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Renewable energy investment and carbon emissions under carbon cap-and-trade mechanisms and renewable portfolio standards

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ABSTRACT

The Chinese government plans to implement Carbon cap-and-trade mechanisms and Renewable portfolio standards in order to promote the transition of low-carbon. Hence, this paper constructs a monopolistic utility company model based on four policy scenarios namely: Reference scenario (FREE), Carbon cap-and-trade mechanisms (CAP), Renewable portfolio standards (RPS), and Mixed scenario (MIX). The mentioned policy scenarios were used to test the impact of various policy situations on utility company investment decision considering the existence of renewables, new conventional energy sources (such as natural gas) and conventional energy sources (such as coal) in the market. In addition, social welfare under each scenario through numerical simulations, together with the impact of key parameters related to emission reduction mechanism on social welfare were compared. The results show both CAP and RPS can effectively reduce carbon emissions. In terms of renewable energy promotion, the effect under MIX is the best comparatively. Further, MIX recorded the highest level of social welfare during the present stages of China's low-carbon transition. The study provides some new suggestions for policy-makers.

Keywords: Carbon cap-and-trade mechanisms, Renewable portfolio standards, Renewable energy investment, Carbon emission, Social welfare

NONMENCLATURE

Abbreviations	
FREE	Reference scenario
CAP	Carbon cap-and-trade mechanisms
RPS	Renewable portfolio standards
MIX	Mixed scenario
Symbols	
N	Index of emission reduction mechanisms including FREE, CAP, RPS and MIX
p^N	Unit electricity price under the mechanism N
$\alpha_c/\alpha_n/\alpha_r$	Unit production cost of conventional energy/ new conventional energy/ renewable energy ($\alpha_r > \alpha_n > \alpha_c$)
$x_c^N/x_n^N/x_r^N$	Production of conventional energy/ new conventional energy /renewable energy
$*$	Indicating the optimal solutions
e_1/e_2	Unit carbon emissions from conventional energy/ new conventional energy ($e_2 < e_1$)
σ/δ	Unit carbon price/TGC price

1. INTRODUCTION

As the world's largest energy consumer, China has pledged to adopt more effective policies and measures, reach the peak of carbon dioxide emissions by 2030, and as well achieve carbon neutrality by 2060 [1]. In order to achieve the "dual carbon" goal more quickly, China has formulated series of carbon emission reduction policies and renewable energy support mechanisms[2] . Carbon cap-and-trade mechanisms (CAP) and Renewable portfolio standards (RPS) have become effective policies for China to actively promote the development of new energy.

Many literatures have theoretically discussed the coordination of carbon emission reduction policy and renewable energy policy [3]. However, comparative studies on the two policies in China are relatively rare [4]. Hence, this paper constructs a utility company model based on related theories to examine the impact of CAP and RPS on investment decisions of the utility company facing existing energy sources.

This paper mainly has the following contributions: (1) Considering the utility company model under CAP and RPS, the policy background is divided into four scenarios. (2) In order to describe the decision-making behavior of public utility companies in details, this paper not only

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considers conventional energy and renewables, but also introduces new conventional energy represented by natural gas. (3) Furthermore, this research not only considers the objective function of enterprise profit maximization, but also accounts for social welfare.

2. METHODOLOGY

2.1 Scenario design

This paper attempts to compare the impact of different policy mechanisms on carbon emission reduction and renewable energy investment. First, this research considers the following four policy scenarios [5] ：

(1) In the Reference scenario, the government does not impose any low-carbon policies.

(2) Under CAP, the government has set a unit carbon emission cap e_0. Companies can be fined if the unit carbon emission is more than e_0. Or companies can trade on the carbon market to avoid penalties.

(3) Under RPS, the government has set the weight θ of responsibility for renewable energy consumption. A company can purchase green certificates to avoid penalties if its renewable electricity consumption does not exceed θ.

(4) The Mixed scenario simulates the simultaneous implementation of Carbon cap-and-trade mechanisms and Renewable portfolio standards in China.

2.2 Model assumptions

In this paper, a monopolistic utility company that can determine the price of electricity in various policy situations is considered. The decision-makers of public utility companies will choose the scheme that benefits them the most on an equal footing.

