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Assessing the Effects of Tradable Green Certificates and Renewable Portfolio Standards through Demand-Side Decision-Making Simulation: A Case of a System Containing Photovoltaic Power

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Abstract: Understanding the effect of a tradable green certificate (TGC) and renewable portfolio standard (RPS) policy mix is of great importance for sustainable renewable-energy development and carbon neutrality, given that the demand side subjects are the responsible subjects under China's RPSs and studies from the demand-side perspective are relatively limited. To fill this gap, this paper analyzes the coupled relationship between the TGC market and the electricity market as well as the reflexivity of the TGC market. Meanwhile, on the basis of modeling TGC prices and renewable-energy uncertainty, this paper constructs a Markov decision process (MDP) model to simulate the sequential decision-making process of the demand side and further proposes a solution model based on dynamic programming and evolutionary algorithms. The results show that: (1) In addition to policy parameters such as RPS weight, TGC price caps and penalties, a preference for short-term benefits and renewable-energy uncertainty also affect transaction behaviors on the demand side. (2) Increasing RPS weight within an appropriate range can stimulate demand for renewable power and TGC, while excessively low RPS weight will result in accumulation of unsold TGC. In addition, the preference for short-term benefits can stimulate demand for renewable power and curb demand for TGC. (3) An increase in the TGC price cap can stimulate demand for renewable power and restrain demand for TGC, but this phenomenon may not exist when RPS weight is too low or responsible subjects prefer short-term benefits. (4) Setting a penalty of no less than the TGC price cap is of great significance to ensure the operation of the TGC market and RPSs.

Keywords: renewable-energy policy; tradable green certificates; renewable portfolio standard; reflexivity; decision-making; sustainable development

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1. Introduction

1.1. Background

As one of the largest energy producers and consumers, China has a strong dependence on fossil fuels; coal consumption accounts for 56.8% of the total primary energy consumption, and the power industry accounts for nearly 40% of China's total carbon emissions [1]. Therefore, increasing the proportion of renewable energy has become the key to achieving carbon neutrality and China's green transformation.

To promote development of renewable energy and accelerate the green transformation process, since the 2010s, the Chinese government has implemented a series of policies [2–6], as shown in Table 1.

Since 2011, under the implementation of financial subsidies and full guaranteed acquisition, renewable energy has witnessed rapid development in China [7], as shown in Figure 1. However, the reliance of renewable-energy development on preferential policies has put great pressure on state finances.

Table 1. Relevant policies issued by China.

Time	Policy Name	Relevant Content
November 2011	Interim Measures for the Administration of Collection and Use of Renewable Energy Development Funds	Promotes renewable-energy development and reduces the price difference between renewable power and thermal power through national financial subsidies.
May 2016	Notice on Full Guaranteed Acquisition of Wind Power and Photovoltaic Power Generation	States that grid companies shall purchase wind and photovoltaic power in full, and subsidies should be paid to renewable-energy manufacturers.
February 2017	Notice on Trial Implementation of Green Certificates and Voluntary Subscription System	States that TGCs can be issued for each megawatt–hour of renewable on-grid power. TGCs can be sold for profit.
March 2018	Renewable Power Quota and Assessment Method	States that RPSs will be implemented in China and TGCs can be used to complete the RPS target.
May 2019	Notice on Establishing and Improving the Renewable Power Consumption Guarantee Mechanism	States that the demand side is the responsible subjects of the RPSs, and the RPS target is calculated by multiplying the annual power consumption and a government-specified weight.

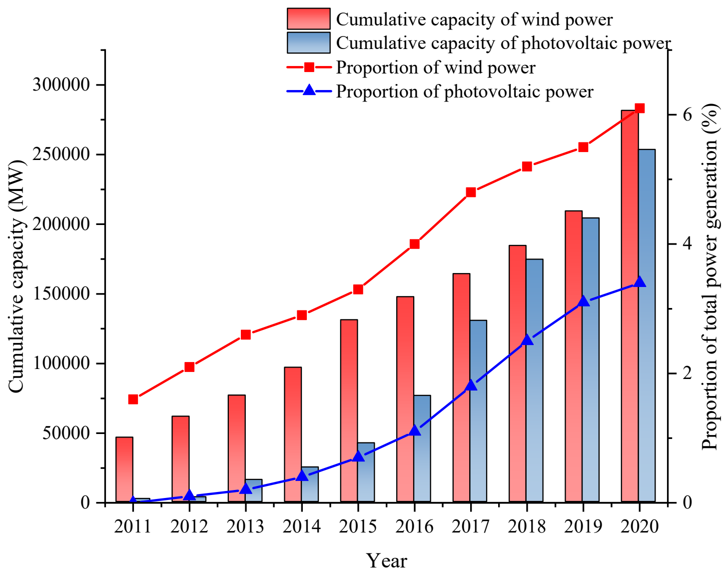


Figure 1. Trends of renewable-power development in China from 2011 to 2020.

In 2017, to ensure sustainable development of renewable energy and ease financial pressure, China introduced TGC issuing and a voluntary subscription policy. However, due to the lack of mandatory constraints and assessment mechanisms, the scale of TGC transactions is very limited.

From 2018 to 2019, China issued the Renewable Power Consumption Guarantee Mechanism after three revisions, marking the implementation of RPSs in China. The policy states that the responsible subject is made up of demand side subjects and needs to complete the RPS target; meanwhile, as with purchasing renewable power, purchasing of TGCs can be used to complete the RPS target. To sum up, a "TGC transaction + RPS assessment" policy mix has been formed.

Since the cost of renewable power will still be higher than that of thermal power [8], transactions of TGCs are expected to be a solution that alleviates the financial pressure and operation pressure of renewable manufacturers. In this context, research on the effects of the "TGC + RPS" policy can provide suggestions for the government to improve relevant policies and the subjects of this responsibility to complete the RPS target.

This paper is organized as follows: Section 1.2 expounds the relevant research achievements in recent years and summarizes the contributions of this paper. Section 2 analyzes the characteristics of China's TGC market, discusses the reflexivity of the TGC market and gives research assumptions. In Section 3, a sequential decision-making model considering reflexivity is constructed and a solution is elaborated. In Section 4, simulation results are discussed. Section 5 presents the main conclusions and policy implications.

1.2. Literature Review

At present, studies on "TGC + RPS" mainly include three aspects:

(1) The impact on the supply side. Marchenko et al. [9] and Qu et al. [10] pointed out that TGC transactions can increase the profits of renewable-energy manufacturers, thereby promoting generation of renewable energy. As an important way to make up for the gap in subsidies, TGC transactions provide additional funds for renewable energy, which can promote the green transformation of the power-supply side [11,12]. In addition, Song et al. [13] and Zhang et al. [14] applied system dynamics (SDs) and pointed out that TGC transactions can promote investment in the renewable-energy industry, thereby improving the structural proportion of renewable energy on the supply side. Similarly, Zhao et al. [15] constructed an evolutionary-game model and proposed that TGC transactions could promote renewable-energy development in the long term.

(2) The impact on power dispatching and transactions. Considering the environmental value of TGCs, Liang et al. [16], Yuan et al. [17] and Li et al. [18] pointed out that the TGC + RPS policy can reduce the amount of discarded photovoltaic power. In addition, the coupled interaction between TGCs and the power market has a significant impact on the behavior of power producers [19,20]. For example, Wang et al. [21] constructed a decision-optimization model considering subjects' preferences and utility, and the results showed that TGC price is an important factor affecting the profitability of energy manufacturers.

(3) Exploration of TGC price mechanisms. A reasonable price mechanism can support the development of the TGC market, RPSs and the renewable-energy industry [22,23]. For example, Tu et al. [24] proposed that setting the unit price of TGCs between 84.57 CNY and 330.28 CNY could reduce investment risk and promote development of photovoltaic power. Zhao et al. [25] pointed out that under the voluntary subscription mechanism, the impact of factors such as assessment period, the discount rate and subsidies should be considered when setting TGC prices.

According to the above, there is still room for further in-depth research:

(1) The existing research focuses on the effect of the "TGC + RPS" policy on supply-side subjects from a long-term perspective. According to China's RPS, demand-side subjects are the subjects of responsibility, subjects' decision-making behaviors and market performance are affected by changes in supply and demand in a short period (the one-year assessment period) and relevant research is limited.

(2) Current research on the relationship between the TGC market, power dispatching and power trading usually regards the TGC market as an external static boundary, and few studies have considered the impact of power transactions on TGC market performance.

(3) Most existing studies design the TGC price mechanism from a static perspective, ignoring the causal feedback relationship among responsible subjects' decision-making behaviors, TGCs and the electricity market.

Compared with previous studies, the contributions in this paper can be summarized as follows:

(1) In terms of research perspective, this paper focuses on the demand side and reveals the causal feedback relationship between the demand side and TGC market performance, namely, reflexivity. This expands the perspective from research objects and theory.

(2) In terms of research content, on the basis of analyzing factors affecting China's TGC market performance, this paper casts demand-side responsible subjects' decision-making behaviors as a sequential decision-making process and analyzes the influences of RPS weight, the TGC price cap, penalties and discount factors on responsible

subjects' behaviors. These make up for the shortcomings of previous studies in demand-side behavior analysis and dynamic TGC-price evolution.

(3) In terms of research methods, an MDP model was constructed to simulate the sequential decision-making of responsible subjects, and the Gaussian mixture model was used to deal with renewable-energy uncertainty. Through applying dynamic programming (DP) and evolutionary algorithms (EAs) to solve the MDP model, this paper discusses the decision-making trends of responsible subjects, thus providing a reference for relevant policy improvement.

2. The TGC Market under RPSs and Research Assumptions

2.1. China's TGC Market

Considering the background, the "TGC transaction + RPS assessment" policy mix will promote the interaction between the TGC market and the electricity market [5,6], as shown in Figure 2.

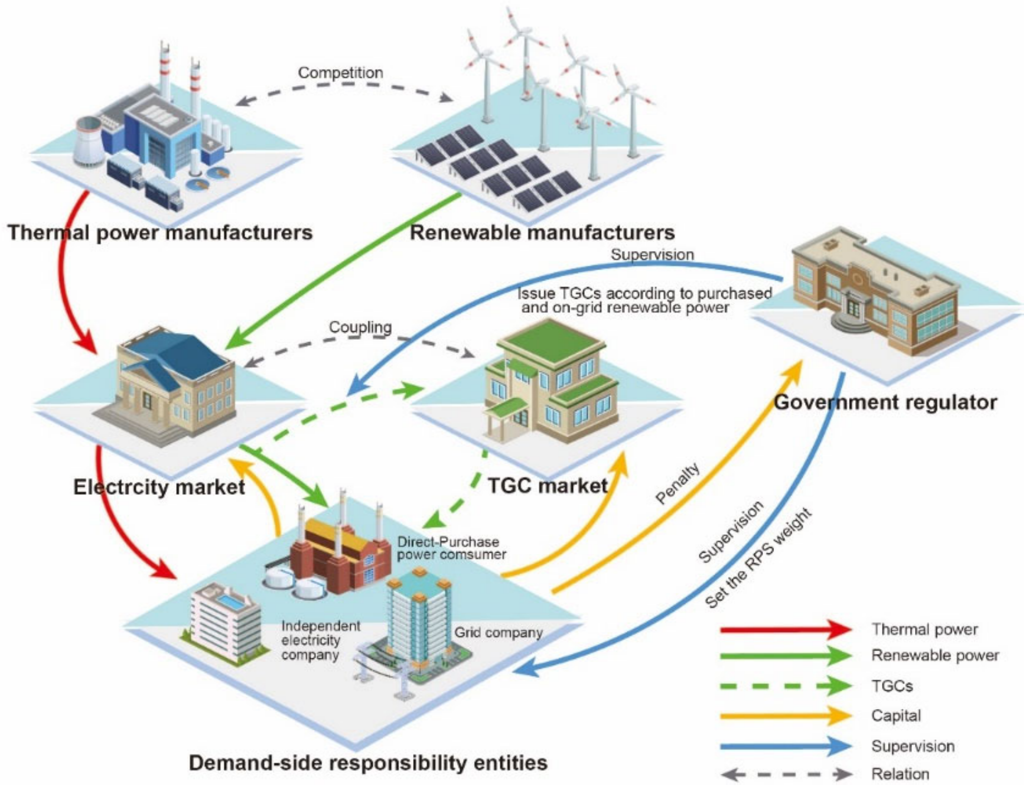


Figure 2. Interaction between the TGC market and the electricity market.

