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How to design renewable energy support policies with imperfect carbon pricing?

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Based on the emission trading scheme (ETS), this study built a design framework of renewable energy support policies (RES), which is employed to assess the interaction between RES and ETS. For RES, we consider two policy instruments: feed-in-tariff (FIT) and renewable portfolio standards (RPS). Based on the partial equilibrium model, taking the case of China's electricity market, this study quantitatively discusses the implementation effects of six different policy mix scenarios from three aspects: emission reduction, production of green electricity, and social welfare. According to the results, there were big differences among the implementation effects of different RES instruments based on ETS. The renewable subsidy policy, on the whole, is better than renewable portfolio standards in terms of emission reduction, but worse in terms of improving the production of green electricity. In addition, different from the renewable subsidy policy, the renewable portfolio standards can reduce social welfare. When the emission quota is eased, RES can be implemented to significantly improve social welfare. These simulation results inspire China for the design of effective energy policies.

KEYWORDS

carbon pricing, renewable portfolio standards, social welfare, feed-in tariffs, emission trading scheme

1 Introduction

In recent years, energy shortage and environmental pollution have become increasingly serious, and the energy transition by promoting, developing, and utilizing renewable energy sources has become a consensus and concerted action of the international community (IEA, 2020). However, due to immature technologies and the high cost of renewable energy sources, its market competitiveness is weak. To support the development of the renewable energy industry, many OECD countries have implemented different types of renewable energy support policies. For example, the renewable energy feed-in-tariff (FIT), renewable portfolio standards (RPS), and other policies that can directly stimulate the installed capacity of renewable energy. Different from FIT where a fixed amount of money is paid for each kWh of green electricity, RPS compulsorily stipulates the market share of green electricity in the form of law. Fossil fuel power generation companies can meet RPS by purchasing renewable energy credits (RECs) from the green electricity generation companies or paying heavy fines; thus REC is a policy instrument to implement RPS. Moreover, an emission trading scheme (ETS) is also widely applied. Although it was not specifically designed for renewable energy, it can indirectly stimulate investment in renewable energy by increasing the cost of fossil energy. Since 2013, the Chinese government has formulated a series of policies for the production of green electricity and determined RES as a key component of its development plan (Mischke and Karlsson, 2014; Wang et al., 2014).

Among many renewable energy support policies, FIT is considered to be more effective because it can provide investors with long-term financial stability, but the high cost of subsidies imposes a heavy financial burden on the governments (Zhang et al., 2018). To reduce the aforementioned burden, RPS and REC become alternatives in different jurisdictions (Zhou and Zhao, 2021). Meanwhile, REC can bring economic incentives to cost-effective renewable energy companies, but there is still the risk of price volatility. When the primary goal is reducing emissions, a single RES-E policy (whether FIT or RPS) is always less cost-effective than a carbon pricing policy (Palmer and Burtraw 2005; Fischer and Newell 2008). Some scholars point out that a single policy cannot effectively meet multiple policy goals at the same time (Fischer and Carolyn, 2010). The successful transition to a low-carbon economy depends on the joint effect of low-carbon technology investment and renewable energy development, so it is necessary to adopt policy mixes (Gugler et al., 2021). But due to the volatility and intermittency of RES, these policies may restrain each other to some extent.

To avoid the possible negative effects or to take advantage of the potential synergistic effect of multiple policies, it is necessary to understand how different policy mechanisms interact with each other. In the case of two competing energy sources, which policy can bring more renewable energy investment, lower carbon emissions, and higher social welfare? How does the emission cap in ETS affect the implementation effect of renewable energy support policies? If the goal of the government is to raise the renewable energy share, what does the impact of the subsidy instruments and market mean? However, these issues are seldom talked about in current studies (Kök et al., 2018).

The research objective of this study is to quantify the effectiveness and interaction of ETS and renewable energy support policies. First of all, we built a partial equilibrium model to discuss the interaction mechanisms between ETS and renewable energy support policies. Then, we, combining the theoretical model and numerical model and taking the case of China's electricity market, assessed the performances of different policies in emission reduction, production of green electricity, and social welfare. According to the model result, there were big differences among the implementation effects of different renewable energy support policy instruments based on ETS. The renewable subsidy policy is better than RPS in terms of emission reduction and social welfare, but less effective in terms of improving the production of green electricity.

The rest of this study is organized as follows: the second part introduces the studies on ETS and renewable energy support policies conducted by domestic and foreign scholars. The third part presents the analytical model and describes the supply and demand situation of the electricity market under different policy scenarios as well as the decision-making behavior of two major market players—producers and consumers. The fourth part describes the numerical model and method design. The fifth part discusses the results, and the sixth part draws a conclusion and gives policy implications.

2 Literature review

Domestic and foreign scholars have conducted a series of studies on ETS and renewable energy support policies. First, according to the investigations and research, ETS alone cannot realize the emission reduction and energy objective. Second, we reviewed the necessity, implementation effects, and interactions of the policy mixes.

The economic theory clearly emphasizes that market means should be made full use of to fix a price for social losses caused by greenhouse gas emissions, which will help to stimulate the internalization of externalities of carbon emissions (Pigou, 1920). Therefore, many economists (Branger et al., 2015; Metcalf, 2009) have always considered the emission trading scheme (ETS) as an important emission reduction instrument for a long time, because it can realize emission reduction at the lowest cost. In the real world, however, there are many restrictions on making environmental policies. The economically effective and optimal emission trading market requires a valid high carbon price, which is difficult to realize. This is also proven by the empirical evidence from the EU emission trading market (Perino and Jarke, 2015). The supply–demand imbalance of emission quotas and various uncertainties in the electricity market lead to a low carbon price (Lecuyer and Quirion, 2016). Therefore, ETS alone is not enough to stimulate emission reductions (IEA, 2020). The energy transition requires the deployment of green electricity, but ETS has a limited effect on renewable energy development and cannot provide sufficient incentives for technological innovation. Another reason why ETS is not enough is that ETS is indirect. Firms can also decarbonize by using efficiency measures or switching fuel (e.g., from coal to gas). Firms can even reduce their production to decarbonize, especially under the historical allocation mechanism. On the demand side, many of them only have such measures. For electricity firms, it is the same. Furthermore, under the historical allocation mechanism in ETS, the production reduction of the steel sector can lead to a lower carbon price and reduce the renewable investment in the electricity sector. The experience of the EU tells us that apart from ETS, a specific renewable energy objective is also needed (Schmidt et al., 2012).