$Demand$. When the electricity price changes, consumers' demand for electricity changes linearly with respect to the electricity price, i.e., $D^N = a - bp^N$. Where, a represents the potential electricity demand in the market, and b denotes the sensitivity coefficient of consumers to the electricity price; $a > 0$, $b \in (0,1)$.

$Supply$. Suppose the utility company already owns a fleet of conventional power plants and considers additional investments in new conventional energy and renewable energy. Among them, the new conventional energy, such as advanced natural gas power plant, it's production cost is higher than that of existing conventional energy but lower than renewable energy. Due to the different variable operating costs of energy sources, the variable operating costs can be reduced in this model when renewables first enters the power grid to meet the electricity demand, followed by new conventional energy, and finally conventional energy [6].

$Cost$. This model unifies the investment cost and generation cost of energy into production cost, and as well assumes that the production cost function of three types of energy is quadratic. It is assumed that the unit production cost of conventional energy is $G_c = \frac{\alpha_c}{2} x_c^2$, that of new conventional energy and renewable energy is $G_n = \frac{\alpha_n}{2} x_n^2$ and $G_r = \frac{\alpha_r}{2} x_r^2$ correspondingly.

$Carbon\ Emissions$. It is assumed that the carbon emission intensity for three kinds of energy is e_1, e_2 and 0. Notably e_2 is assumed to be less than e_1.

2.3 Utility company model

This section analyzes a monopolistic utility company in the market to maximize its profits under various policy situations, by determining the electricity price and controlling the investment in new conventional energy and renewables. The objective function of this model is to maximize the profit of public utility companies, assuming that the profit function is $\Pi^N(p^N, x_r^N, x_r^N)$.

2.3.1 Reference scenario

In this scenario, the government does not have any mandatory low-carbon policy. The profit function is:

$$\Pi^F(p^F, x_n^F, x_r^F) = D^F p^F - \frac{1}{2}\alpha_c(D^F - x_n^F - x_r^F)^2 - \frac{1}{2}\alpha_n {x_n^F}^2 - \frac{1}{2}\alpha_r {x_r^F}^2 \quad (1)$$

There are four items on the right side of Eq. (1). The first item corresponds to the electricity sales income of the utility company, and the last three items are the production costs of three types of energy.

2.3.2 Carbon cap-and-trade mechanisms

The profit of the utility company is expressed as:

$$\Pi^C(p^C, x_n^C, x_r^C) = D^C p^C - \frac{1}{2}\alpha_c(D^C - x_n^C - x_r^C)^2 - \frac{1}{2}\alpha_n {x_n^C}^2 - \frac{1}{2}\alpha_r {x_r^C}^2 + [e_0 D^C - e_1(D^C - x_n^C - x_r^C) - e_2 x_n^C]\sigma \ (2)$$

The right side of Eq. (2) consist of five items which in systematic order includes, the company's electricity sales revenue, production costs of conventional energy, new conventional energy and renewable energy, and additional cost of carbon emissions. The last item is caused by the carbon emissions generated by the company's power generation. Specifically, D^C represents the total power generation under this scenario, whereas, $e_0 D^C$ represents total carbon quota allocated according to unit carbon quota.

2.3.3 Renewable portfolio standards

In this situation, The profit of the utility company is

$$\Pi^R(p^R, x_n^R, x_r^R) = D^R p^R - \frac{1}{2}\alpha_c(D^R - x_n^R - x_r^R)^2 - \frac{1}{2}\alpha_n {x_n^R}^2 - \frac{1}{2}\alpha_r {x_r^R}^2 + (x_r^R - \theta D^R)\delta \ (3)$$

There are five items on the right of equation (3), which includes the company's electricity sales income, production costs of conventional energy, new conventional energy and renewable energy correspondingly. The last one is the additional cost that companies may incur by investing in renewable generation. D^R is the total power generation in this scenario, whiles θD^R is the total renewable energy consumption allocated according to the responsibility.