According to Figure 2, it can be analyzed that China's TGC-market performance will be affected by the following factors:

(1) Renewable-power and TGC transactions. TGCs can be issued after renewable power is traded, which means that renewable-power transactions will affect not only RPS target completion but also TGC supply capacity; meanwhile, TGC transaction results can directly change the stock of TGCs, thus changing the supply–demand relationship in the TGC market.

(2) RPS weight. When power-consumption demand and renewable-energy unit capacity are constant, the RPS weight can determine the RPS targets to be accomplished, thereby affecting the demand for TGCs.

(3) Penalties. The difference between penalty cost and transaction cost can affect responsible subjects' TGC purchase strategies directly. In reference to the experiences with the "TGC transaction + RPS assessment" mechanism in various countries, setting a penalty mechanism is an important means to improve the TGC market mechanism

and ensure consumption of renewable power. That is, when responsible subjects fail to complete the RPS target, they will be required to pay the penalty per megawatt–hour.

(4) TGC utility. TGC utility represents the ability of purchased TGCs to satisfy the needs of responsible subjects. Based on cardinal utility theory, at the beginning of the assessment period, the RPS target would be far from being completed, so the utility generated by purchasing TGCs is obvious, and the acceptable TGC price for responsible subjects is high; as the unfulfilled RPS target decreases, the utility will gradually weaken and the acceptable price will decrease.

(5) Assessment period. As the remaining time in the assessment period decreases, in order to reduce the penalty cost and recover the operating cost, enthusiasm of market subjects to participate in TGC transactions will be enhanced. Therefore, the acceptable price for buyers may rise, while the acceptable price for sellers may decrease [25]. Meanwhile, as the assessment period comes to an end, the supply of renewable power and TGCs will weaken, and the acceptable TGC price for sellers may rise.

2.2. Reflexivity of the TGC Market

Reflexivity refers to a structured activity in which subjects project expectations of the future into behaviors after reflecting on previous behaviors and evaluating the current state [26,27]. Reflexivity theory promotes that the market presents significant reflexivity under the impact of incompleteness; subjects' decision-making behaviors are based on cognition of the market state and their own preferences and future expectations. Meanwhile, subjects' decision-making behaviors will reshape the future market state, and the future market state will in turn change subjects' cognition and decision-making behaviors [28]. The reflexivity processes can be represented by functions proposed by Soros:

$$y = f(x) \tag{1}$$

$$x = g(y) \tag{2}$$

$$y = f(g(y)) \tag{3}$$

$$x = g(f(x)) \tag{4}$$

Equation (1) is the cognition function, indicating that subjects' decision-making behaviors are based on their cognition of the current state; x refers to the dimension describing the current market state, such as product price, demand, market supply capacity, etc.; and y refers to the dimension describing subjects' decision-making behaviors, such as product purchase volume, etc. Equation (2) is the participation function, indicating that shaping of the market will be affected by subjects' behaviors. Equations (3) and (4) indicate that subjects' behaviors and the market state will influence each other. The past, present and future will present a state of entanglement.

Compared with the electricity market, the TGC market does not need to meet constraints such as real-time supply–demand balance; responsible subjects can flexibly adjust the purchase time and quantity of TGCs. Therefore, in combination with Section 2.1, reflexivity is reflected in two aspects:

(1) Market states determine responsible subjects' purchasing decisions. The available renewable-energy output, renewable power and TGC trading results will affect the supply capacity, utility and price of TGCs and further affect responsible subjects' transaction decisions.

(2) Responsible subjects' behaviors will shape the future market state. The timing and quantity of responsible subjects' purchases of renewable power and TGCs will indirectly or directly change the supply of TGCs, thus affecting the supply–demand relationship, utility and price of TGCs in the future market.

2.3. Research Assumption

To facilitate research, for this paper, we established the following assumptions:

(a) Suppliers in the electricity market are renewable-energy manufacturers, and thermal-power manufacturers and suppliers in the TGC market are also renewable-energy manufacturers.
(b) As buyers in the electricity and TGC markets, responsible subjects are rational subjects that pursue cost minimization.
(c) TGCs and renewable power are not bundled for trade.
(d) The electricity market and the TGC market are monthly markets. The trading deviations in the electricity market due to renewable-power uncertainty can be balanced by trading in the balanced market.

3. Methodology

3.1. Problem and Model Description

According to the reflexivity of the TGC market and research assumptions, given the policy parameters of RPSs and TGCs (RPS weight, TGC price cap, penalty), responsible subjects will optimize monthly purchasing decisions to pursue cost minimization based on the market state during the one-year RPS assessment period. These purchasing decisions will affect the next month's market state and further affect responsible subjects' purchasing decisions in the next month. This is a typical sequential decision problem with an obvious non-aftereffect property.

As a methodology in the field of reinforcement learning, the MDP has excellent adaptability for solving sequential decision-optimization problems with non-aftereffect properties. Therefore, in this paper, we introduced the MDP to simulate the process, as shown in Figure 3, and major symbols and variables are listed in Nomenclature.

The MDP can be described as quintuple variables: $M = (\mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \lambda)$. Among them, $\mathcal{S}$ is a set of states that responsible subjects are theoretically in. In this paper, states refer to the market supply–demand relationship, commodity prices (TGCs, renewable power, thermal power), completion of the RPS target, etc. in a certain month. $\mathcal{A}$ is a set of actions representing all possible decisions of responsible subjects: that is, monthly purchasing of renewable power, TGCs and thermal power. $\mathcal{P}$ represents the transitions from a certain state (this month) to the next (next month) after certain actions. $\mathcal{R}$ is the reward function, representing the rewards obtained after actions. In this paper, it refers to the costs of power, TGCs and penalties. λ is discount factors, representing responsible subjects' preference for short-term benefits. The closer the value is to 0, the more the responsible subjects prefer short-term benefits.

Usually, the MDP comprises [29,30]:

(a) A sequence of time steps, $\mathcal{T} = \{1, 2, \cdots, t, \cdots, T\}$, where T = 12.
(b) A set of uncontrolled inputs, $\mathcal{I} = \{1, 2, \cdots, i, \cdots, I\}$, where each i is represented by a state variable: $s_t^i \in \mathcal{S}$.

According to assumptions, the available renewable-energy and thermal-power outputs, the power demand, the TGC price and the electricity price are uncontrolled inputs.

(c) A set of controlled inputs, $\mathcal{J} = \{1, 2, \cdots, j, \cdots, J\}$, where each j is represented by a decision variable: $a_t^j = \mathcal{A}$.

According to assumptions, purchases of renewable power, thermal power and TGC are controlled inputs, namely decision variables.

(d) Constraints for state and decision variables, including thermal power and renewable-energy-unit output constraints, power supply–demand balance constraints, etc.
(e) A transition function, $s_{t+1} = f(s_t, a_t)$, where s_t consists of the constraints of the variables at time step t.

(f) An objective function, $F = \mathbb{E}\left\{\sum_{t=1}^{T} R_t(s_t, a_t)\right\}$, where R_t represents the reward incurred at time step t. In this work, the reward is the sum of the costs of purchasing renewable power, thermal power, TGCs and penalties.

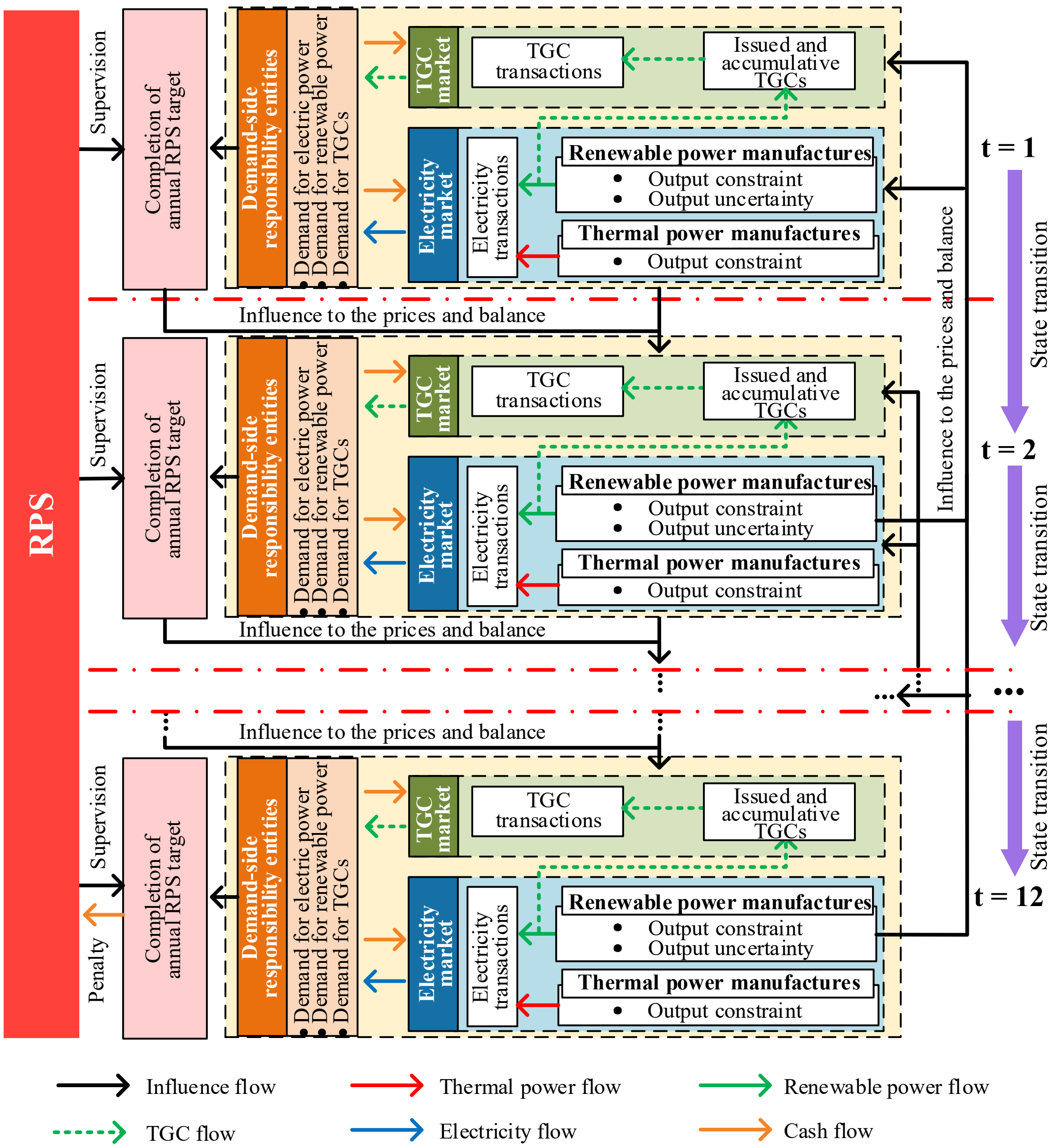


Figure 3. Responsible subjects' decision-making process.