To achieve multiple policy goals, it is particularly important to mix ETS and renewable energy support policies (Duan et al., 2018). However, the effect of policy mixes has always been a focus of controversy in academic circles. Many scholars have considered the synergistic effect between ETS and renewable energy support policies and confirmed the importance of policy mixes to achieve desired emission reduction and energy objectives in the most cost-effective manner (Cheng et al., 2016; Fan et al., 2016). Some studies employed the computable general equilibrium model or partial equilibrium model to assess the social and economic impact of policy mixes. For example, some scholars have discussed the interaction between emission cap and REC or the interaction between emission cap and FIT (Böhringer and Behrens, 2015; Jos, 2005). Lots of quantitative studies have shown that although policy mixes can reduce social welfare and cause GDP losses, they can more efficiently reduce the electricity generation from fossil fuels and increase the production of RE, thus promoting the energy transition (Mu et al., 2017; Wu et al., 2017; Wu et al., 2020). There are some similar viewpoints that the policy mixes can help to realize deep decarbonization of energy systems quickly (Hepburn et al., 2020; Rosenbloom et al., 2020).

However, mixed policies may also cause conflicts and even lead to the failure of some policy instruments, thus increasing the social cost of policy implementation. Some scholars pointed out that the impact of renewable energy support policies on ETS should be admitted (Fischer et al., 2010). The implementation of renewable energy support policies can help ETS meet the emission cap and reduce the carbon price, which is thus relatively beneficial to fossil energy. In some studies, it is believed that excessive renewable energy objectives will restrain the demand for carbon emission quotas, thus leading to a low carbon price (Nordhaus, 2011; Berghet al., 2013; Lindberg, 2019). Similarly, the trials of ETS in China also show that the risk of emission quota over-allocation may lead to a drop in carbon price and reduce market efficiency (Wu et al., 2017). Therefore, to achieve climate goals and low-carbon transition, we must fully understand the interaction mechanism between different policies and give play to the advantages of each policy instrument, which is of great significance for China to achieve carbon peak and carbon neutrality.

To sum up, it is necessary and important to study policy mixes, but most of the previous studies focused on quantitative research and ignored the theoretical discussion. Specifically, there is no study on the interaction between China ETS and renewable energy support policies. Based on the partial equilibrium model, this study analyzes how ETS and different renewable energy support policies affect the game behavior of market players. In addition, based on China's electricity market, it simulates CO_2 emissions, production of green electricity, and social welfare under different policy scenarios, which inspires China's design of energy policies.

3 Theoretical model

3.1 Policy description

To explore the interaction mechanism between renewable energy support policies and carbon emission trading, we built a partial equilibrium model and described the supply and demand situation of the electricity market as well as two major market players—producers and consumers—and their decision-making behaviors. The following policies are involved in the model.

An emission trading scheme refers to a mechanism where a certain number of emission credits are assigned to the participants. These credits thus become a commodity, which can be "consumed" by the participants themselves or "traded" with others in the carbon market, which depends on the marginal abatement cost. As a market-driven instrument, it first sets emission caps and then fixes a price for CO_2 produced by burning fossil fuels. Feed-in tariff (FIT), also known as renewable subsidy policy, means that the governments give subsidies for each kWh of electricity to renewable energy power generators (such as PV electricity generators, wind electricity generators, etc.). Many countries have adopted this policy to support and stimulate the green electricity markets at an early stage (such as several member states of the EU, Australia, and several states of the United States). Because high policy cost is needed to implement the renewable subsidy policy, it is not as good as the marketized instruments in the long run and the policy should gradually retreat. To reduce the financial burden caused by subsidies, renewable portfolio standards (RPS) and purchased renewable energy credits (REC) are two alternative market instruments. Green electricity generation companies can make extra profit by selling purchased renewable energy credits.

In the model, the electricity price depends on the supply–demand relationship in the state of equilibrium. ETS can affect the production cost of fossil fuel companies through the carbon price. Renewable energy support policies can change the equilibrium price and production by affecting the electricity generation cost and electricity demand. By comparing the differences among carbon emissions, production of green electricity, and social welfare, we can assess the impact of policies on the economy, environment, and society.

3.2 Behavior of market players

3.2.1 Electricity generators

When fossil fuels are used to generate electricity, pollutants are discharged, leading to environmental externalities. In such a case, the policymakers need to choose the optimal policy instrument to realize the externality, and such intervention is bound to affect other economic agents in the market. The electricity generators are all in pursuit of profit maximization. They will measure the marginal cost and marginal revenue of electricity generation according to policymakers' decisions and then adjust their production $(X_i, i = f, r)$ to ensure their profit maximization.

Suppose that the production cost functions of each technology i are $C_i(X_i), i = f, r$, and it is a continuous convex function (Lecuyer and Quirion, 2016): $C_i^{'}(X_i) = \partial(C_i(X_i))/\partial X_i > 0$ and $C_i^{''}(X_i) = \partial^2(C_i(X_i))/\partial X_i^2 > 0$. Considering the great space change in the availability of wind energy resources and solar energy resources, the sites with the highest resource quality will be used, followed by the sites with the lower quality. The cost function of each technology i is described with the most classical linear quadratic form:

$$C_i(X_i) = a_i X_i^2 + b_i X_i, \quad i = f, r \tag{1}$$

In this function, a_i and b_i are parameters to the cost function of each technology i. The profit of the electricity generator is as follows:

$$\prod\left(p, x_f, x_r, \kappa, \pi, a, b\right) = p \cdot X_f + \pi \cdot X_r - C_{r\&f}\left(X_{r\&f}\right) - \kappa \cdot u \cdot X_f \tag{2}$$

In this function, p stands for electricity price in the market, which is also the marginal revenue of conventional technology companies. π stands for the marginal revenue from the sale of renewable energy, which depends on which renewable energy support policy the regulator chooses. Considering RPS and REC scenarios, $\pi = p + \eta$, in which η stands for renewable energy credits price and endogenously calculated by the following constraint:

$$X_r \geq \gamma \cdot \left(X_f + X_r\right) \perp \eta \geq 0 \tag{3}$$

That requires that a certain share of γ must be from renewable energy sources to form a green certificate equilibrium price η. In the case of the FIT policy, $\pi = S$, in which S stands for tariff level. When ETS is alone, the benefits of renewables just come from electricity price, so $\pi = p$.

In an ETS system, κ stands for the shadow price formed under the constraint of emission cap Ω, and represents the carbon price, which is endogenously determined by the following constraint:

$$\Omega \geq u \cdot X_f \perp \kappa \geq 0 \tag{4}$$

When the emission cap Ω is binding, κ will be positive. When the emission cap Ω is equal to the total amount of CO_2, the emission cap will lose its constraining force and the carbon price $\kappa = 0$.

3.2.2 Consumers

Consumers are always in pursuit of utility maximization, but since China's electricity price is regulated by the government, it can be considered that changes in demand will not lead to significant changes in electricity price. Although the functional relationship between electricity price in the market and electricity demand is not clear, there is still a functional relationship between electricity price in the market p and electricity demand D. We assume that there is a linear relationship between consumer demand D and electricity price in market p in the model (Liu et al., 2019), which is defined as follows:

$$D = B - Ap \tag{5}$$

If the inverse demand function is defined as $p(D)$, the consumer surplus is as follows:

$$CS(\mathrm{p}) = \int_0^q p(x)dx - p \cdot D(p) \tag{6}$$

In this function, x stands for the production of electricity. The consumer surplus function CS is a strictly convex function: $CS' > 0$ and $CS'' > 0$.