2.3.4 Mixed scenario

In this scenario, decisions of the utility company are jointly constrained by e_0 and θ. The profit of the utility company is derived through the following equation:

$$\Pi^M(p^M, x_n^M, x_r^M) = D^M p^M - \frac{1}{2}\alpha_c(D^M - x_n^M - x_r^M)^2 - \frac{1}{2}\alpha_n {x_n^M}^2 - \frac{1}{2}\alpha_r {x_r^M}^2 + [e_0 D^M - e_1(D^M - x_n^M - x_r^M) - e_2 x_n^M]\sigma + (x_r^M - \theta D^M)\delta \quad (4)$$

Evidently, the right side of Eq. (4) consist of six items which in systematic order includes, the company’s electricity sales revenue, production costs of conventional energy, new conventional energy and renewable energy, additional cost of carbon emissions generated by the company's power generation, and the possible additional cost of investing in renewable generation correspondingly.

2.4 Optimal solution

With reference to the assumptions in section 2.2 and the profit function in section 2.3, the optimal solution of electricity price p^N, new conventional energy investment x_n^N and renewable energy investment x_r^N under four policy situations can be solved. Combined with the optimal solution of electricity price, new conventional energy investment and renewable energy investment together, the market demand D^{N^*} and total carbon emission E^{N^*} under the optimal solution can be obtained. Some results are listed here, as shown in Table 1.

Table 1

Optimal renewable energy production($x_r^{N^*}$)[1].

N	$x_r^{N^*}$
F	$\frac{a\alpha_c\alpha_n}{I_1}$
C	$\frac{a\alpha_c\alpha_n + 2\alpha_c e_2\sigma + 2\alpha_n e_1\sigma + \alpha_c\alpha_n b e_0\sigma}{I_1}$
R	$\frac{a\alpha_c\alpha_n + 2\alpha_c\delta + 2\alpha_n\delta + \alpha_c\alpha_n b\delta - \alpha_c\alpha_r b\theta\delta}{I_1}$
M	$\frac{a\alpha_c\alpha_n + 2\alpha_c e_2\sigma + 2\alpha_n e_1\sigma + \alpha_c\alpha_r b e_0\sigma + 2\alpha_c\delta + 2\alpha_n\delta + \alpha_c\alpha_n b\delta - \alpha_c\alpha_r b\theta\delta}{I_1}$

[1] From Table 2, $I_1 = 2\alpha_c\alpha_n + 2\alpha_c\alpha_r + 2\alpha_n\alpha_r + \alpha_c\alpha_n\alpha_r b$.

[2] In Corollary 1, $\theta_1 = \frac{2\alpha_c\delta+2\alpha_n\delta+\alpha_c\alpha_n b\delta-\alpha_c\alpha_n b e_0\sigma-2\alpha_n e_1\sigma-2\alpha_c e_2\sigma}{\alpha_c\alpha_n b\delta}$

[3] In Corollary 1, $\dot{e}_0 = \frac{2\alpha_c\delta+2\alpha_n\delta+\alpha_c\alpha_n b\delta-\alpha_c\alpha_n b\theta\delta-2\alpha_n e_1\sigma-2\alpha_c e_2\sigma}{\alpha_c\alpha_n b\sigma}$

3. THE IMPACT OF EMISSION-REDUCTION POLICIES

This section mainly centers on studying the impact of emission reduction requirements under different policies on renewable energy investment level and carbon emissions by considering the model in Section 2. At the end of this section, the social welfare function is established.

We present the following assumption imposed throughout the paper.

Assumption 1:

$$\alpha_r \geq \max\{\frac{2\alpha_n e_1\sigma}{a\alpha_n + \alpha_n b e_0\sigma - \alpha_n b e_1\sigma - 2e_1\sigma + 2e_2\sigma}, \frac{2\alpha_n\delta}{a\alpha_n - \alpha_n b\theta\delta}, \frac{2\alpha_c e_2\sigma}{a\alpha_c+\alpha_c b e_0\sigma-\alpha_c b e_2\sigma+2e_1\sigma-2e_2\sigma}, \frac{2\alpha_c\delta}{a\alpha_c-\alpha_c b\theta\delta}\}$$

Assumption 1 shows that the production cost of renewable energy is high enough at this stage. Hence, the power generation of new conventional energy and conventional energy in any case cannot be less than 0.