3.2. Modeling

According to the analyses in Sections 2 and 3.1, TGC price, the uncertainty of renewable energy and the goals pursued by responsible subjects can significantly affect responsible subjects' strategies and the implementation effect of policies. In view of this, in order to simulate the behavior of responsible subjects and assess the effects of policies, this section constructs mathematical models of TGC prices, renewable-energy uncertainty, responsible subjects' objective functions and relevant constraints.

3.2.1. TGC Price

Following the principle of matching transactions, we cast the TGC price at time step t as follows:

$$s_t^{\mathrm{p\_TGC}} = \frac{1}{2}\left(s_t^{\mathrm{p\_TGC,buy}} + s_t^{\mathrm{p\_TGC,sell}}\right) \tag{5}$$

According to Section 2, factors such as RPS weight, TGC utility and assessment period influence the acceptable TGC price for buyers, and this can be cast as follows:

$$s_t^{\mathrm{p\_TGC,buy}} = e^{-\mathrm{r}^{\mathrm{buy}}\cdot(T-t)} \cdot \delta_t \cdot U_{\mathrm{TGC}} \tag{6}$$

where $\delta_t \in [0,1]$ represents the degree of responsible subjects' demand for TGC. U_{TGC} is the initial TGC utility, and its value usually equals the TGC price cap.

In more detail, based on the cardinal utility theory (Section 2.1), as a state variable, δ_t is a decreasing function of the completed target by time step t, $Q_t^{\mathrm{RPS,comp}}$; the total RPS target, $Q^{\mathrm{RPS,total}}$, and the completed target by time step t, $Q_t^{\mathrm{RPS,comp}}$, can be cast in Equation (7); and its transition function can be cast as Equation (8):

$$\begin{cases} s_t^{\delta} = f_{\mathrm{utility}}\left(Q^{\mathrm{RPS,total}}, Q_t^{\mathrm{RPS,comp}}\right) \\ Q^{\mathrm{RPS,total}} = \varsigma \cdot \sum\limits_{t}^{T} s_t^{\mathrm{demand}} \\ Q_t^{\mathrm{RPS,comp}} = \sum\limits_{1}^{t}\left(a_{t-1}^{\mathrm{Re}} + a_{t-1}^{\mathrm{TGC}}\right) \end{cases} \tag{7}$$

$$s_{t+1}^{\delta} = f\left(s_t^{\delta}, a_t^{\mathrm{Re}}, a_t^{\mathrm{TGC}}\right) \tag{8}$$

According to Section 2.1, renewable-energy output, the assessment period and TGC supply capacity can affect the acceptable TGC price for sellers; therefore, the price can be obtained with [31]

$$s_t^{\mathrm{p\_TGC,sell}} = e^{-\mathrm{r}^{\mathrm{buy}}\cdot(T-t)} \cdot s_t^{\mathrm{p\_}TGC,0} \cdot \mathbb{E}_t\left[1_{\{\int_t^T s^{\mathrm{Re}}(x)dx + s_t^{\mathrm{TGC\_avl}} < s_t^{\mathrm{PRS\_remain}}\}}\right] \tag{9}$$

where $\mathbb{E}_t\left[1_{\{\int_t^T s^{\mathrm{Re}}(x)dx + s_t^{\mathrm{TGC\_avl}} < s_t^{\mathrm{PRS\_remain}}\}}\right]$ represents the conditional expectation that the TGC supply capacity will be less than the uncompleted RPS target from time step t. In addition, the value of $s_t^{\mathrm{p\_}TGC,0}$ can be equal to the TGC price cap.

To sum up, the transition function of the TGC price can be cast as

$$s_{t+1}^{\mathrm{p\_TGC}} = f\left(s_t^{\mathrm{p\_TGC}}, a_t^{\mathrm{Re}}, a_t^{\mathrm{TGC}}\right) \tag{10}$$

3.2.2. Renewable-Energy Uncertainty

Available renewable-energy output affects TGC price and responsible subjects' transaction decisions. Considering the uncertainty in long-term forecasts, the available output can be cast as Equation (11), and according to the MDP, Equation (11) can be further written as Equation (12):

$$P_t^{\mathrm{Re}} = \widetilde{P}_t^{\mathrm{Re}} + \Delta P_t^{\mathrm{Re}} \tag{11}$$

$$s_t^{\mathrm{Re}} = s_t^{\mathrm{Re\_tech}} + s_t^{\mathrm{Re\_}error} \tag{12}$$

The forecast error-distribution characteristics in different intervals are significantly different; it is difficult for a single distribution model to present the characteristics of asymmetry, sharp peaks and thick tails. Therefore, we cast the problem as a Gaussian mixture model, as follows [32,33]:

$$\begin{cases} f^k\left(s_t^{\text{Re\_}error}\right) = \sum_n^N \omega_n \cdot f_{\text{normal}}\left(s_t^{\text{Re\_}error}\middle|\mu_n, \sigma_n^2\right) \\ 0 < \omega_n < 1 \\ \sum_n^N \omega_n = 1 \end{cases} \tag{13}$$

Applying Equations (12) and (13) directly to the MDP may lead to conservative results. To optimize the performance of the MDP, the power interval of a certain confidence level was obtained by confidence interval estimation. The confidence interval could be solved according to Equation (14) [34,35]:

$$\begin{cases} \min\left(s_t^{\text{Re\_error,upper}} - s_t^{\text{Re\_error,lower}}\right) \\ F\left(s_t^{\text{Re\_error,upper}}\right) - F\left(s_t^{\text{Re\_error,lower}}\right) = 1 - \alpha \end{cases} \tag{14}$$

3.2.3. Objective Function

The objective of responsible subjects is to find the optimal policy, $\pi^* : s \to a$, to minimize the expected sum of future costs over the RPS assessment period.

$$F^{\pi^*} = \min_{\pi^*}\mathbb{E}\left\{\sum_{t=1}^{T} C_t(s_t, \pi^*(s_t))\right\} = \min_{\pi^*}\mathbb{E}\left\{\sum_t^T \left(C_t^{\text{Re}} + C_t^{\text{TH}} + C_t^{\text{TGC}}\right) + C^{\text{penalty}}\right\} \tag{15}$$

According to the previous, the costs of purchasing renewable power, thermal power, TGCs and penalties can be represented as

$$C_t^{\text{Re}} = \begin{cases} a_t^{\text{Re}} \cdot s_t^{\text{p\_Re}} \cdot \Delta t & a_t^{\text{Re}} \leq s_t^{\text{Re}} \\ s_t^{\text{Re}} \cdot s_t^{\text{p\_Re}} \Delta t + (a_t^{\text{Re}} - s_t^{\text{Re}}) \cdot s_t^{\text{p\_balance}} \cdot \Delta t & a_t^{\text{Re}} > s_t^{\text{Re}} \end{cases} \tag{16}$$

$$C_t^{\text{TH}} = a_t^{\text{TH}} \cdot s_t^{\text{p\_TH}} \cdot \Delta t \tag{17}$$

$$C_t^{\text{TGC}} = a_t^{\text{TGC}} \cdot s_t^{\text{p\_TGC}} \tag{18}$$

$$C^{\text{penalty}} = \max\left(0, \varsigma \cdot \sum_t^T s_t^{\text{demand}} - \sum_t^T \left(a_t^{\text{Re}} + a_t^{\text{TGC}}\right) \cdot \Delta t\right) \cdot s^{\text{p\_penalty}} \tag{19}$$

3.2.4. Constraints

The energy-balance constraint is given by Equation (20), and the constraints of the decision variables are given by Equation (20) to Equation (23):

$$(a_t^{\text{Re}} + a_t^{\text{TH}}) \cdot \Delta t = s_t^{\text{demand}} \tag{20}$$

$$0 \leq a_t^{\text{Re}} \leq s_t^{\text{Re\_tech}} + s_t^{\text{Re\_}error} \tag{21}$$

$$\begin{cases} s_t^{\text{TH,min}} \leq a_t^{\text{TH}} \leq s_t^{\text{TH,max}} & a_t^{\text{Re}} \leq s_t^{\text{Re}} \\ s_t^{\text{TH,min}} \leq a_t^{\text{TH}} + (a_t^{\text{Re}} - s_t^{\text{Re}}) \leq s_t^{\text{TH,max}} & a_t^{\text{Re}} > s_t^{\text{Re}} \end{cases} \tag{22}$$

$$0 \leq a_t^{\text{TGC}} \leq s_t^{\text{TGC\_avl}} \tag{23}$$

The transition function governs how the state variable, $s_t^{\text{TGC\_avl}}$, evolves over time, and the transition function of $s_t^{\text{TGC\_avl}}$ is as follows:

$$s_t^{\text{TGC\_avl}} = s_{t-1}^{\text{TGC\_avl}} + a_{t-1}^{\text{Re}} - a_{t-1}^{\text{TGC}} \tag{24}$$

3.3. Solution

According to Sections 3.1 and 3.2, the optimization problem proposed in this manuscript is a typical nonlinear problem. The problem is a composite function composed of a piecewise function, an exponential function and other nonlinear functions and has corresponding nonconvex characteristics. To solve the optimization problem directly, a series of operations such as increasing relaxation variables and transforming constraints are needed; these operations are not only complicated but also greatly increase computational burden and cost. However, it is worth noting that the key to the optimization problem proposed in this manuscript is to assess the effects of the policy and provide reference for optimization of responsible subjects' strategies. Considering the actual situation and the possibility of engineering applications, the satisfactory solution of the optimization problem can well meet its needs, and it is not worth increasing the computational cost to try to obtain the optimal solution of the problem. Meanwhile, considering the high efficiency, accuracy and stability of DP and EAs in solving nonlinear problems, the solution can be handled as an iterative process, and the pseudocode of the solution is shown in Algorithm 1.

Algorithm 1: Solution based on DP and EAs

Initialize a_t^{Re}, a_t^{TGC}, a_t^{TH}, maximum of iterations K, $\Delta V_{\text{threshold}}$
    for k = 1 to K
        for t = 1 to T
            Calculate $s_t^{\text{p\_TGC}}$, $V_t^{\pi}(s)$
        end for
        for t = T to 1
            Use EA to extract optimal policy by solving Equation (27), update a_t^{Re}, a_t^{TGC}, a_t^{TH}
        end for
        Calculate objective function at kth iteration
        Calculate the variation between objective function of kth and (k−1)th, ΔV
        if $\Delta V < \Delta V_{\text{threshold}}$
            break
        end if
        k = k + 1
    end for
Return the optimal policy and objective function value

As action-to-reward mapping, the value function represents the relationship between the current state, the reward (cost), actions and the expected future cost of following the policy. In more detail, applying DP can transform the MDP into a backward induction and compute the value function at each time step, which would also contain the expected future cost:

$$V_t^{\pi}(s) = R_s^a + \gamma \sum_{s' \in s} P_{ss'}^a V_{t+1}^{\pi}(s') \tag{25}$$

According to Bellman's optimality condition, the optimal policy is a set of sequential actions that minimize Equation (26):

$$V_t^{\pi^*}(s_t) = C_t(s_t, \pi^*(s_t)) + \gamma \cdot \mathbb{E}\left\{ V_{t+1}^{\pi^*}(s') \middle| s_t \right\} \tag{26}$$

Further, EAs can be applied to extract the optimal policy through selecting a minimum value action for each state:

$$\pi^* = \underset{a \in \mathcal{A}, s \in \mathcal{S}}{\operatorname{argmin}} V_t(s_t, a_t) \tag{27}$$

4. Simulations and Discussion

According to the above, RPS weight, the TGC price cap, penalties and discount factors (preference for short-term benefits) can affect responsible subjects' behaviors and market performance. This section will analyze the impacts of these factors.

4.1. Basic Scenario and Data

To facilitate this research, basic scenario S0 was designed according to statistics released by the National Energy Administration and the China green certificate transaction platform [36,37]. In S0, the RPS weight = 13%, the TGC price cap = 350 CNY, the penalty = 350 CNY, the discount factors = 1 and the discount rate = 6% [38].