3.3 Supply–demand equilibrium model of electricity

First, a perfectly competitive market with symmetric information was assumed in the model (Lecuyer and Quirion, 2016). Second, we considered two technological types of electricity companies i, whose electricity generation is X_i. For conventional energy electricity generation companies, $i = f$ stands for fossil fuel technologies (coal, gas, etc.). For clean-energy electricity generation companies, $i = r$ stands for carbon-free technologies (wind, PV, etc.). Each technology cannot produce more than its available capacity in any period of time (Abrell et al., 2019):

$$\alpha_i \cdot M_i \geq X_i \perp \mu_i \geq 0 \forall i \tag{7}$$

Considering the intermittency of renewable energy resources, the electricity generation from wind and solar energy is greatly affected by weather conditions and geographical location, so $\alpha_i$is used to measure the availability of renewable energy resources in this study. For conventional technologies, it can also reflect the service condition of electricity generators (there is the possibility of maintenance or downtime). M_i stands for the total existing installed capacity of each energy technology. μ_i is the shadow price of the generating capacity of each technology, which is determined by Eq. 1. If the production is below the capacity limit, the shadow price will be zero $(\mu_i = 0)$; if they are equal, the shadow price will be positive $(\mu_i > 0)$.

In a perfectly competitive market, no company will be hindered from entering or leaving the market, and no seller or buyer can determine the price, which meets Pareto optimality. In the equilibrium model, the production costs and benefits of electricity generators determine the production of each technology i (Abrell al., 2019). For fossil fuel technologies:

$$C_f\left(X_f\right)/\partial X_f + \kappa + \mu_f \geq p \perp X_f > 0 \tag{8}$$

For carbon-free technologies:

$$C_r\left(X_r\right)/\partial X_r + \mu_r \geq \pi \perp X_r > 0 \tag{9}$$

where $C_i\left(X_i\right)$ stands for the production cost of each technology. When the marginal cost is higher than the marginal revenue, if the company continues the production, it will lead to losses, so $X_i = 0$. When they are equal, the company will increase production, so $X_i > 0$. Meanwhile, the aggregate demand $D$for electricity in the market should be equal to the aggregate supply in any period of time.

$$\sum_i X_i = D \, \forall i \tag{10}$$

3.4 Social welfare maximization

When analyzing the interaction between renewable energy support policies and ETS, we mainly examined the ability to solve the pollutant externalities under two policy scenarios. In a decentralized market economy, the equilibrium decision of energy supply and demand depends on utility maximization for consumers and profit maximization for electricity generators. Therefore, policymakers should focus on social welfare maximization. The social welfare function is as follows (Lecuyer and Quirion, 2016; Abrell et al., 2019):

$$\max_{\Omega,\gamma,s} W = CS(p) + \Pi\left(p, x_f, x_r, \pi, \kappa, \gamma\right) - E\left(x_f\right) - Sub\left(x_r\right) + T\left(x_f\right) \tag{11}$$

$$E\left(x_f\right) = \delta \cdot u \cdot x_f \tag{12}$$

$E\left(x_f\right)$ is the loss function. δ stands for the social cost of carbon, implying the constant marginal loss in a certain period of time. u stands for the carbon intensity of fossil fuels in the power sector (in the model, different coals and natural gases are distinguished).

$$Sub\left(x_r\right) = (\pi - p) \cdot x_r \tag{13}$$

$$T\left(x_f\right) = \kappa \cdot u \cdot x_f \tag{14}$$

$Sub\left(x_r\right)$ is the cost of subsidies, meaning the total cost paid by the governments to the renewable energy producers as subsidies under the scenario of renewable energy support policies. $T\left(x_f\right)$ means that the carbon emission costs paid by fossil energy enterprises are transferred to the government regulatory revenue and then used for redistribution. The last two formulas stand for changes in social welfare under different policy scenarios.

4 Empirical quantitative framework and results

4.1 Description of numerical model

To quantify the implementation effect of the policy mixes, we built a numerical model which was calibrated with data about China's electricity market in 2018. First of all, we found out the differences between different electricity generation technologies i (coal, gas, wind, PV, etc.) including carbon intensity, production cost, installed capacity, and other indicators. Importantly, since China's electricity market is still dominated by coal electricity generation, we further classify coal into coal and coal gangue, so that we can describe policy-induced changes of each technology portfolio on the production and supply sides from the perspective of finer granularity. Then, two renewable energy support policy instruments, renewable subsidy policy and REC, were introduced to the model, and the efforts to implement the policies were also considered. With ETS alone as the benchmark, this study analyzed the effect of policy mixes on social welfare, production of green electricity, and CO_2 emissions.

4.2 Data sources and explanation

Taking the case of China's electricity market in 2018, we conducted an empirical analysis based on the aforementioned theoretical model. In the model, the following parameters are required: α, the availability of renewable energy (wind energy and solar energy) resources which changes over time (Wu et al., 2013; Chang et al., 2014; Yang et al., 2012), and κ_i, the cumulative installed capacity of various energy technologies i (National Energy Commission Administration, 2017). We found that the installed capacity of renewable energy accounted for 20%, but its electricity production only accounted for 8%, which indicates that there is still partial wind and PV curtailment in China, and the availability of renewable energy is low. In combination with the data of α, this study can better describe the heterogeneity and intermittency of renewable energy resources. When calculating the social losses caused by carbon externalities, we got the result by multiplying carbon emissions during electricity production by the social cost of carbon. We got the result of carbon emissions by multiplying the sum of carbon intensity and annual service hours of various conventional technologies by the installed capacity (National Energy

Commission Administration, 2017) (see Supplementary Appendix S1 for other data mentioned in the text).

According to the data about carbon intensity, compared with Germany, the carbon intensity of China's coal electricity plants and the electricity market is dominated by coal electricity in China, which partly contributes to the high ratio of China's carbon emissions over global carbon emissions. Later, we obtained data about China's social cost of carbon (Ricke et al., 2018; Tianet al., 2019). Last, the production cost functions and emission cost functions of various technologies were obtained (Abrell et al., 2019; Liu et al., 2014; Feng et al., 2018). Through the calibration unit, we obtained the electricity demand function (Liu et al., 2019; Lin and Purra, 2019; Pu et al., 2020). The aforementioned data were all calibrated again in the numerical model.

4.3 Design of empirical methods

Based on the partial equilibrium model, we made use of the mixed complementarity formula to describe China's electricity supply–demand market. All nonlinear inequalities can be divided into two kinds: zero profit and market clearing, which form complementary conditions with production X and ω shadow price, respectively. In addition, there is a dynamic game between the two types of competitive companies and policymakers, namely the former pursues profit maximization, while the latter aims to maximize social welfare. In this process, the decision-making variables of the other side need to be taken into account. This is a two-level optimization problem, that is, a low-level constraint set equilibrium problem of maximization objective function. Therefore, we should transform the part of the low-level equilibrium problem into a mixed complementarity problem (MCP). To solve it, we employed the general algebraic modeling system, namely, the path solver in General Algebraic Modeling System (GAMS) software.