3.1 Renewable energy investment levels

First, considering the impact of emission-reduction policies on the investment level of renewable energy, we can obtain Corollary 1[2,3]:

Corollary 1: When $\theta \leq \theta_1$ $(e_0 \leq \dot{e}_0)$, $x_r^{F^*} \leq x_r^{C^*} \leq x_r^{R^*} \leq x_r^{M^*}$; When $\theta \geq \theta_1$ $(e_0 \geq \dot{e}_0)$, $x_r^{F^*} \leq x_r^{R^*} \leq x_r^{C^*} \leq x_r^{M^*}$.

According to the date given in Section 4, we can deduce that $\frac{2\alpha_c\delta+2\alpha_n\delta+\alpha_c\alpha_n b\delta-\alpha_c\alpha_n b\theta\delta-2\alpha_n e_1\sigma-2\alpha_c e_2\sigma}{\alpha_c\alpha_n b\sigma}$ is much greater than 1. Therefore, it is certain that $e_0 \leq \frac{2\alpha_c\delta+2\alpha_n\delta+\alpha_c\alpha_n b\delta-\alpha_c\alpha_n b\theta\delta-2\alpha_n e_1\sigma-2\alpha_c e_2\sigma}{\alpha_c\alpha_n b\sigma}$, that is, $x_r^{F^*} \leq x_r^{C^*} \leq x_r^{R^*} \leq x_r^{M^*}$. It is evident that under MIX, the output of renewable energy is the largest, followed by that under RPS, whereas the promotion effect of renewable energy under FREE had the least record. According to Corollary 1, we can get Proposition 1.

Proposition 1: For renewable energy promotion, MIX has the best effect, followed by RPS.

3.2 Total carbon emissions

In this section, the impact of emission-reduction policies on total carbon emissions is considered. By comparing the total carbon emissions under different various scenarios, Corollary 2 can be derived.

Corollary 2[4]**:** When $e_0 \leq \underline{e_0}$, $E^{M^*} \leq E^{C^*} \leq E^{R^*} \leq E^{F^*}$; When $\underline{e_0} \leq e_0 \leq \widetilde{e_0}$, $E^{M^*} \leq E^{R^*} \leq E^{C^*} \leq E^{F^*}$; When $\widetilde{e_0} \leq e_0 \leq \overline{e_0}$, $E^{R^*} \leq E^{M^*} \leq E^{F^*} \leq E^{C^*}$; and When $e_0 \geq \overline{e_0}$, $E^{R^*} \leq E^{F^*} \leq E^{M^*} \leq E^{C^*}$.

[4] We assume $L_3 = 2\alpha_n e_1^2\sigma + \alpha_n\alpha_r b e_1^2\sigma + 2\alpha_r e_1^2\sigma + 2\alpha_c e_2^2\sigma + \alpha_c\alpha_r b e_2^2\sigma + 2\alpha_r e_2^2\sigma - 4\alpha_r e_1 e_2\sigma$, $\underline{e_0} = \frac{L_3-2\alpha_n e_1\delta-\alpha_n\alpha_r b\theta e_1\delta-2\alpha_c e_2\delta-\alpha_c\alpha_r b\theta e_2\delta}{\alpha_n\alpha_r b e_1\sigma+\alpha_c\alpha_r b e_2\sigma}$, $\widetilde{e_0} = \frac{L_3}{\alpha_n\alpha_r b e_1\sigma+\alpha_c\alpha_r b e_2\sigma}$, $\overline{e_0} = \frac{L_3+2\alpha_n e_1\delta+\alpha_n\alpha_r b\theta e_1\delta+2\alpha_c e_2\delta+\alpha_c\alpha_r b\theta e_2\delta}{\alpha_n\alpha_r b e_1\sigma+\alpha_c\alpha_r b e_2\sigma}$.