A region in East China was selected as the research object; there were seven thermal-power units and a photovoltaic power station. The power demand, available thermal-power output and monthly transaction price, according to historical statistics obtained from a survey, are shown in Figures 4–6. In addition, in order to handle the uncertainty of photovoltaics according to Section 3.2.2, in this paper, the photovoltaic output is divided into three segments, (0, 0.3], (0.3, 0.6] and (0.6, 1], and applies a Gaussian mixture to fit the output prediction errors in different segments. The available photovoltaic output was obtained by solving the confidence interval of 95% [34], as shown in Figure 7.

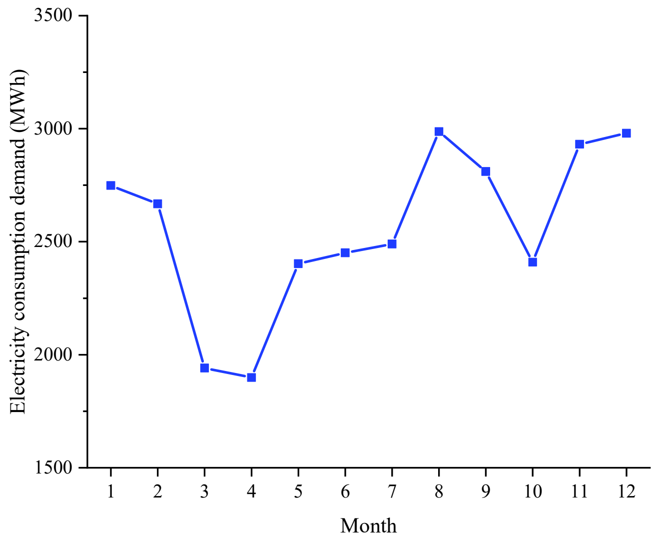


Figure 4. Monthly power demand.

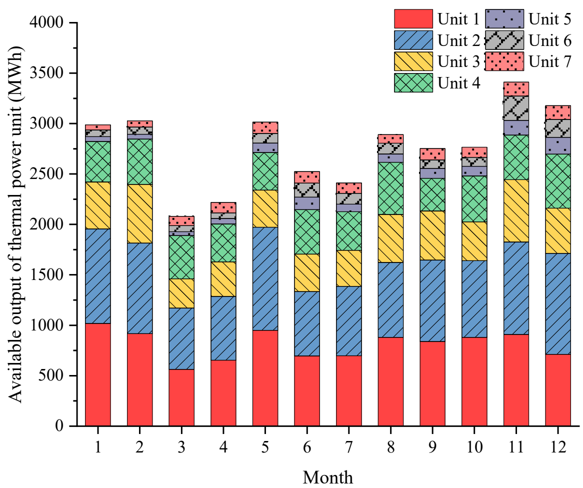


Figure 5. Monthly available thermal-power output.

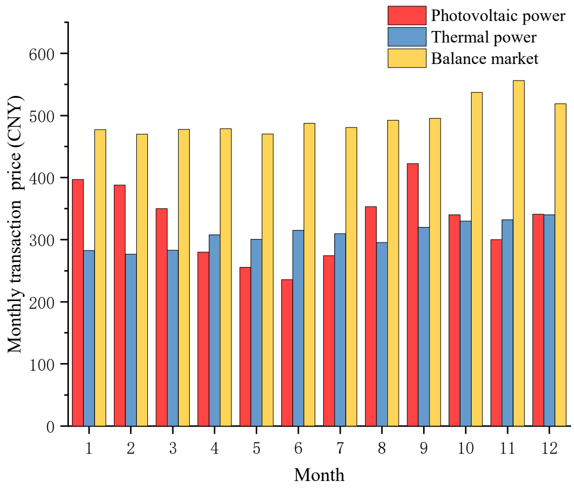


Figure 6. Monthly price in the electricity market.

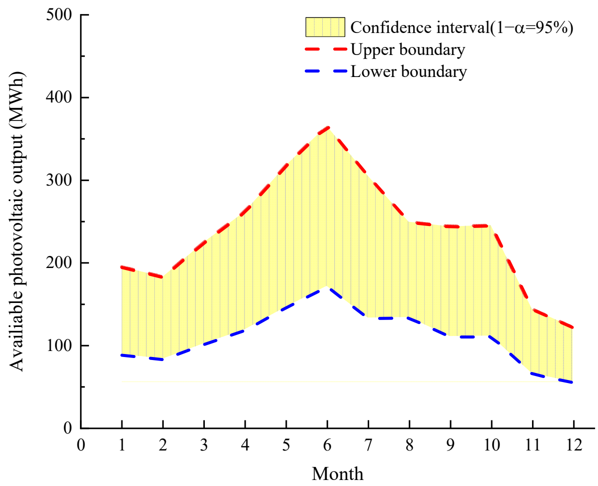


Figure 7. Monthly available photovoltaic-power output.

4.2. RPS Weight

In this paper, five scenarios were designed to simulate the impact of RPS weight, as shown in Table 2.

Table 2. Scenarios for analyzing the impact of RPS weight.

Scenario	RPS Weight	TGC Price Cap	Penalty
S_0	13%	350	350
S_1	5%	350	350
S_2	7%	350	350
S_3	9%	350	350
S_4	19%	350	350

Figure 8a,b shows trends of accumulative trading volume and monthly trading volume of renewable power.

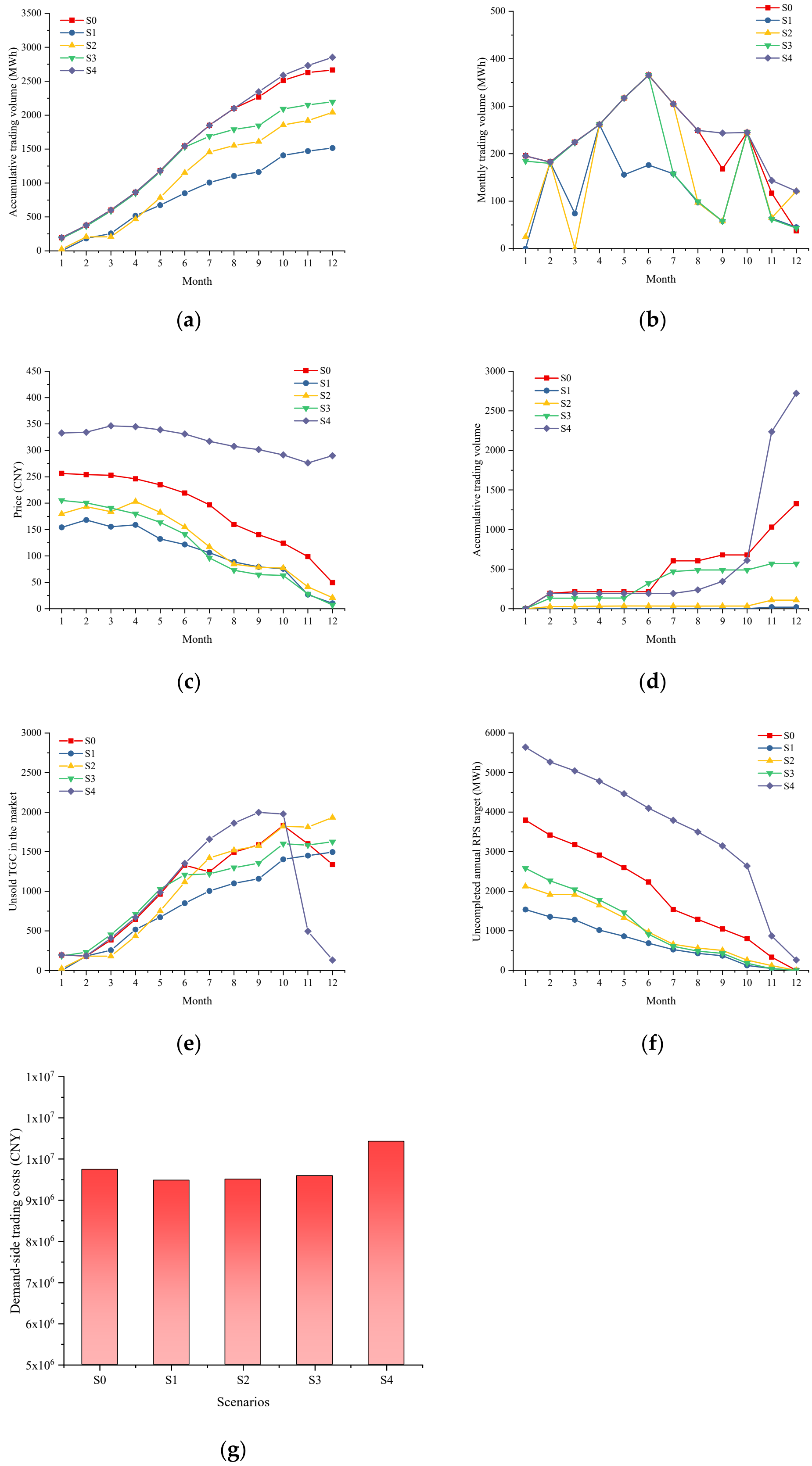


Figure 8. Trends of decision-making and market performance under different RPS weights. (**a**) Accumulative renewable-power trading volume. (**b**) Monthly renewable-power trading volume. (**c**) TGC price. (**d**) Accumulative TGC trading volume. (**e**) Accumulative unsold TGCs. (**f**) RPS target completion. (**g**) Responsible subjects' cost.

As shown in Figure 8a, in S2, S0 and S4, the trends reached 2117.84 MWh, 2666.58 MWh and 2852.20 MWh, respectively, in December. When the RPS weight increased from 7% to 13%, the transaction volume increased by 548.74 MWh, while the volume only increased by 185.62 MWh when the weight increased from 13% to 19%. These data indicate that an increase in RPS weight can promote demand for renewable power; however, as RPS weight continues to increase, the marginal effect of promotion will weaken.

In Figure 8b, the increase in RPS weight affects responsible subjects' strategies of purchasing renewable power in the monthly market, but it is not necessarily a positive correlation. For example, from January to March, the renewable-power price was significantly higher than the thermal-power price; as the RPS weight increased, responsible subjects tended to purchase more renewable power. From May to July, the renewable-power price was lower, while the RPS weights were far different; subjects' strategies of purchasing renewable power were almost the same in S0, S2, S3 and S4, and the strategies were close to the upper boundary of the confidence interval. These data indicate that although renewable-energy uncertainty may bring potential costs (costs in the balanced market), responsible subjects are willing to bear greater risks and choose to purchase more renewable power. It is worth noting that in November, the renewable-power price was lower than that of thermal power, but the renewable power purchased was significantly lower than the upper bounds of the confidence intervals in S0, S1, S2 and S3. The reason is that the price difference between renewable power and thermal power was small, and the price in the balanced market was high, which led to a high expectation of cost caused by renewable-energy uncertainty, so the responsible subjects tended to adopt conservative strategies. However, in S4, due to the high RPS weight, the expectation of the penalty cost was higher, so the responsible subjects still adopted more aggressive strategies.

Figure 8c–e shows the trends of price, accumulative trading volume and unsold volume in the TGC market.

In Figure 8c, the TGC price rises with the increase in RPS weight, indicating that an increase in RPS weight can stimulate responsible subjects' demand for TGCs. Meanwhile, the trends in S1, S2 and S3 are relatively close and almost coincide after July. These data show that when RPS weight changes in a low range, the stimulating effect of increasing weight on demand for TGCs will weaken over time. In contrast, the trends in S0 and S4 were relatively flat, indicating that increasing RPS weight can suppress price fluctuations in the TGC market.

In Figure 8d, the trends in S1, S2, S3, S0 and S4 indicate that an increase in RPS weight can promote demand for TGCs. It is worth noting that in comparison of Figure 8c,d, the TGC price trend in S1 is close to that of S3, but the annual trading volume is significantly lower than that of S3, indicating that a low RPS weight can lead to coexistence of "nominal price" and "extremely low trading volume" in the TGC market.