In addition, we need to explain some parameters in the model. The emission cap Ω is always an exogenous variable, which should be constantly adjusted during the program run before the optimal solution is found. When policy mixes are implemented, the subsidy S to renewable energy and renewable energy quota γ are also exogenous variables. The optimal value S may fall at any point of the interval 0.05 yuan/kWh–0.5 yuan/kWh, and the optimal value γ may fall at any point of the interval 6%–12%. At this point, we discretize and assign values to Ω, S, and γ at the same time, and the model will constantly be iterated until the optimal solution is found.

4.4 Basic settings of the model

4.4.1 Policy scenarios and benchmark setting

In the empirical analysis, we assessed the interaction between ETS and two alternative renewable energy support policies—purchased renewable energy credits (REC) and renewable subsidy policy. Later, we considered the efforts to implement each renewable energy support policy and divided them into different policy scenarios. The specific scenarios are shown in Table 2. Scenario 1 and Scenario 2 differ in mandatory market share in RPS: S1 = 0.08 and S2 = 0.1. Scenario 3, Scenario 4, and Scenario 5 differ in the amount of policy in renewable subsidy policy: S4 = 0.1, S5 = 0.2, and S6 = 0.3. Moreover, ETS alone is used as the benchmark in this study to compare the different policy scenarios.

4.4.2 Scale setting

As shown in Figures 2, 5, to better show the changes in CO_2 emissions during the implementation of policy mixes compared with those during the implementation of ETS alone, ΔR is defined in this study, which represents emissions during the implementation of ETS alone minus emissions during the implementation of both ETS and renewable subsidy policy. $\Delta R = E_{S3-S5} - E_{S0}$. Similarly, to better show the changes in social welfare during the implementation of policy mixes compared with those during the implementation of ETS alone, ΔW is defined in this study, which represents social welfare during the implementation of both ETS and renewable subsidy policy minus social welfare during the implementation of ETS alone. $\Delta W = W_{S3-S5} - W_{S0}$.

As shown in Figures 1, 3, 4, % is defined in this study, which represents the changing rate of CO_2 emissions, production of green electricity, and social welfare under the policy mix scenarios S1–S5 compared with benchmark scenario S0, namely, $\% = (S_{1-5} - S_0)/S_0$.

5 Analysis of empirical results

5.1 CO_2 emissions

Figure 1 shows the changes in emission reduction in scenarios S1–S5 compared with benchmark scenario S0. According to this figure, we can see that when the emission cap is relatively stringent, implementing ETS and renewable energy support policies at the same time may promote emission reduction more than implementing ETS alone, but the effect varies according to the types of RES and the efforts to implement the policy. The emission reduction effect of implementing renewable subsidy policy (S3–S5) is generally better than that of RPS and RECs (S1, S2), and the greater the subsidy amount and the higher the mandatory market share, the better the emission reduction effect. When the cap is 10 million tons, the emission reduction ratio of S1 and S2 is between 0.9% and 1.3%, while that of S3–S5 is between 1% and 2.8%.

In fact, the subsidies could decrease the carbon price. As shown in Supplementary Table S1, for the same cap, the carbon price decreases with the increase of subsidies. The more

TABLE 1 Variables and parameters in the analysis model.

Variables and parameters in the analysis model	Value	Dimension	Description
x_r	-	MWh	Electricity from renewable sources
x_f	-	MWh	Electricity from fossil fuels
α_i	-	——	Availability of capacity
M_{coal}	1007940	MW	Existing production capacities
M_{gas}	83130	MW	Existing production capacities
M_{wind}	184665	MW	Existing production capacities
M_{pv}	175016	MW	Existing production capacities
$a_{(coal)}$	3.69*10–^{4}	MWh^2/RMB	Slope of generation cost functions
$b_{(coal)}$	17.24	MWh/RMB	Slope of generation cost functions
μ_i	-	RMB/MWh	Shadow price of e-generating capacity
p	-	RMB/kWh	Electricity price
κ	-	RMB/ton	CO$_2$ price
η	-	RMB/MWh	Renewable energy credits price
Ω	8–30	Million tons	Emissions cap
u	-	tCO2/MWh	CO$_2$ intensity of fossil-based electricity
δ	156	RMB/ton	Social carbon costs
γ	8%–10%	——	Share of RE in total electricity
π	-	RMB/kWh	Effective marginal revenue of renewables
A	-	——	Intercept of demand function
B	-	——	Slope of demand function
S	0.05–0.5	RMB/kWh	Subsidy price

TABLE 2 Policy scenarios.

Scenario	Subsidy (RMB/kWh)	Renewable energy share (γ)
Emission trading scheme only (Benchmark)		
S0	×	×
Emission trading scheme and tradable green certificates		
S1	×	8%
S2	×	10%
Emission trading scheme and renewable subsidy policy		
S3	0.1	×
S4	0.2	×
S5	0.3	×

renewables are deployed, the greater the impact on the carbon price. According to the scenarios of S1–S5, the proportions of renewables in the FIT scenarios are much less than in the RPS scenarios, so the former leads to higher carbon prices than the latter. For example, when the cap = 6 million tons and the tariff is 0.5 RMB, the shares of green electricity are just 2.04%. This is far lower than the green certificate case, which is at least 8.02% under the same cap, see Supplementary Tables S1, S3. The descending carbon price encourages coal-fired generation; therefore, the emission reduction ratio of S1 and S2 is lower than those of the scenarios of S3–S5.

5.1.1 The implementation effect of ETS mixed with FIT

Figure 2 more clearly shows the interaction between renewable subsidy policy and the emission cap. However, whether FIT policies actually contribute to CO$_2$ reduction when overlapping with an ETS is a question. Under the mixed policy scenario of renewable energy subsidies and carbon market at the same time, through the interaction between subsidy price and emission cap, we find that the results are divided into the following two cases:

On the one hand, when the emission cap of the carbon market is very loose, the carbon price will be much less than the social cost of carbon (SCC) (SCC = 156 RMB/ton, κ = 74.9 RMB/ton), and it is necessary to implement the subsidy policy with a low subsidy level. This is because when the subsidy level is low, the effect of renewables on carbon prices is limited. In addition, low carbon prices cannot or can only trigger a small part of fuel switching between coal and natural gas, and also the renewable energy target cannot be reached. Meanwhile, in such a case, it is necessary to combine the renewable subsidy policy with ETS to

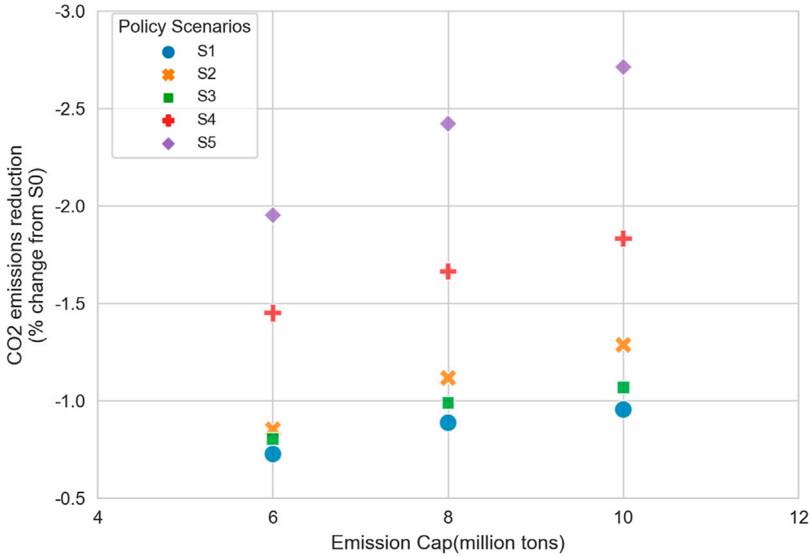

FIGURE 1
CO_2 emissions under different policy scenarios.