Observing Corollary 2, it is evident that when the unit carbon quota is relatively low ($e_0 \leq \widetilde{e_0}$), the effect of MIX on controlling carbon emissions is the best, while that of FREE is the worst. On the one hand, renewable energy produces no emission. On the other hand, MIX aims not only to promote renewable energy, but also to reduce carbon emissions. Therefore, at this time, the total carbon emission under MIX is estimated to be the lowest. However, FREE does not implement any carbon emission control measures, hence the total carbon emission is the highest. When the unit carbon quota is high ($e_0 \geq \widetilde{e_0}$), the emission-reduction effect of RPS is regarded as the best, whereas that of CAP is the worst. This is because when e_0 is relatively large, it means that the government is not strict in carbon emission control, and CAP is mainly controlled by e_0, so the total carbon emission under CAP is the highest. The implementation of RPS is mainly affected by θ. When e_0 is high, RPS still needs to achieve the goal of producing quantitative renewable energy. Hence the total carbon emission under RPS is recorded as the lowest.

From the data in Section 4, we can get $\underline{e_0} = -40.018$, $\widetilde{e_0} = 5.549$, $\overline{e_0} = 51.115$. Obviously, there is $\underline{e_0} \leq e_0 \leq \widetilde{e_0}$. Through calculation, $E^{M^*} \leq E^{R^*} \leq E^{C^*} \leq E^{F^*}$ can be obtained, hence the corollary is reasonable.

Proposition 2: The optimal carbon emission regulation mechanism for the utility firm is [7]:

(1) MIX if $e_0 \leq \widetilde{e_0}$;

(2) RPS if $e_0 > \widetilde{e_0}$.

3.3 Social welfare maximization

This section mainly examines the maximization of social welfare, so that utility companies and consumers can benefit from it.

3.3.1 Consumer surplus

According to the assumptions in Section 2.2, consumer surplus can be expressed as $CS^* = \int_0^D p(D)dp - p(D) \times p = \frac{a^2 - 2abp^* + b^2p^{*2}}{2b} = \frac{(a-bp^*)^2}{2b}$. The consumer surplus is observed as a quadratic function of electricity price p^*.

3.3.2 Social welfare function

Social welfare is the appropriate criterion for evaluating any policy or plan [8]. Considering the benefits of the two economic actors of manufacturers and consumers together with the environmental negative externality of power plant production, social welfare is regarded in this stage as a consumer surplus plus producer profit minus the external cost caused by carbon emission:

$$SW^* = CS^* + \Pi^* - C_E^* \quad (5)$$

Among Eq. (5): C_E^* is the external cost caused by the production of non-renewable energy, and is given by the relation $C_E^* = \beta\alpha_c x_c^* + \gamma\alpha_n x_n^*$. C_E^* is related to the production cost and output of two non-renewable energy sources. β and γ are the impact factors of conventional energy and new conventional energy on ecological environment, and $0 < \gamma < \beta < 1$.

4. SIMULATION AND DISCUSSION

4.1 Data

We select parameter values based on information provided in industry reports and the study in the literature [9,10]. We set $b = 0.72(\text{kwh})$, $a = 6264(\text{Gwh})$. $\sigma = 0.04(\text{yuan/kg})$, $\delta = 0.4(\text{yuan/kwh})$, $\alpha_c = 0.385(\text{yuan/kwh})$, $\alpha_r = 0.645(\text{yuan/kwh})$, $\alpha_n = 0.452(\text{yuan/kwh})$, $e_1 = 0.96(\text{kg/kwh})$, $e_2 = 0.443(\text{kg/kwh})$. The standards of renewable energy quota θ and the unit carbon quota e_0 vary in different provinces and regions. In this section, the different values of the two quotas are divided into three cases namely: low standard, medium standard and high standard.

4.2 Sensitivity analysis

From the Eq. (5), social welfare is seen to be affected by the parameters e_0 and θ. Hence, in order to ensure the accuracy of the simulation results, this paper conducts sensitivity analysis on these two parameters respectively. We assumed $\beta = 0.1$ and $\gamma = 0.05$.

4.2.1 Unit carbon quota e_0

When observing the impact of e_0 on social welfare, we set three scenarios according to the renewable energy quota are set as follows: $\theta = 15\%$ corresponds to low standard, $\theta = 25\%$ corresponds to medium standard, and $\theta = 40\%$ corresponds to high standard.

From Fig.1(a)-(c), we can deduce that the social welfare level increases with increasing e_0 value. This can be due to the reason being that, as the unit carbon quota increases, the profits of public utility companies in the carbon trading market gradually increased, and as such causes the overall level of social welfare to rise.