In Figure 8e, the accumulative unsold TGCs in the five scenarios are 1495, 1932, 1626, 1339 and 132, namely, S2 > S3 > S1 > S0 > S4. This indicates that when RPS weight changes within a low range, the promotion effect of increasing RPS weight on TGC transactions is weaker than that on renewable-power transactions, which leads to more unsold TGCs. This phenomenon is contrary to the intention of setting RPSs and TGCs to promote renewable-energy development and relieve financial pressure.

Figure 8f,g shows RPS target completion and trading costs.

In Figure 8f, the trends in S1, S2 and S3 are similar after July, indicating that when RPS weight is in a low range, an increase in RPS weight will have little impact on the process of RPS target completion. Further, according to Figure 8g, increasing RPS weight within a reasonable range will not excessively increase the cost of the demand side (S0, S1, S2, S3).

4.3. TGC Price Cap

In this section, scenarios were designed with RPS weights of 7% and 13% to study the impact of the TGC price cap, as shown in Table 3.

Table 3. Scenarios for analyzing the impacts of TGC price caps.

Scenario	RPS Weight	TGC Price Cap	Penalty
S_5	7%	300	350
S_2	7%	350	350
S_6	7%	400	350
S_7	7%	800	350
S_8	13%	300	350
S_0	13%	350	350
S_9	13%	400	350
S_{10}	13%	800	350

Figure 9a,b shows trends of accumulative trading volume of renewable power.

In Figure 9a, the trends in S5, S2, S6 and S7 are similar, almost overlapping after May and reaching around 2100 MWh in December. These data indicate that when the RPS weight = 7%, increasing the TGC price cap will have little impact on responsible subjects' demand for renewable power. Meanwhile, in Figure 9b, although the trends in S8, S0, S9 and S10 almost overlap before June, they start to diverge in July and reach 2581.82 MWh, 2666.59 MWh, 2744.61 MWh and 2823.37 MWh, respectively, in December. These data indicate that when the RPS weight = 13%, increasing the TGC price cap can increase responsible subjects' intentions to purchase renewable power to a certain extent.

Figure 9c–h shows the trends of price, accumulative volume and unsold volume in the TGC market.

In Figure 9c, as time proceeds, the trends in S5, S2 and S6 gradually overlap, and the TGC prices in the four scenarios in December are all around 17 CNY. These data indicate that when the RPS weight = 7%, the impact of increasing the TGC price cap on the supply–demand relationship in the TGC market will weaken over time, and an excessive increase in the TGC price cap will lead to sharp price fluctuations (S7). In contrast, in Figure 9d, the price relationship is S10 > S9 > S0 > S8. This indicates that when the RPS weight = 13%, an excessive increase in the price cap will lead to a high price throughout the year.

It is worth noting that in comparison of Figure 9c,d, the annual decline rate of the TGC prices in S0, S9 and S10 (80.67%, 83.67%, 58.44%) is less than in S2, S6 and S7 (88.29%, 95.05%, 98.00%). This confirms the conclusion in Section 4.2: when the price cap is not less than the penalty, an increase in RPS weight can stabilize price fluctuation in the TGC market.

In Figure 9e, the trends in S5, S2, S6 and S7 are almost parallel to the X-axis, indicating that the trading volume and trading times of TGCs are very limited. In combination with Figure 9g, the trends in S5, S2, S6 and S7 all keep rising and are relatively similar. The above indicates that when the RPS weight = 7%, changes in the TGC price cap have no significant impact on TGC market performance.

When the RPS weight = 13%, in terms of accumulation, in Figure 9f, the trends in S8, S0, S9 and S10 reach 1409, 1326, 1248 and 1169, respectively. Meanwhile, in Figure 9h, the accumulative unsold TGCs in S8, S0, S9 and S10 are 1172, 1339, 1495 and 1654, respectively. These data show that an increase in the price cap may have a negative impact on TGC market performance. It is worth noting that the trading volume in S10 was 240 less than that in S8, but the amount of unsold TGCs was 482 more than that in S8. This indicates that a substantial increase in the TGC price cap will not only reduce the demand for TGCs but also generate more unsold TGCs due to the promotion of demand for renewable power.

In terms of transaction time, in Figure 9f, all the trends change gently in the early stage but rise rapidly in the later stage, and the time of rising is delayed as the TGC price cap increases. These data indicate that with an increase in the TGC price cap, responsible subjects will delay their purchases of TGCs in order to reduce the cost as much as possible.

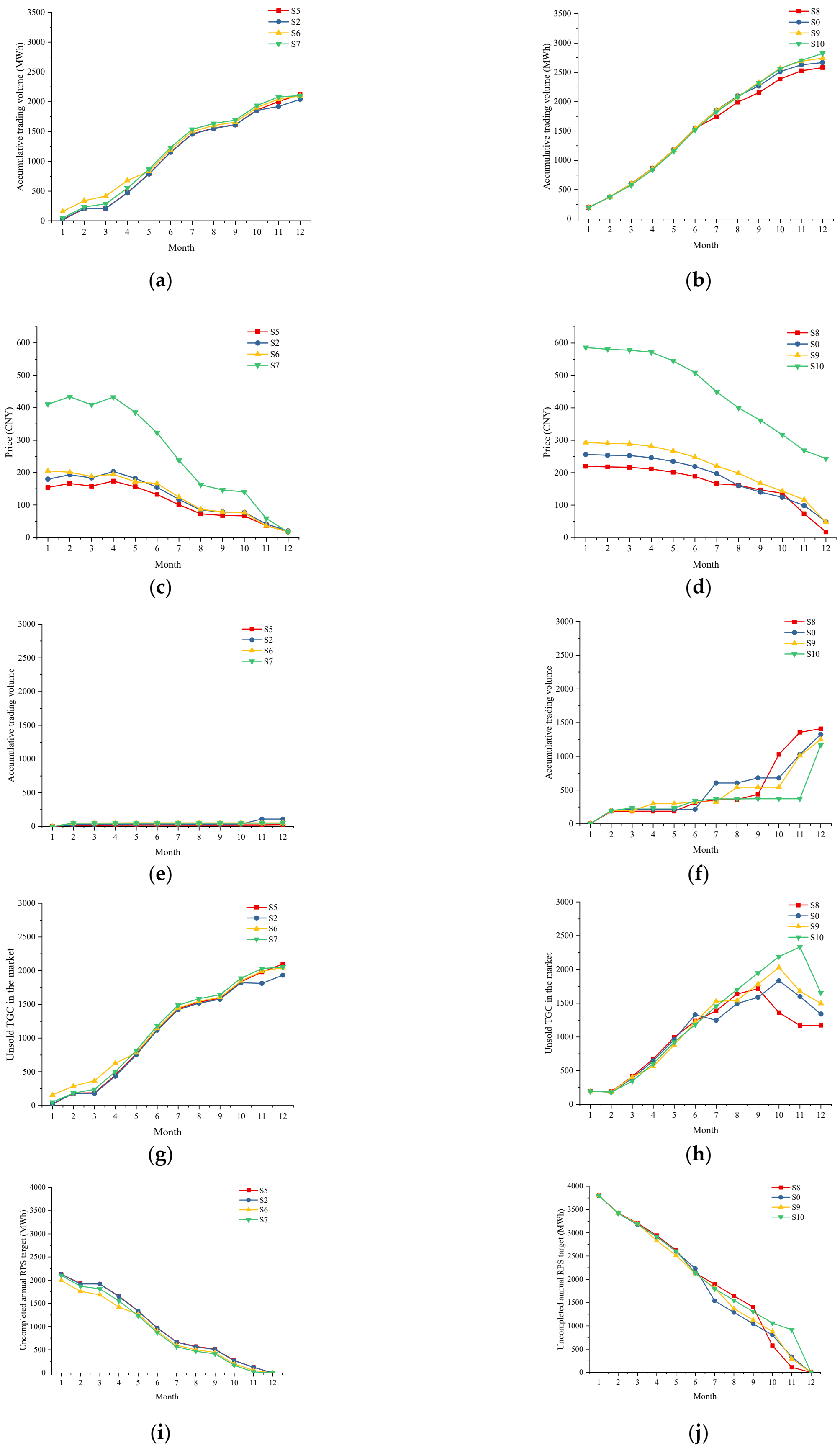
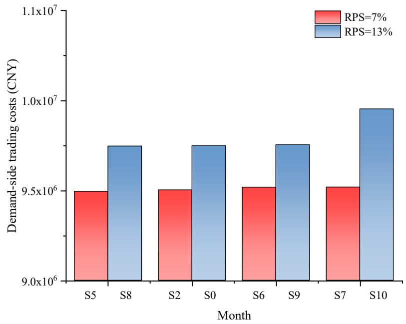


Figure 9. *Cont.*



(**k**)

Figure 9. Trends of decision-making and market performance under different TGC price caps. (**a**) Accumulative renewable-power trading volume (RPS weight = 7%). (**b**) Accumulative renewable-power trading volume (RPS weight = 13%). (**c**) TGC price (RPS weight = 7%). (**d**) TGC price (RPS weight = 13%). (**e**) Accumulative TGC trading volume (RPS weight = 7%). (**f**) Accumulative TGC trading volume (RPS weight = 13%). (**g**) Accumulative unsold TGCs (RPS weight = 7%). (**h**) Accumulative unsold TGCs (RPS weight = 13%). (**i**) RPS target completion (RPS weight = 7%). (**j**) RPS target completion (RPS weight = 13%). (**k**) Responsible subjects' cost.

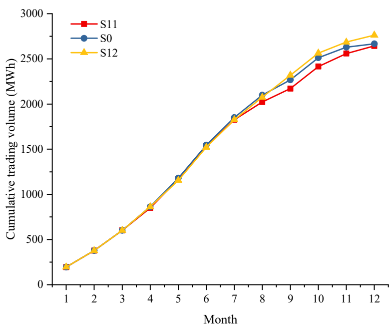
Figure 9i–k shows the RPS target completion and the trading cost.

In comparison of Figure 9i,j, the trends in S5, S2, S6 and S7 are similar, indicating that when the RPS weight = 7%, the change in price cap has no significant impact on the progress of completing the RPS target; in S8, S0, S9 and S10, the trends decline more slowly in scenarios with higher price caps, and this is closely related to the tendency of responsible subjects' delays in purchasing TGCs. Meanwhile, as shown in Figure 9k, when the RPS weight = 7%, a change of price cap has little impact on the cost. When the RPS weight = 13%, the costs in S8, S0 and S9 are relatively close to each other, while the cost in S10 reaches 9952719 CNY, indicating that a moderate increase in the TGC price cap will not significantly increase the cost.

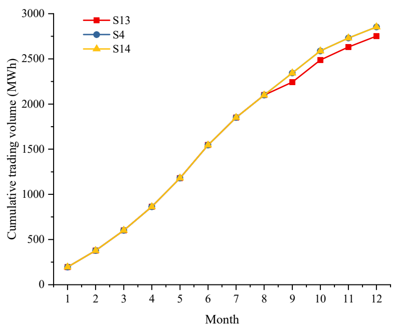
4.4. Penalty

To study the impacts of penalties, this section contains scenarios designed as shown in Table 4.

Figure 10a,d shows trends of accumulative trading volume and monthly trading volume of renewable power.