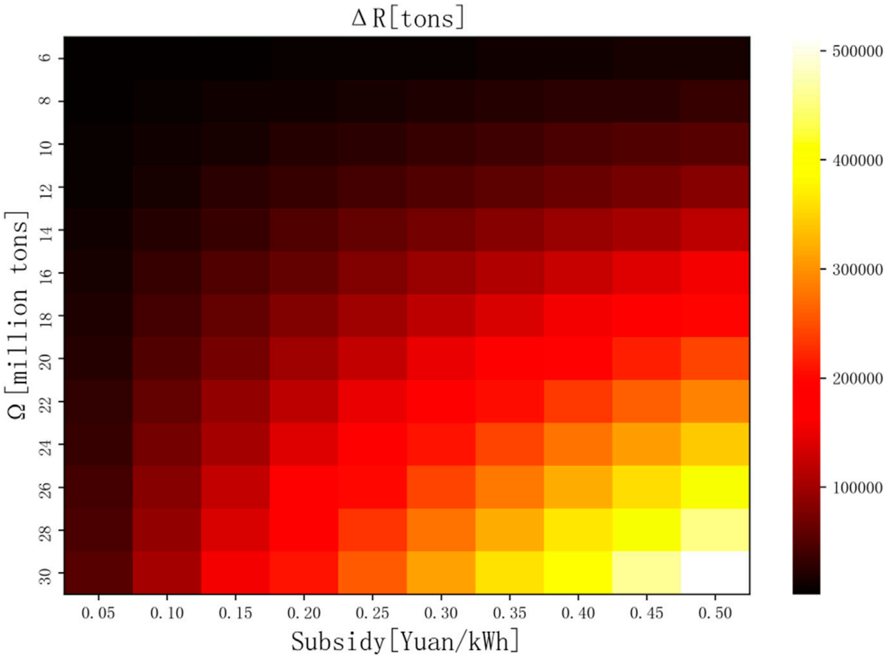

FIGURE 2
Carbon emissions of subsidy and carbon market combination policy.

promote the increase of renewable energy sources, which will achieve emission reduction by a greater order of magnitude.

However, with the high subsidy level combined with the loose emission cap, the situation is unclear. In this situation, the carbon price may be much lower, and high subsidies exacerbate this situation. Since the dirtier coal-fired generation benefits from the carbon price decrease, to maintain the same level of emissions, it must decrease natural gas generation more than

TABLE 3 Electricity generation.

Renewable energy subsidy [RMB/kWh](S)		**Electricity generation change (%)**			
		Coal	**Gas**	**Wind**	**PV**
Cap = 6 million tons					
S3	0.10	−0.303%	+1.161%	+0.567%	+1.463%
S4	0.20	−0.602%	+2.301%	+1.134%	+2.926%
S5	0.30	−0.947%	+3.459%	+1.737%	+4.416%

coal-fired generation. Meanwhile, the emissions may exceed the alternative emission reductions which brought about encouraging renewable deployments. Just as shown in Figure 2, when the cap = 30 million tons, the emission in the case of 0.50 yuan/kWh is surprisingly higher than that of the 0.05 yuan/kWh. Moreover, with the increase in the amount of subsidies, the emission reduction effect will be more significant, but at the same time, it will require greater policy costs.

On the other hand, when the cap is strictly stringent, the carbon price will be approximately equal to 156 RMB/ton. Since implementing ETS alone can achieve the theoretically optimal emission reduction effect, it is unreasonable to implement a subsidy policy at the same time.

5.1.2 The emission reduction path of ETS mixed with FIT

The emission reduction path of scenarios S3–S5 where ETS and FIT are implemented at the same time is shown in Table 3. Under benchmark scenario S0, the production of coal electricity is 17,789.941 TWh, that of natural gas electricity is 6,263.900 TWh, that of wind electricity is 101.627 TWh, and that of photoelectric power is 90.260 TWh. We found two reasons for this:

First, S3–S5 promote fuel conversion among fossil fuels, realizing the transition from high-emission coal electricity generation to natural gas electricity generation. After the introduction of a subsidy policy based on the emission cap control alone, cap = 6 million tons, S = 0.1 RMB/kWh, the terminal demand increases by 0.9%. This part of electricity demand is mainly met by electricity generated from natural gas, supplemented by wind electricity and PV electricity, while the proportion of coal electricity decreases.

Second, S3–S5 promote an increase in the production of renewable energy, so that renewable energy can replace fossil fuels. According to the results of the model, compared with wind electricity, the increase in the production of PV electricity is more significant, which is because the investment in wind electricity generation is larger than that in PV electricity generation. If they are given the same amount of subsidies without considering different renewable energy technologies, the investors may invest more in the PV industry, thus making the proportion of the increase in production of PV electricity larger. For example, when the cap is 6 million tons, as the amount of subsidy gradually increases to 0.3 RMB/kWh from 0.1 RMB/kWh, the proportion of the increase in production of PV electricity becomes 4.416% and that of wind electricity becomes 1.737%. Therefore, when implementing the subsidy policy, the government should take both policy cost and investment benefit into account and implement differentiated subsidies for different renewable energy technologies.

5.1.3 The carbon emissions of ETS mixed with RPS

The performance of the mixed policy of the green certificate and carbon market in carbon emissions are further discussed in the following. As shown in Figure 3, with the increase of the proportion of green electricity, the emission reduction has a fluctuation phenomenon of first decreasing and then increasing, then decreasing and then increasing again. For example, when cap = 6 million tons, when the proportion γ = 16% (see Supplementary Appendix S1 and Table 3), the emission is the lowest, and then increases. This is the very famous phenomenon of "green promotes dirty." The main reason is that when the renewable energy market share increases, the demand for fossil energy power will decrease, resulting in a decline in fossil energy power generation and carbon emissions (cap = 6 million tons, γ = 10% or 16%) (see Supplementary Appendix S1 and Table 3). However, with the increase in proportion, the demand for carbon emission quotas of fossil energy will be further reduced. See Supplementary Appendix S1, Table 3. At this time, the market carbon price will be reduced (γ=16%, κ = 61.2 RMB/ton) and the power generation cost for coal-fired power enterprises will be reduced, which will seize the fossil energy power market and squeeze cleaner natural gas power generation out of the market. For example, when the renewable energy market share γ = 18%, compared with 16%, coal power increases by 1.6%, natural gas power generation decreases by 3.6%, and the total emissions also increase accordingly (see Supplementary Appendix S1 and Table 3). Therefore, there is a situation where "cleaner power" is replaced by "dirty power"-based market (see Supplementary Appendix S1 and Table 4).