According to Fig.1(a)-(c), we can analyze that: when the renewable energy quota θ is 15%, compared to CAP, MIX can achieve a higher level of social welfare. On the one hand, this may be because if MIX is implemented when θ is set relatively low, public utility companies can make profits in the green certificate market. On the other hand, according to Corollary 1, the investment in renewable energy under MIX is the largest, hence the environmental externality cost is low. Furthermore, when θ is low, CS^{MIX} is always larger than CS^{CAP}. These three reasons lead to a higher level of social welfare under MIX. When $\theta = 25\%$, the renewable energy quota is medium, the social welfare level of CAP and MIX evidenced to be similar. When $\theta = 40\%$, the renewable energy quota at this stage is relatively high, which should appear in the middle and late stages of promoting renewable energy in China. If the public utility company still cannot reduce the cost of renewable energy generation through innovation, the reduced environmental externality cost under MIX will no longer be able to offset the lost profits in the market. Furthermore, when θ is relatively high, CS^{MIX} is always smaller than CS^{CAP}, therefore, social welfare will be lower under MIX.

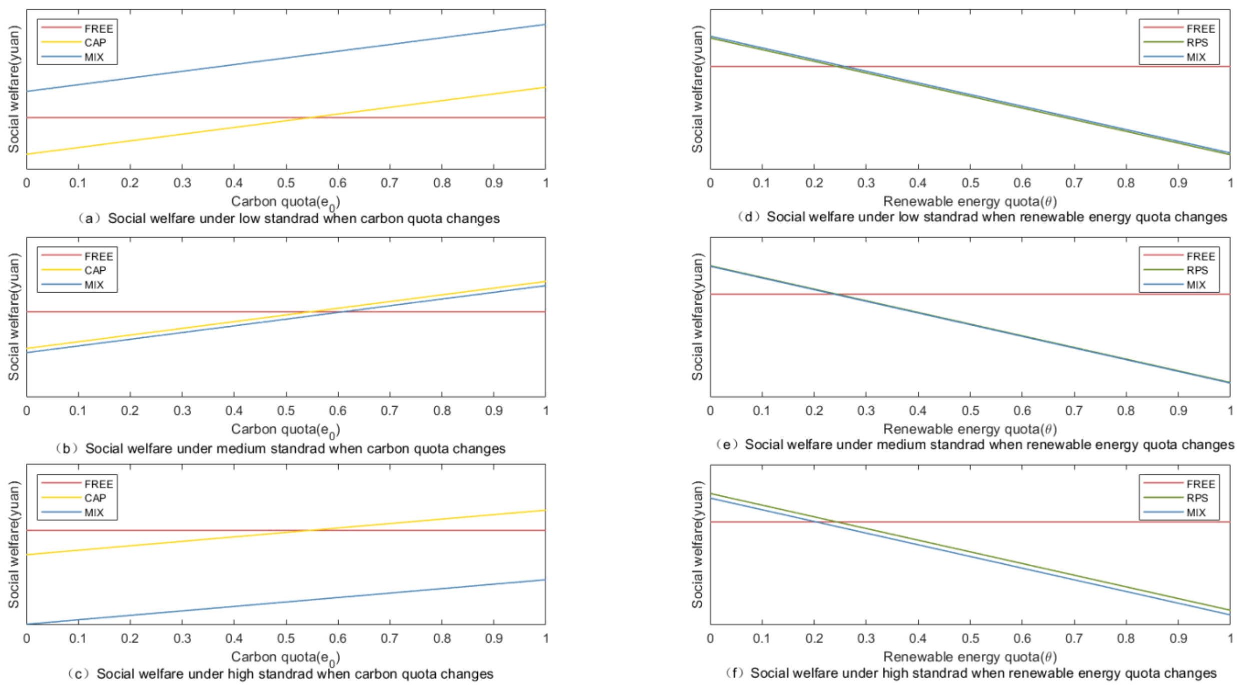

Fig.1. Social welfare under FREE, CAP, RPS, MIX

4.2.2 Renewable energy quota θ

When observing the impact of θ on social welfare, three scenarios are also set according to the unit carbon quota e_0: $e_0 = 70\%$ corresponds to low standard, $e_0 = 50\%$ corresponds to medium standard and $e_0 = 15\%$ corresponds to high standard.