(**a**)



(**b**)

Figure 10. *Cont.*

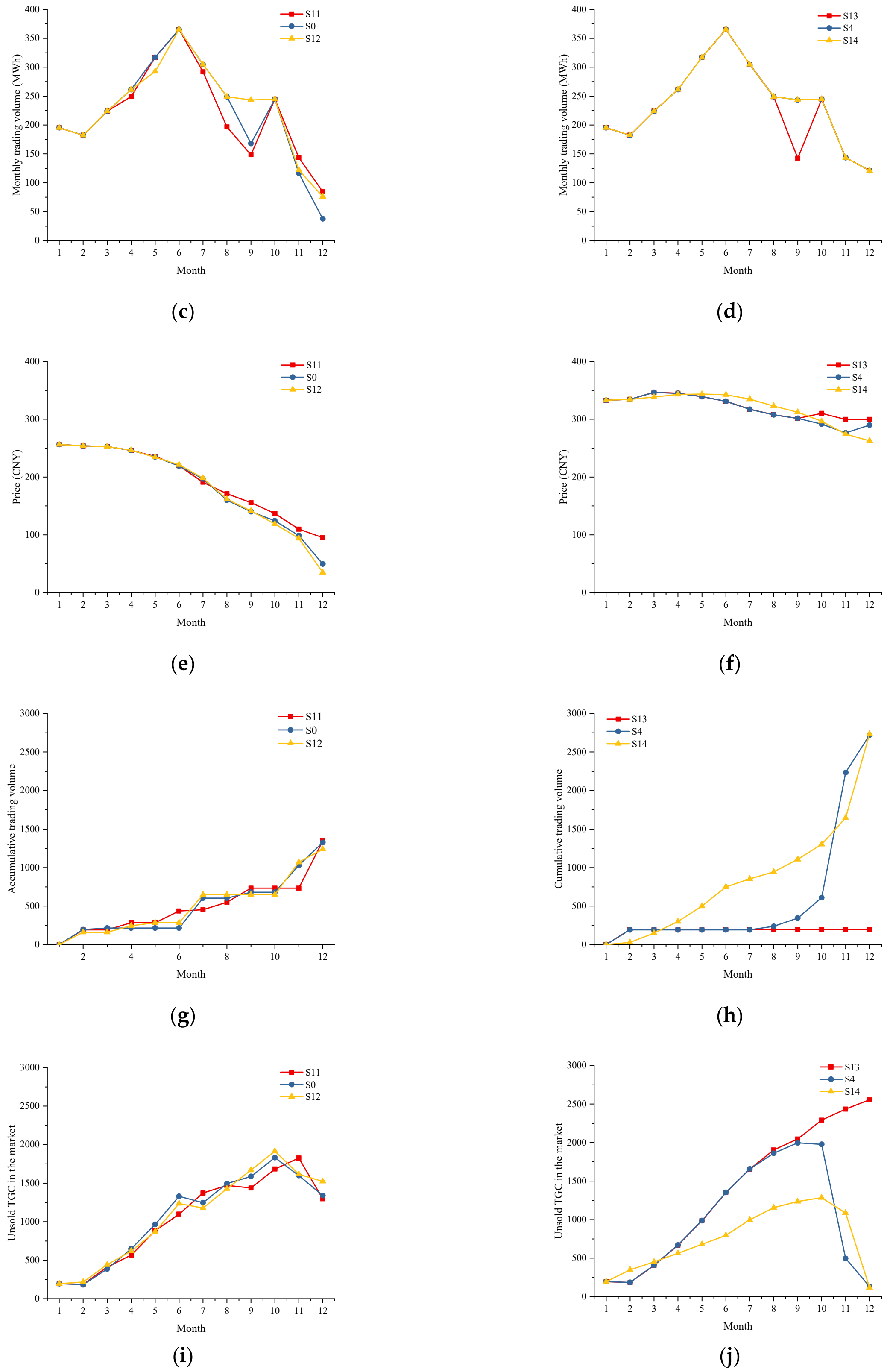
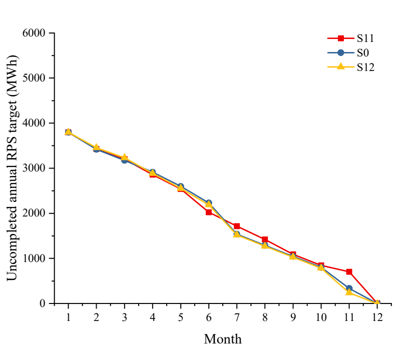
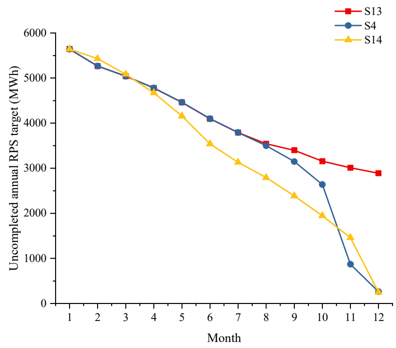


Figure 10. *Cont*.



(**k**)



(**l**)

Figure 10. Trends of decision-making and market performance under different penalties. (**a**) Accumulative renewable-power trading volume (RPS weight = 13%). (**b**) Accumulative renewable-power trading volume (RPS weight = 19%). (**c**) Monthly renewable-power trading volume (RPS weight = 13%). (**d**) Monthly renewable-power trading volume (RPS weight = 19%). (**e**) TGC price (RPS weight = 13%). (**f**) TGC price (RPS weight = 19%). (**g**) Accumulative TGC trading volume (RPS weight = 13%). (**h**) Accumulative TGC trading volume (RPS weight = 19%). (**i**) Accumulative unsold TGCs (RPS weight = 13%). (**j**) Accumulative unsold TGCs (RPS weight = 19%). (**k**) RPS target completion (RPS weight = 13%). (**l**) RPS target completion (RPS weight = 19%).

Table 4. Scenarios for analyzing the impacts of penalties.

Scenario	RPS Weight	TGC Price Cap	Penalty
S11	13%	350	250
S0	13%	350	350
S12	13%	350	450
S13	19%	350	250
S4	19%	350	350
S14	19%	350	450

In Figure 10a,b, S11 and S13 are the scenarios with the lowest accumulative trading volumes, indicating that setting a penalty of no less than the TGC price cap can stimulate demand for renewable power. Meanwhile, in Figure 10c,d, although the price of renewable power is higher than that of thermal power in August and September, with the increase in the penalty, responsible subjects increase their purchases of renewable power (S12 > S0 > S11, S14 > S4 > S13), indicating that an increase in the penalty makes responsible subjects willing to bear the risks brought by renewable-energy uncertainty.

Figure 10e–j shows the trends of price, accumulative trading and unsold volume in the TGC market.

In Figure 10e, the trends decline faster in scenarios with higher penalties from July onward, and the TGC price relationship is S11 > S0 > S12 in December, indicating that an increasing penalty can widen the supply–demand gap in the TGC market and lead to an increase in the speed and range of price declines. Similarly, a consistent conclusion can be drawn according to Figure 10f.

As shown in Figure 10g, in December, the accumulative trading volume of TGCs in S11, S0 and S12 reached 1346, 1326 and 1237, respectively. Meanwhile, according to Figure 10i, the accumulative volumes of unsold TGCs in these three scenarios are S12 > S0 > S11. These data show that when the RPS weight = 13%, with an increase in the penalty, responsible subjects will preferentially choose to purchase renewable power to complete the RPS target and reduce their purchases of TGCs.

In Figure 10h, when the penalty is significantly lower than the TGC price cap (S13), the trend of the TGC accumulative trading volume remains at 195 throughout the year, while in S4 and S14, the trends reach 2720 and 2733 in December. In Figure 10j, the trend of unsold TGCs in S13 keeps increasing, while the trends in S4 and S14 each drop to around 120 after the initial increase. These data indicate that setting a penalty of no lower than the TGC price cap is a guarantee for normal operation of the TGC market, and when the penalty is further increased, responsible subjects will tend to purchase TGCs in each month rather than at the end of the year. The reason lies herein: to minimize the expectations of penalty cost, responsible subjects will try to transfer to a state with lower expectations of penalty costs through purchasing TGCs every month.

In Figure 10k, when the RPS weight = 13%, the increase in the penalty has no significant impact on the completion of RPS target. However, in Figure 10l, when the RPS weight = 19%, a penalty of lower than the TGC price cap may have resulted in the RPS target not being completed.

4.5. Discount Factor

According to Sections 4.2–4.4, the RPS weight, the TGC price cap and penalty will have significant impacts on responsible subjects' behavior. Therefore, in order to improve the rationality of analysis and results, the scenario should be subdivided according to RPS weight, TGC price cap and penalty in order to analyze and quantify the influence of discount factors.

4.5.1. RPS Weight

To study the impacts of discount factors under different RPS weights, this section contains scenarios designed as shown in Table 5.

Table 5. Scenarios for analyzing impacts of discount factors under different RPS weights.

Scenario	RPS Weight	TGC Price Cap	Penalty	Discount Factor
S2	7%	350	350	1
S15	7%	350	350	0.7
S0	13%	350	350	1
S16	13%	350	350	0.7
S4	19%	350	350	1
S17	19%	350	350	0.7

Figure 11a shows trends of accumulative trading volume of renewable power.

In Figure 11a, in terms of vertical comparison, when the RPS weight = 7%, the trend in S15 is lower than in S2, and the difference between S15 and S2 reaches 214.42 MWh in December. When the RPS weights are increased to 13% and 19%, the corresponding differences are 405.54 MWh (S16 and S0) and 782.3 MWh (S4 and S17), respectively; in terms of horizontal comparison, the annual accumulative trading volumes of renewable power in S15, S16 and S17 are 1800.12 MWh, 2261.05 MWh and 2069.91 MWh, respectively. Two conclusions can be drawn: From a vertical comparison, responsible subjects' preference for short-term benefits will lead to a decline in annual renewable-power trading volume, and this phenomenon will be more significant with an increase in RPS weight; from a horizontal comparison, different from Section 4.2, when subjects prefer short-term benefits, blindly increasing RPS weight cannot always promote demand for renewable power.

Figure 11b–e shows the trends of TGC price, trading volume, unsold volume and RPS target completion.

In Figure 11b, the trends in S15, S16 and S17 are higher than in S2, S0 and S4, respectively, especially in S19, when the TGC price would have increased further without the TGC price cap. These data indicate that the demand side's preference for short-term benefits can alleviate a downward trend of TGC price.