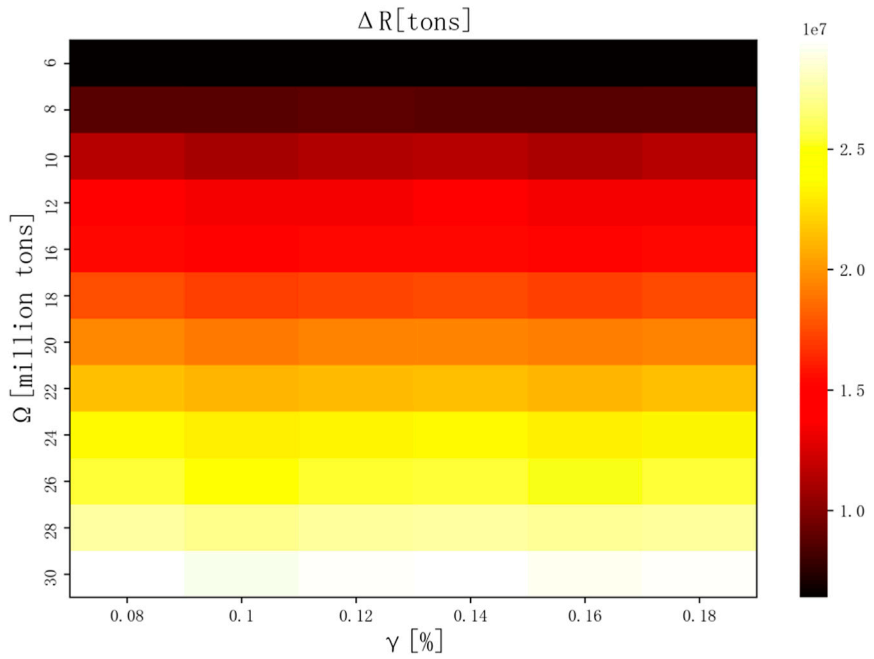

FIGURE 3
Carbon emissions of green credits and carbon market combination policy.

TABLE 4 Comparison of policy scenarios.

Scenario	Carbon price (RMB)	Electricity price (RMB)	Credits price (RMB)
S0	225.8	0.38	
S1	85.6	0.39	1.401
S3	234.3	0.38	

Lastly, we will explain why the emission reduction effect in S1 and S2 are lower than those of S3–S5 on the whole. There might be two reasons: under scenarios S1 and S2, the carbon price is relatively low and the natural gas electricity generation transits to coal electricity generation within the fossil fuels. In some studies, some scholars believe that excessive renewable energy objectives will restrain the demand for carbon emission quotas, thus leading to a low carbon price (Lindberg et al., 2019). This is consistent with the results of the model. As shown in Table 4, the lower case is compared. S0, S1, and S3 deliver similar green electricity generation while leading to quite different carbon prices. For example, the carbon price under scenarios S1 = 85 RMB/ton, far lower than S0 and S3. Moreover, the mandatory renewable energy share will make investors invest in renewable energy electricity generation, which will lead to underinvestment in natural gas electricity generation. However, wind electricity generation and PV electricity generation are intermittent, so backup coal electricity generation units are required for peak-load regulation. At last, the result might be over-reliance on backup (coal-fired) generators (Aflaki and Netessine, 2017), which is consistent with the results of the model. According to the results of the model, when the share of green electricity increased from 10% to 12%, the share of coal electricity increased by 2%.

5.2 Production of green electricity

Figure 4 presents the changes in the production of green electricity under scenarios S1–S5 compared to benchmark scenario S0. We can see that compared with S0, all scenarios S1–S5 can improve the production of green electricity, among which S1 and S2 have better effects. When cap = 10 million tons, increasing proportion under scenarios S1 and S2 ranges from

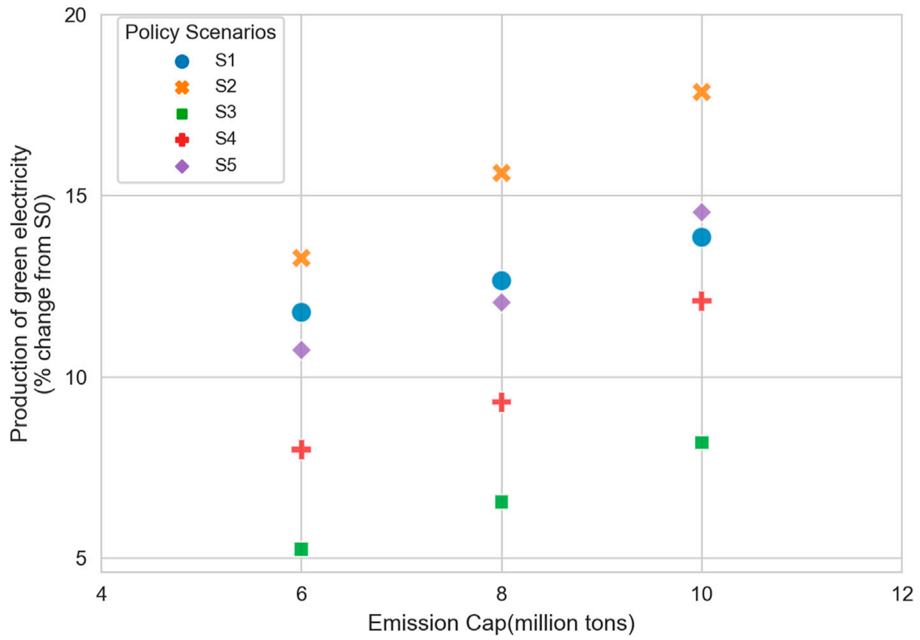

FIGURE 4
Production of green electricity under different policy scenarios.

13% to 18%, while that under scenarios S3–S5 ranges from 8% to 15%. In addition, we can find that S1 and S5 have similar effects on increasing the production of green electricity, but S5 has higher policy costs and cannot solve the long-term incentive problem in the development of the renewable energy industry. Therefore, with a similar effect, REC, as a marketized instrument, maybe a better choice.

First, according to the results of the model, we will analyze the reasons why S1 and S2 can stimulate the increase in the production of green electricity. First, the government stipulates the market share of green electricity, which directly stimulates the investment in RES; as the proportion of γ increases, the share of renewable energy also increases. In the case of cap = 8 million tons, when γ is 0.08, the share of RE is 7.42%; when γ is 0.1, the share of RE is 7.86%. Second, the price of a green certificate can bring extra benefits to renewable energy companies. In the case of cap = 6 million tons, when $\gamma = 0.08$, the quota price is 1.401 RMB/kWh. Since China's quota and green certificate market are still in the early stage, the price of green certificates is low and has volatility risk, but there is still a large space for development.