Figure.1(d)-(f) clearly shows that as the value of θ increases, the overall level of social welfare decreases. That is because when θ continues to increase, the pressure on public utility companies to produce renewable energy will increase sharply. This therefore greatly causes the production cost to increase, resulting in a sharp rise in the electricity price, and as a result leads to market turbulence, which in turn declines the market demand and company profits sharply. The above lead to the decline in social welfare level.

When $e_0 = 70\%$, the government's requirements for unit carbon emission are relatively low, which means that utility companies can obtain higher profits in the carbon trading market under MIX. In addition, the promotion effect of renewable energy under MIX is the best, hence the environmental externality cost is relatively low. Furthermore, when e_0 is high, CS^{MIX} is always larger than CS^{RPS}. The outlined reasons therefore lead to a higher level of social welfare under MIX. Further, when $e_0 = 50\%$, the government's requirements for unit carbon emission are at a medium level and the level of social welfare in the two scenarios is similar. Moreover, when $e_0 = 15\%$, policy makers control carbon emissions more strictly. If the production cost of renewable energy for the utility company remains unchanged, the profit lost in the carbon trading market under MIX therefore cannot be offset by the reduced environmental externality cost, hence the social welfare under MIX will be lower than that under RPS.

5. CONCLUSION AND POLICY IMPLICATIONS

This paper constructs a utility company model, designs four policy scenarios, compares the optimal decisions of the company under these scenarios, and as well examines the impact of different policy scenarios on renewable energy investment and carbon emissions. In particular, the study utilized numerical simulations to compare the level of social welfare under each scenario. Through the analysis of this paper, the main conclusions are as follows:

(1) Both CAP and RPS can effectively reduce carbon emissions. When carbon quota is relatively low, MIX has the best effect on controlling carbon emissions, while FREE has the worst effect. On the other hand, when carbon quota is relatively high, the emission-reduction effect of RPS is the best whereas that of CAP is the worst.

(2) In terms of renewable energy promotion, MIX has the best effect. Both CAP and RPS have positive effects on the promotion of renewable energy. Hence, no matter which policy is implemented, the promotion effect of renewable energy will not be as good as that under MIX.

(3) According to the current carbon quota and renewable energy quota, the social welfare level under MIX is the highest. However, when China's social low-carbon transformation develops to the middle and late stages, MIX will lose the advantage of the highest level of social welfare, if there is still no technical breakthrough in the production of renewables.

Based on the research results obtained, we put forward some policy suggestions.

Firstly, in order for the government to meritoriously exert the effectiveness of the policy, it needs to flexibly combine CAP and RPS, reasonably control the size of unit carbon quota, and set the weight of renewable energy power consumption according to the actual situation. While giving full play to the role of the market to regulate carbon price and TGC price, the government should also play a regulatory role.

Secondly, when the carbon quota is relatively low, decision makers of utility companies prefer MIX to control carbon emissions. With the increase of carbon quota, decision makers are more inclined to choose RPS. This provides an effective idea for the negotiation between the government and public utility companies. When reasonably allocating the emission-reduction task to power companies, it is necessary to combine the setting of carbon quota with the control mechanism, otherwise it will be difficult to have an optimistic emission-reduction effect.

Finally, whether at this stage or in the middle and late stage of China's social low-carbon transformation, if the government still implements CAP and RPS at the same time, and as well wants to obtain a higher level of social welfare, it should reduce the cost of renewable energy power generation from the perspective of technological innovation and encourage utility companies to invest heavily in renewable energy.

This study considers the optimal decisions made by monopolistic utility companies to invest in renewable energy and conventional energy under four emission-reduction policy scenarios. Due to the nature of the model, this research has certain limitations. Firstly, this article does not take into account the volatility of renewable energy supply over time. The variable operation cost of natural gas is low. Therefore, how to increase the investment in natural gas for peak shaving can be a research direction in the future. Secondly, the generation cost of renewables changes over time. With the technological innovation, the cost of renewable energy power generation and energy storage is gradually reduced. Therefore, the variability of power generation cost of renewable energy over time can be included in the scope of future research. These research directions are worthy of further exploration.

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