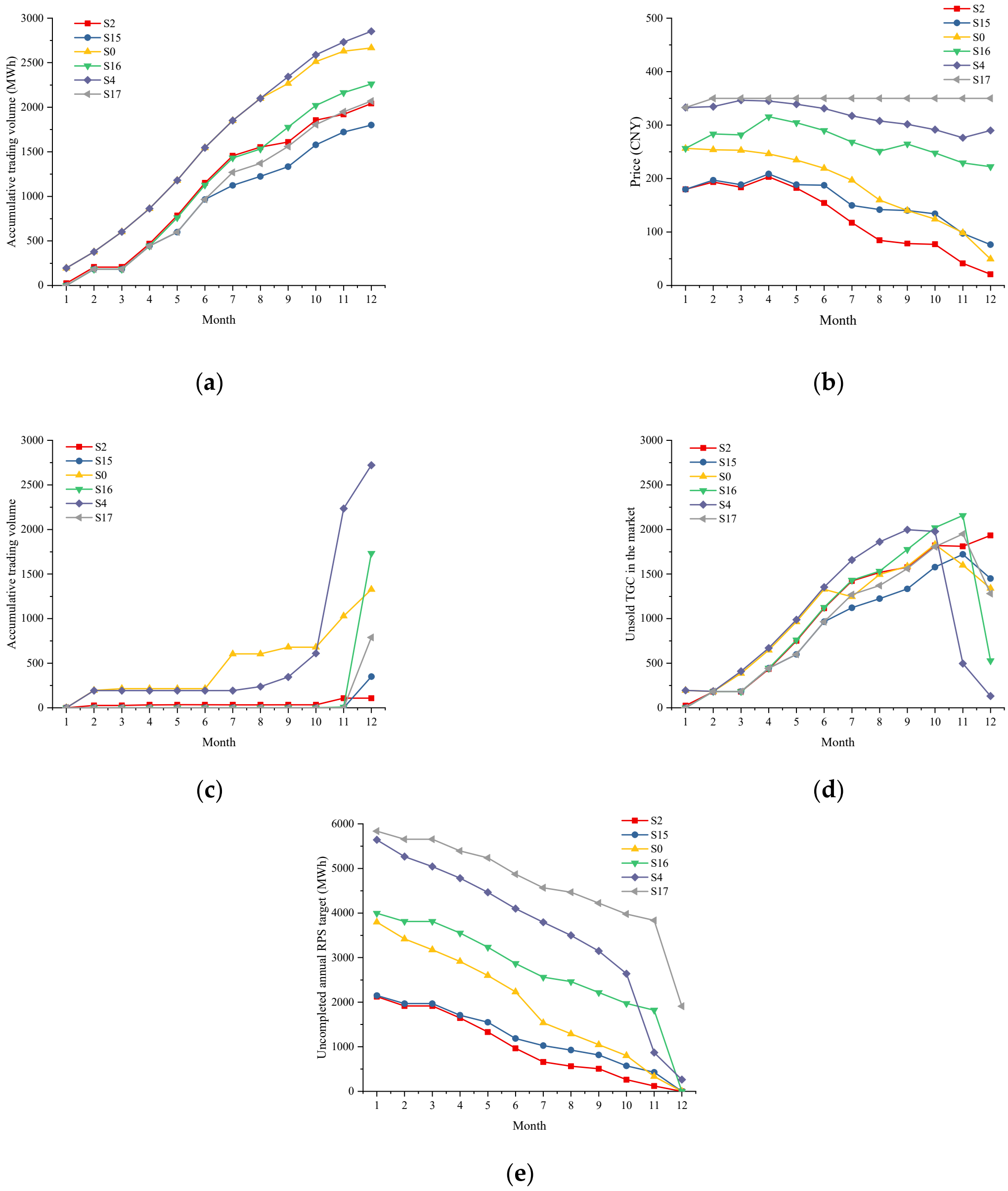


Figure 11. Trends of decision-making and market performance under different discount factors and RPS weights. (**a**) Accumulative renewable-power trading volume. (**b**) TGC price. (**c**) Accumulative TGC trading volume. (**d**) Accumulative unsold TGCs. (**e**) RPS target completion.

In Figure 11c,d, when the RPS weight = 7%, accumulative volume of unsold TGCs in S15 decreases by 483 compared with S2. Meanwhile, when the RPS weight is increased to 13%, the unsold TGC in S16 is 811 less than that in S2. These data indicate that a preference for short-term benefits can stimulate responsible subjects' demand for TGCs, and the phenomenon becomes more obvious when the RPS weight is appropriately increased. However, when the RPS weight = 19%, the willingness to purchase TGCs is greatly reduced. In the end, in S17, the accumulative transactions of TGCs were only 789, the accumulative unsold TGCs reached 1281, and the RPS target had 1910 MWh remaining (Figure 11e); the market performance was much worse than in S4, which again highlights the importance of the penalty being higher than the TGC price cap.

4.5.2. TGC Price Cap

To study the impacts of discount factors under different TGC price caps, six scenarios are designed as shown in Table 6.

Table 6. Scenarios for analyzing impacts of discount factors under different TGC price caps.

Scenario	RPS Weight	TGC Price Cap	Penalty	Discount Factor
S8	13%	300	350	1
S18	13%	300	350	0.7
S0	13%	350	350	1
S16	13%	350	350	0.7
S9	13%	400	350	1
S19	13%	400	350	0.7

Figure 12a shows trends of accumulative trading volume of renewable power.

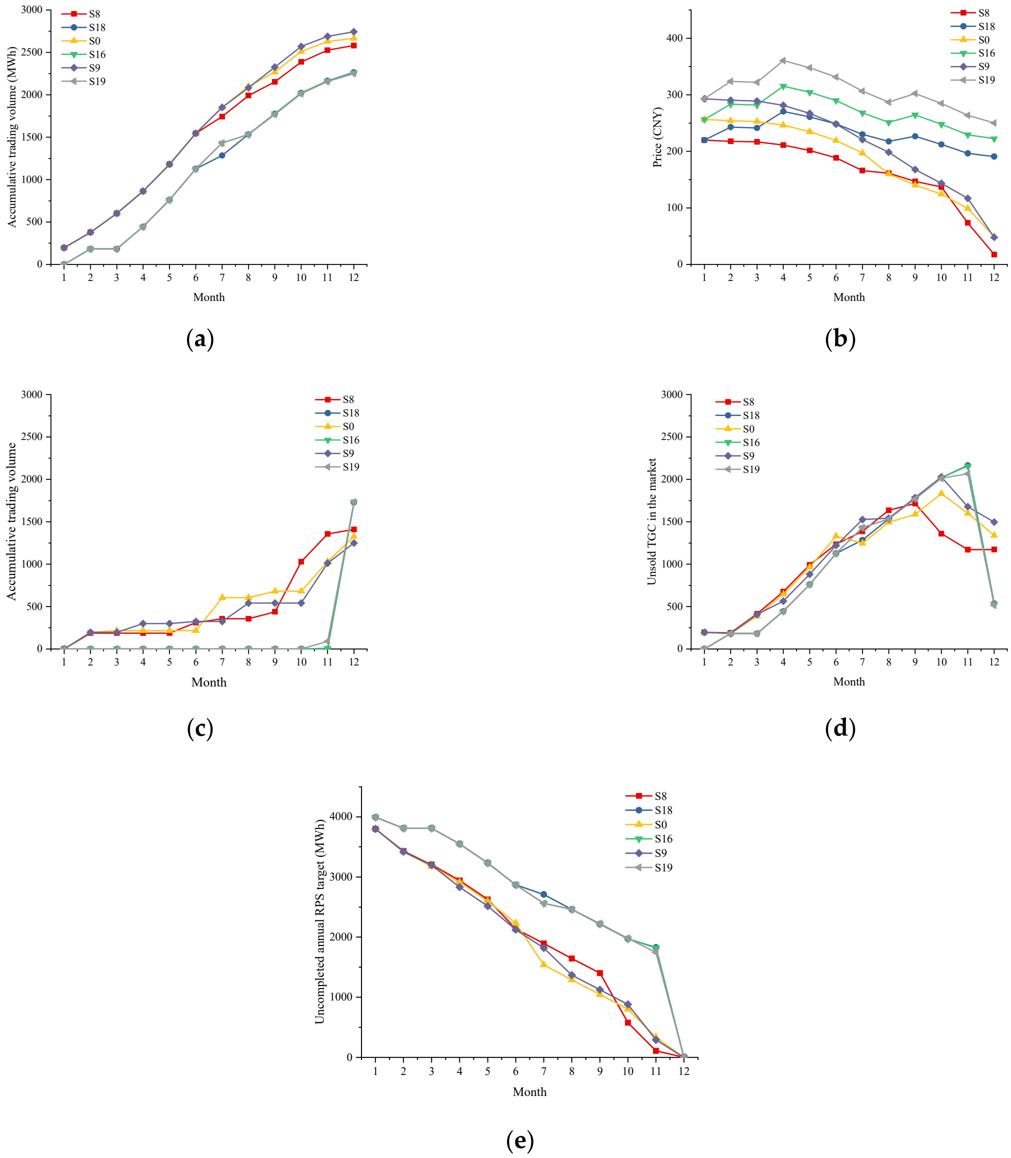


Figure 12. Trends of decision-making and market performance under different discount factors and TGC price caps. (**a**) Accumulative renewable-power trading volume. (**b**) TGC price. (**c**) Accumulative TGC trading volume. (**d**) Accumulative unsold TGCs. (**e**) RPS target completion.

In Figure 12a, the differences between the trends in S8 and S18, S0 and S16 and those in S9 and S19 are 2265.47 MWh, 405.54 MWh and 494.67 MWh in December. The above indicates that the decline of renewable-power trading volume caused by responsible subjects' preference for short-term benefits becomes more obvious with the increase in TGC price caps. In addition, it is not difficult to notice that the trends in S18, S16 and S19 almost overlap, indicating that when responsible subjects prefer short-term benefits, different from the conclusion in Section 4.3, a change in TGC price cap will have no significant impact on demand for renewable power.

Figure 12b–e shows the trends of TGC price, trading volume, unsold volume and RPS target completion.

In Figure 12b, in S18, S16 and S19, the TGC price differences are almost constant during the assessment period. The above shows that when responsible subjects prefer short-term benefits, the phenomenon proposed in Section 4.3, that TGC price increases due to increases in the price cap will decay over time, may no longer exist.

In Figure 12c, the trends in S18, S16 and S19 are very similar and reach around 1730, which is 318, 405 and 486 higher than in S8, S0 and S9, respectively. Meanwhile, in Figure 12d, the trends in S18, S16 and S19 reach around 530 in December, which is 634, 811 and 981 lower than in S8, S0 and S9, respectively. It can be concluded that the phenomenon proposed in Section 4.5.1, that preference for short-term benefits can promote purchases of TGC sand reduce the amount of unsold TGCs, will become more significant as the price cap increases; meanwhile, when short-term benefits were preferred, different from the conclusion in Section 4.3, the increase in the TGC price cap had no significant impact on TGC accumulative trading volume and unsold volume or RPS target completion (Figure 12e).

4.5.3. Penalty

To study the impacts of discount factors under different penalties, six scenarios were designed, as shown in Table 7.

Table 7. Scenarios for analyzing impacts of discount factors under different penalties.

Scenario	RPS Weight	TGC Price Cap	Penalty	Discount Factor
S0	13%	350	350	1
S16	13%	350	350	0.7
S20	13%	350	400	1
S21	13%	350	400	0.7
S12	13%	350	450	1
S22	13%	350	450	0.7

Figure 13a,b shows trends of accumulative trading volume and monthly trading volume of renewable power.

In Figure 13a, the trends in S16, S21 and S22 are similar to and lower than in S0, S20 and S12. Meanwhile, in Figure 13b, taking S0 and S16 as examples, the trend in S16 is lower than in S0 in January, March and August, while it is higher than in S0 in September, November and December. According to the above, the preference for short-term benefits will lead subjects to reduce their purchases of renewable power when the renewable-power price is significantly higher than that of thermal power and adopt more aggressive strategies and purchase more renewable power in other periods, and this phenomenon becomes more obvious with increases in penalty (S20 and S21, S12 and S22). On a full-year basis, preference for short-term benefits will still lead to a decline in accumulative purchases of renewable power, but this can be mitigated by setting a higher penalty.

Figure 13c–e shows the trends of price, accumulative volume and unsold volume in the TGC market.