Second, we will discuss the effect of the interaction between renewable subsidy policy and ETS on the production of green electricity, as shown in Table 3. First, with the same cap, as the amount of subsidy increases, the production of green electricity increases. For example, when cap = 8 million tons, if S increases to 0.5 RMB/kWh from 0.1 RMB/kWh, the shares of green electricity increase by 6.5% and 17.3%, respectively. Since the cost of investment in such renewable energy as wind electricity and PV energy is high, coupled with their natural intermittency and technical thresholds, renewable energy is not very competitive in the electricity market. Nonetheless, the implementation of a renewable subsidy policy can make up for its disadvantage in cost and promote technological innovation. However, the amount of subsidy and the opportunity to retreat should be well grasped. Second, a gradually relaxed cap requirement for ETS that could render the same RPS percentage is correspondingly difficult to achieve. For example, when the RPS percentage requirement is 0.08, if the cap increases to 8 million tons from 6 million tons, the shares of green electricity will decrease by 8.66% and 6.58%, respectively. The scholars believe that raising the carbon price may reduce the overall proportion of green electricity (Aflaki et al., 2017), which is consistent with the result of our model. This means that controlling the emission cap alone can directly stimulate emission reduction, but cannot achieve the goal of renewable energy development. Therefore, to achieve the multiple policy objectives of China, renewable energy support policies must be implemented as supplementary means.

5.3 Social welfare

Figure 5 shows the changes in social welfare of scenarios S1–S5 compared with the benchmark scenario S0. With S0 as the benchmark, scenarios S1 and S2 will reduce social welfare, while scenarios S3–S5 will improve social welfare. In the case of cap = 10 million tons, the social welfare decreases by about 0.0468%–

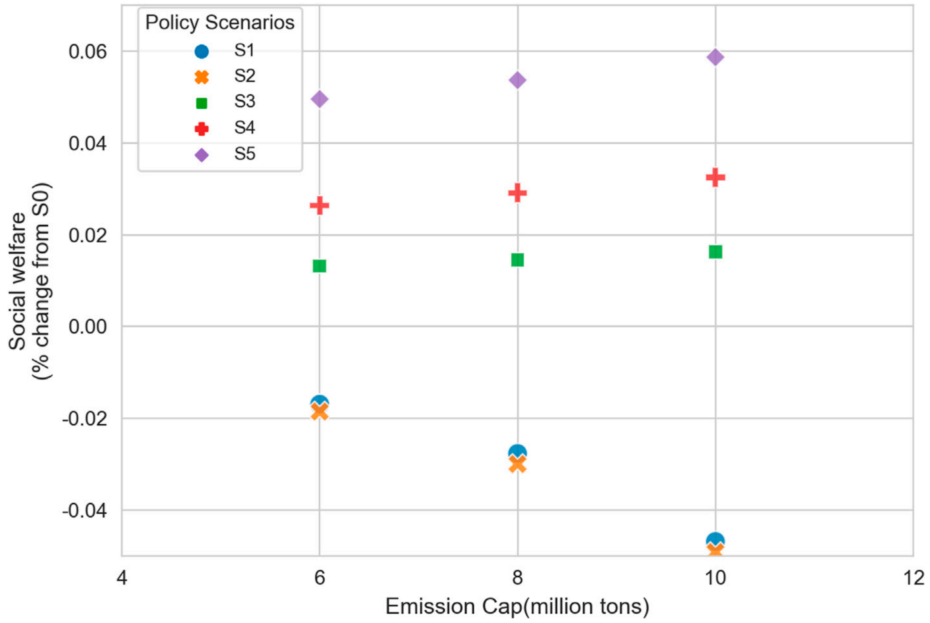

FIGURE 5
Social welfare under different policy scenarios.

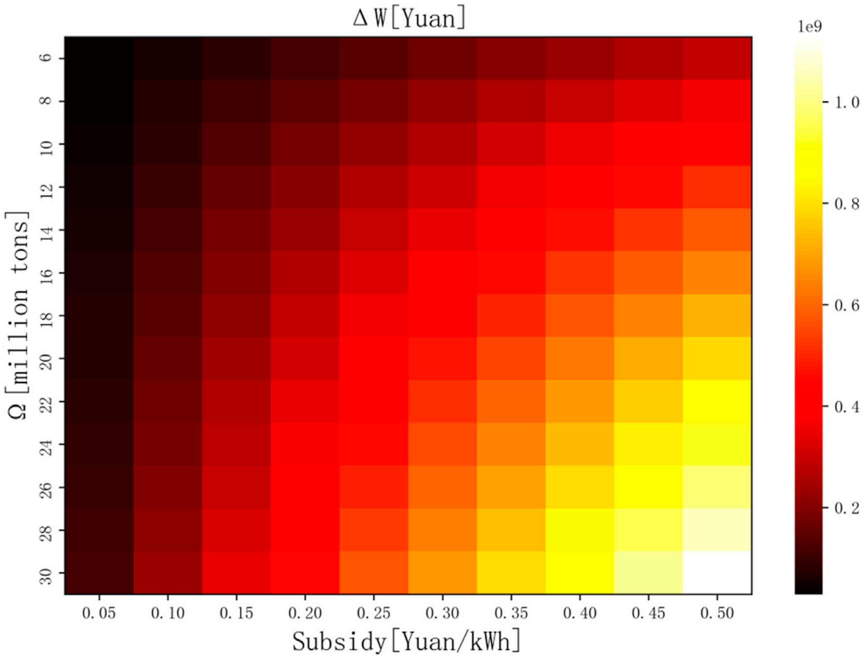

FIGURE 6
Social welfare under subsidy and carbon market combination policy.

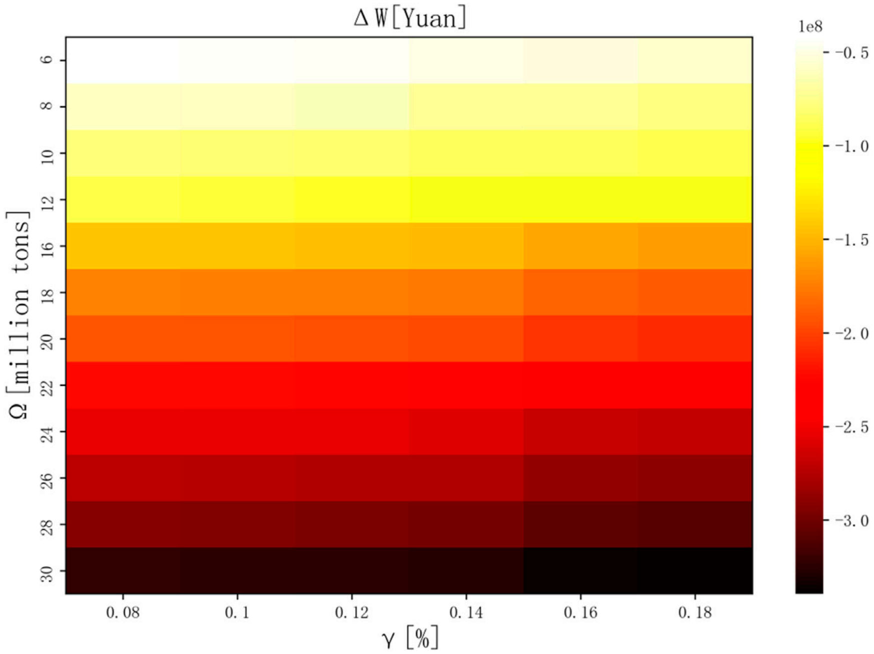

FIGURE 7
Social welfare under green credits and carbon market combination policy.

