[\left(1-\rho\right)A - \rho k^T\right]^2}{4\left(1-\rho\right)b} + \rho\frac{\left[2\left(A+k^T\right)-B\right]^2}{9b}$$

(A.1)

$$E\{\pi^{Tdc}(q^{T''} = x^T)\} = b\left[x^{T*}\right]^2 = \frac{\left(2A-\rho B\right)^2}{b\left(4-\rho\right)^2} \qquad \text{(A.2)}$$

Subtract (A.1) from (A.2), we get

$$E\{\pi^{Tdc}\left(q^{T''} = x^T\right)\} - E\{\pi^{Tdc}\left(q^{T''} < x^T\right)\}$$
$$= \frac{1}{b}\left\{\frac{36\left(1-\rho\right)\left[4A^2 - 4\rho AB + \rho^2 B^2\right] - 9\left(4-\rho\right)^2\left[A-\rho\left(A+k^T\right)\right]^2 - 4\rho\left(1-\rho\right)\left(4-\rho\right)^2\left[4\left(A+k^T\right)^2 - 4\left(A+k^T\right)B + B^2\right]}{36\left(1-\rho\right)\left(4-\rho\right)^2}\right\} \qquad \text{(A.3)}$$

Equation (A.3) can be simplified to a quadratic function of B , then

$$E\{\pi^{Tdc}\left(q^{T''} = x^T\right)\} - E\{\pi^{Tdc}\left(q^{T''} < x^T\right)\}$$
$$= \frac{1}{b}\left\{\frac{-4\rho\left(1-\rho\right)^2\left(16-\rho\right)B^2 + 16\rho\left(1-\rho\right)\left[\left(4-\rho\right)^2\left(A+k^T\right) - 9A\right]B + 144\left(1-\rho\right)A^2 - 9\left(4-\rho\right)^2\left[A-\rho\left(A+k^T\right)\right]^2 - 16\rho\left(1-\rho\right)\left(4-\rho\right)^2\left(A+k^T\right)^2}{36\left(1-\rho\right)\left(4-\rho\right)^2}\right\}$$

(A.4)

The coefficient of quadratic term $-4\rho\left(1-\rho\right)^2\left(16-\rho\right)$ of the equation (A.4) is less than 0, given $0<\rho<1$. It's a parabola pointing downwards. Base on $\Delta = 144\rho^2\left(1-\rho\right)^2\left(4-\rho\right)^2\left[A-\rho\left(A+k^T\right)\right]^2 > 0$, the range of B causes a difference in the size of $E\left\{\pi^{Tdc}\left(q^{T''}=x^{T}\right)\right\}$ and $E\left\{\pi^{Tdc}\left(q^{T''}<x^{T}\right)\right\}$. Let B_1, B_2 be the solutions of the quadratic function of B, where $B_1=\frac{(4-\rho)\left(A+k^{T}\right)-3A}{2(1-\rho)}$, $B_2=\frac{(1-\rho)(40-7\rho)A+(4-\rho)(16-7\rho)k^{T}}{2(16-\rho)(1-\rho)}$.

Due to $q^{T''}\le x^{T}$, $(4-\rho)k^{T}\le(1-\rho)(2B-A)$ holds. Substitute the inequality into B_1, $B_1\le B$ holds. Especially, when $(4-\rho)k^{T}=(1-\rho)(2B-A)$, $B_1=B$.

When $\vartheta_1>0,\ \vartheta_2=0,\ \vartheta_3>0$, $q^{T''}-x^{R}=v^{R}+k^{R}/\rho-w-v^{T}$. In terms of the connection to the grid at an equal price of solar power, $v^{R}+k^{R}/\rho\approx v^{T}+k^{T}$. And in practice, the traditional power will not be immediately replaced by solar power. Thus, $w<k^{T}$. i.e. $q^{T''}-x^{R}>0$. From this, it can be concluded that $A+k^{T}>B$. Substitute this conclusion to B_2-B, it will be known to all that $B_2>B$.

Comprehensively, we get $B_1<B<B_2$, the $E\left\{\pi^{Tdc}\left(q^{T''}=x^{T}\right)\right\}>E\left\{\pi^{Tdc}\left(q^{T''}<x^{T}\right)\right\}$ holds. The traditional generator operates at full load when the sun is shining and there is no sun.

2. The solution infeasibility of Condition (ii) in the CP scenario

The Condition (ii) $\vartheta_1>0,\ \vartheta_2=0,\ \vartheta_3>0$ corresponds to $q^{T}=x^{T},\ q^{T''}<x^{T},\ q^{R}=x^{R}$.

Formulating the Lagrange function of formula (10), we get

$$\begin{cases} L\left(q^{T''},q^{R}\right)=\left(a-bq^{T}-bq^{R}-v^{T}\right)q^{T''}-\theta wq^{T''}+\left(a-bq^{T}-bq^{R}-v^{R}\right)q^{R} \\ \qquad +(1-\theta)wq^{R}+\vartheta_2\left(x^{T}-q^{T''}\right)+\vartheta_3\left(x^{R}-q^{R}\right) \\ \frac{\partial L}{\partial q^{T'}}=a-2bq^{T''}-2bq^{R}-v^{T}-\theta w-\vartheta_2=0 \\ \frac{\partial L}{\partial q^{R}}=a-2bq^{T''}-2bq^{R}-v^{R}+(1-\theta)w-\vartheta_3=0 \end{cases} \tag{A.5}$$

As $\vartheta_2=0,\ \vartheta_3>0$, we get $q^{T''}=\frac{a-2bq^{R}-v^{T}-\theta w}{2b}$;

$q^R = \dfrac{a - 2bq^{T''} - v^R + (1-\theta)w - \vartheta_3}{2b}$. Take $q^R = x^R$ into the expected net profit function in stage 1, we get $\vartheta_3 = k^R / \rho$. $q^{T''}$, q^R can not satisfy the last two equations of (A.5). There is no equilibrium solutions satisfied Condition (ii) in the CP scenario.

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