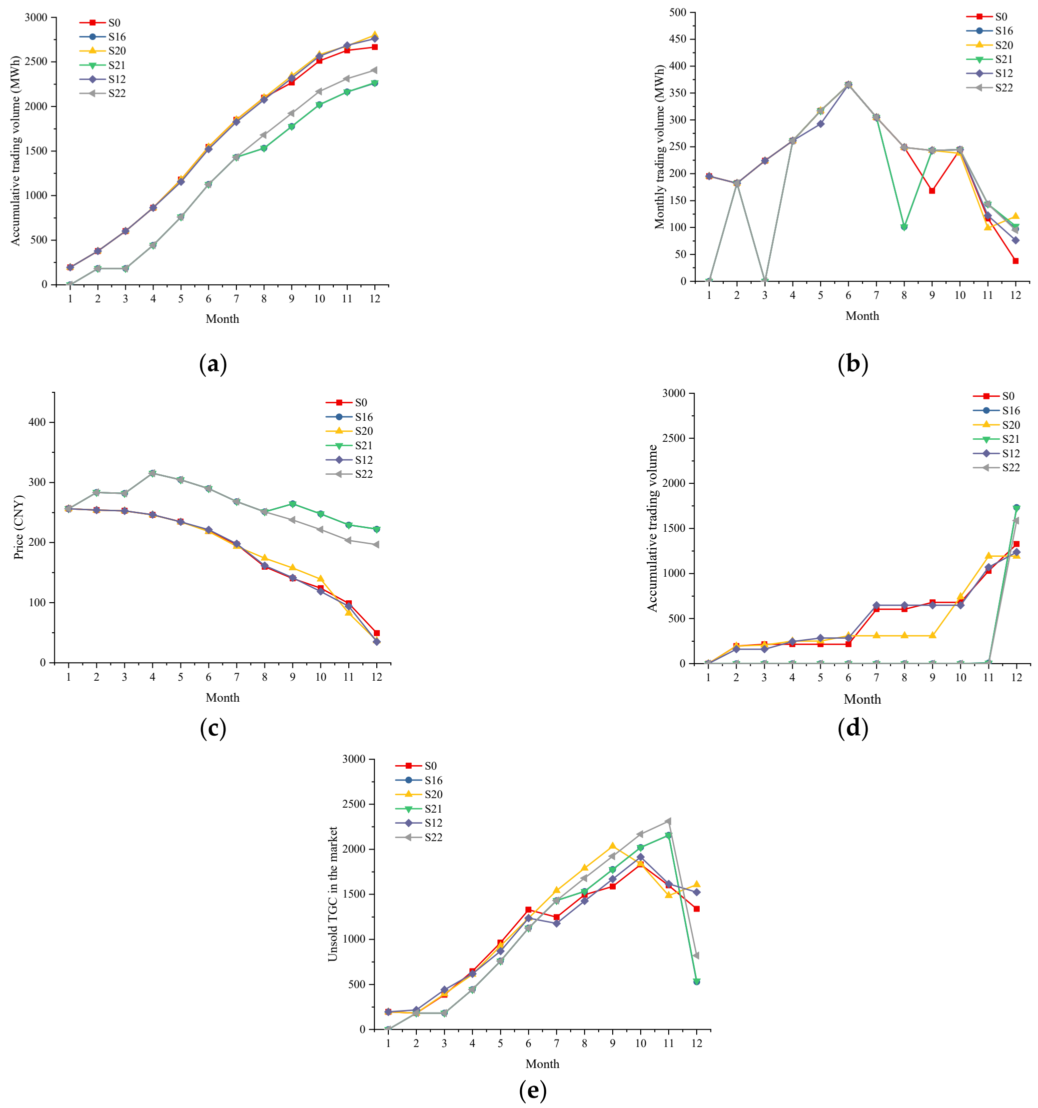


Figure 13. Trends of decision-making and market performance under different discount factors and penalties. (**a**) Accumulative renewable-power trading volume. (**b**) Monthly renewable-power trading volume. (**c**) TGC price. (**d**) Accumulative TGC trading volume. (**e**) Accumulative unsold TGCs.

In Figure 13c, the trends in S16, S21 and S22 are higher than in S0, S20 and S12 over time, and the trend in S22 is lower than that in S16 and S21 at end of the year. These data indicate that when responsible subjects prefer short-term benefits, the phenomenon proposed in Section 4.4, that an increase in the penalty may lead to an accelerated decline in the TGC price, still exists.

In Figure 13d, the trends in S16, S21 and S22 reach 1732, 1726 and 1586, which are 406, 533 and 348 higher than those in S0, S20 and S12, respectively. Meanwhile, in Figure 13e, the trends of unsold TGC in S16, S21 and S22 reach 528, 540 and 820 compared with S0, S20 and S12, decreasing by 811,1067 and 703, respectively. The above shows that increases in TGC transaction volume and decreases in unsold TGCs caused by preference for short-term benefits are not linear with increases in penalty; when short-term benefits are preferred, an increase in the penalty will lead to a decrease in annual TGC accumulative trading volume and an increase in unsold TGCs, which is consistent with the conclusion in Section 4.4.

5. Conclusions and Policy Implications

5.1. Conclusions

The "TGC transaction + RPS assessment" policy mix plays an important role in China's low-carbon energy transition. To study the policy's effect, this paper analyzes the coupled relationship between the TGC market and the electricity market and proposes factors that could affect TGC market performance. Further, we introduced reflexivity theory into the analysis of the relationship between demand-side responsible subjects' behaviors and the market and simulated the responsible subjects' decision-making process via constructing and solving an MDP model. The main conclusions are as follows:

(1) In general, policy parameters such as RPS weight, TGC price cap and penalty have significant impacts on responsible subjects' renewable power and TGC transaction behavior under the "TGC transaction + RPS assessment" policy mix, and it is by no means true that the higher or lower a parameter is, the more it can promote the demand side to complete the RPS target. Additionally, the policy's effect is also influenced by other factors, including demand-side subjects' preference for short-term benefits, renewable-energy uncertainty, price difference, etc.

(2) Under the annual assessment and penalty mechanism, increasing RPS weight within an appropriate range can improve responsible subjects' enthusiasm for purchasing renewable power and TGCs and willingness to bear the risks caused by renewable-energy uncertainty without significantly increasing costs. Additionally, an increase in RPS weight can effectively alleviate price fluctuation of TGCs. However, when the RPS weight is set at a low range, increasing the RPS weight will have a stronger stimulating effect on the demand for renewable power than on the demand for TGCs, which may lead to excessive accumulation of unsold TGCs; as a result, renewable-energy manufacturers cannot relieve operating pressure via selling TGCs. This is contrary to the original intention of promoting renewable-energy development and alleviating subsidy pressure via establishing the RPS and TGC markets. In addition, when responsible subjects prefer short-term benefits, they tend to increase TGC purchases and reduce renewable-power purchases to complete RPS targets, which will become more and more obvious with increases in RPS weight. In addition, when the penalty is equal to the TGC price cap, excessively increasing RPS weight can lead to a sharp drop in the transaction volumes of renewable power and TGCs.

(3) When the RPS target is higher than the annual available renewable-unit output, appropriately increasing the TGC price cap will not significantly increase the cost of completing the RPS target for responsible subjects and will increase the purchase of renewable energy, but the responsible subjects will reduce the total purchases of TGCs. That is to say, if the TGC price cap is too high, it may lead to accumulation of massive unsold TGCs, which will further increase the difficulty for renewable-energy manufacturers to recover operating costs through TGC transactions. It is worth noting that when the RPS weight is too low and responsible subjects prefer short-term benefits, increasing the TGC price cap has no significant impact on responsible subjects' purchasing strategies for renewable power and TGCs or RPS completion progress.

(4) Setting a penalty of no less than the TGC price cap can ensure effective operation of the TGC market. Appropriately increasing the penalty can increase the willingness of responsible subjects to undertake the uncertainty risk and to purchase more renewable power while not causing a significant impact on transaction costs. However, an increase in the penalty will cause declines in price and trading volume in the TGC market and an increase of unsold TGCs. It should also be noted that when the RPS weight is high, setting a penalty greater than the TGC price cap is necessary to promote the completion of the RPS target, and an increase in the penalty can promote monthly and annual TGC purchases. In addition, when responsible subjects prefer short-term benefits, the increase in renewable-power transactions and unsold TGCs and the decline in TGC transactions and TGC prices due to increased penalties still exist. However, an increase in the penalty can alleviate the decline in renewable-power

transactions caused by the preference for short-term benefits, as mentioned in (1), to a certain extent.

However, there are still some limitations to this study. First, due to the limited data, the demand-side responsible subjects are regarded as a unified whole in this paper, which ignores the differences and competition between responsible subjects. Second, in order to facilitate this simulation, this paper assumes that the electricity price is an external parameter. However, under RPS policy, TGC market performance will affect the demand for renewable power, which in turn affects the electricity price. Finally, according to China's policy, RPS weight is divided into total RPS weight and non-hydro RPS weight; however, the study in this paper did not consider the relevant factors in the simulation due to limited data and unclear policies. In view of this, future studies can be carried out on the competition between responsible subjects, the spillover effect of the TGC market and the ratio of total RPS weight and non-hydro RPS weight so as to provide a more comprehensive reference for formulation and supervision of relevant policies.

5.2. Implications

Based on the simulations and conclusions, we put forward two suggestions, as follows:

(1) Promote the transition of the TGC transaction mode from voluntary subscription to market-oriented transactions. Under the RPS policy, reasonable policy parameter design and market-oriented transactions can fully urge responsible subjects to complete the RPS target. In view of this, while improving RPS policy, the government should continuously improve the TGC market framework from the dimensions of access and exit mechanisms, clearing methods, settlement mechanisms and regulatory mechanisms. These measures can fully restore the commodity attributes of TGCs through cooperation of the "visible hand" and the "invisible hand" and provide support for the implementation of RPSs and the orderly development of the renewable-energy industry.

(2) Build a multilevel coordinated TGC market mechanism. As pointed out in the simulations and conclusions, responsible subjects' trading decisions can be influenced by various factors, such as preference for short-term interests, renewable-energy uncertainty and renewable-energy installation capacity. Considering the differences in renewable-resource endowment, energy structure and other factors between different regions in China, the government should build a TGC market with coordinated operation within and between the provinces. Among them, the intraprovincial market would mainly provide support for the optimal allocation of resources and operating-cost recovery for renewable-energy manufacturers in the province; the interprovincial market would aim to meet the needs of large-scale optimal allocation of resources and promote sustainable development of renewable energy.

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Nomenclature

Symbol	Description
$r^{\text{sell}}, r^{\text{buy}}$	Discount rate of buyer and seller
$Q_t^{\text{RPS,comp}}$	RPS target that has been completed by time step t
$s_t^{\text{p\_TGC}}$	TGC price at time step t
$s_t^{\text{p\_Re}}$	Renewable-power price at time step t
$s_t^{\text{p\_balance}}$	Price of electricity in the balanced market at time step t
s_t^{δ}, δ_t	Utility coefficient at time step t
s_t^{Re}, P_t^{Re}	Actual available renewable-energy output at time step t
$s_t^{\text{Re\_}error}$, ΔP_t^{Re}	Error in predicting output of renewable energy at time step t
s_t^{demand}	Power demand at time step t
$s_t^{\text{TGC\_avl}}$	TGCs available for transactions at time step t, that is, accumulation of unsold TGCs
a_t^{TGC}	TGCs purchased at time step t
ω_n	Weight of the *n*th normal distribution
σ_n^2	Variance of the *n*th normal distribution
C_t^{Re}	Cost of purchasing renewable power at time step t
C_t^{TGC}	Cost of purchasing TGCs at time step t
$Q^{\text{RPS,total}}$	Total RPS target
$s_t^{\text{p\_}TGC,0}$	Highest price of TGCs at time step t
$s_t^{\text{p\_TGC,buy}}$, $s_t^{\text{p\_TGC,sell}}$	Acceptable TGC price for buyers and sellers at time step t
$s_t^{\text{p\_TH}}$	Thermal-power price at time step t
$s^{\text{p\_penalty}}$	Penalty value
$s_t^{\text{PRS\_remain}}$	Uncompleted RPS target at time step t
$s_t^{\text{Re\_tech}}$, $\widetilde{P}_t^{\text{Re}}$	Predicted renewable-energy output at time step t
$s_t^{\text{Re\_error,upper}}$, $s_t^{\text{Re\_error,lower}}$	Upper bound and lower bound of confidence interval for renewable energy at time step t
$s_t^{\text{TH,min}}$, $s_t^{\text{TH,max}}$	Minimum and maximum output of thermal power at time step t
a_t^{Re}	Renewable power purchased at time step t
a_t^{TH}	Thermal power purchased at time step t
μ_n	Mean of the *n*th normal distribution
ς	Value of RPS weight
C_t^{TH}	Cost of purchasing thermal power at time step t
C^{penalty}	Penalty cost

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