0.0491% under scenarios S1 and S2, while social welfare increases by 0.0162%–0.0587% under scenarios S3–S5. In the following, we will explain the differences between the two renewable energy support policies according to the results of the model.

First, Figure 6 presents the effect of interaction between renewable subsidy policy and ETS on social welfare. In the practice of China's carbon market, the carbon price is always lower than its theoretical optimal level. When the carbon price is lower than the optimal level, whether the combination of the carbon market and renewable energy support policies is optimal or cost-effective depends on the deviation degree of the carbon price from the optimal level (Abrell et al., 2019). First, when the cap setting is loose, there is an interval of the carbon price and the combination of the carbon market and renewable energy support policies can improve the social welfare, which is consistent with the scholars' conclusion (Abrell et al., 2019). Second, when the cap is set to be valid, the carbon price is close to the social cost of carbon (SCC = 156 RMB/ton). In such a case, it is unnecessary to adopt the renewable subsidy policy at the same time, which can only increase the policy cost. That is because high carbon price has effectively made use of all the emission reduction channels. If subsidies are given to renewable energy technologies in this case, a twist effect will be produced. According to the results of the model, there is an inflection point when the high carbon price is 210 RMB/ton, at which the implementation of subsidy policy will have a negative effect and lead to the situation where the more subsidies are given, the worse the situation will be.

Second, as shown in Figure 7, with the increase of renewable energy market share, γ social welfare is decreasing, which is consistent with the classical economic theory. We find that there is a nonlinear relationship between the increase in proportion and the decrease in welfare. For example, when cap = 6 million tons and the proportion $\gamma = 0.16$, social welfare is the most optimal (see Supplementary Appendix S1 and Table 3). The reason for this phenomenon is that with the increase of renewable energy market share, the cost of purchasing green certificates by enterprises increases, and the market electricity price increases. The green certificate price will be transmitted to consumers, resulting in the reduction of consumer surplus, thereby reducing social welfare. In addition, we find that carbon prices and the price of green certificates fluctuate at times. Specifically, the price of green certificates fluctuates greatly. According to the results of the model, the carbon price ranges from 63 RMB/ton to 85 RMB/ton, and the price of green certificates ranges from 0.713 RMB/kWh to 1.401 RMB/kWh. Price volatility has led to fluctuations in the production of electricity from both conventional energy and renewable energy sources.

6 Conclusion and policy implications

6.1 Conclusion

In recent years, policymakers in many countries have begun to implement or seriously consider renewable energy support policies. With the widespread application of renewable energy support policies, the overlap of different policy instruments of RES and ETS may have an important impact on the implementation of regulatory policies. To avoid the possible negative effects or to take advantage of the potential synergistic effect of multiple policies, it is necessary to understand how different policy mechanisms interact with each other.

Based on the aforementioned problems, we, first of all, built a partial equilibrium model to discuss the interaction mechanisms between ETS and renewable energy support policies. Then, we, combining the theoretical model and numerical model and taking the case of China's electricity market in 2018, conducted an empirical analysis and specifically presented the interactions between different policies from three aspects—emission reduction, production of green electricity, and social welfare.

According to the results of the model, there were big differences among the implementation effects of different renewable energy support policy instruments. Based on ETS, the renewable subsidy policy (S3–S5) is better than REC (S1 and S2) in terms of emission reduction, but worse in terms of improving the production of green electricity. In addition, different from the renewable subsidy policy (S3–S5), REC (S1 and S2) can reduce social welfare.

6.2 Policy implications

A renewable subsidy policy is the starting point of the low-carbon transition, but it cannot serve as the core driver for long. Although the policy effect of the renewable subsidy policy completely depends on the government's willingness to reduce emissions, it still faces a large policy cost. According to Figures 2, 5, when the subsidy level is set, the setting of the emission cap should be fully considered, but should not be only based on the investment cost and environmental value of renewable energy sources. In short, the renewable subsidy policy is not a long-term solution and should gradually "retreat." One of the preconditions for subsidy retreat is that the carbon market is efficient. According to the result of the model, when the cap is loose, the carbon price will be much less than the social cost of carbon (SCC = 156 RMB/ton), and it is necessary to implement the subsidy policy. When the carbon market runs effectively, the carbon price will be approximately equal to 156 RMB/ton, it is unnecessary to implement the subsidy policy at the same time. Therefore, to realize subsidy retreat, an effectively running carbon market is needed.

In the trend of subsidy retreat, the country encourages renewable energy enterprises to sell renewable energy green electricity certificates, and the income from it can be used for financial expenditure. According to the result of the model, under scenarios S1 and S5, the effects of increasing the production of green electricity were similar. The income of the renewable energy companies under scenario S1 is approximately equal to the policy cost paid under scenario S5, and at this moment, $\kappa = 85.62$ RMB/ton and $\eta = 1.40$ RMB/kWh. Therefore, it is the core of policy design to gradually improve the carbon market and green certificate market and give full play to the pricing and incentive function of their externalities. In addition, the results of the model show that if the market share goal of green electricity is too radical, there will be a transition from "clean" to "dirty." For example, when the share of green electricity increases from 10% to 12%, the share of coal electricity increases by 2%. Therefore, the government should well grasp the development rhythm of renewable energy and strengthen macro-control with the carbon price and price of green certificates as signals.

Certified emission reduction (CER) is an emerging offset mechanism that can theoretically serve as a complementary instrument to the carbon market. It is a project with certified emission reduction as the main commodity based on the clean development mechanism. In addition, CER can not only further reduce the emission reduction cost of emission reduction entities, but also promote the development of renewable energy. According to the data of the model, it can be inferred that if this market is opened, CER will bring benefits to renewable energy companies that are approximately equal to the amount of subsidy S = 0.15 RMB/kWh, which will thus greatly save the policy cost. Therefore, we believe that the country should open this market and rely on market means to drive China's energy transition.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, LL and YW; writing—original draft preparation, XC and WB; writing—review and editing, LL and YW; supervision, LL; project administration, LL; funding acquisition, LL and YW. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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