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Coordinating carbon pricing policy and renewable energy policy with a case study in China

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Abstract

In order to reduce greenhouse gas (GHG) emissions, many countries have set various kinds of policy targets and introduced policy instruments accordingly, such as carbon pricing and renewable electricity subsidies. As a consequence, potential interactions and, especially, conflicts between these co-existing instruments have become a significant concern. In this paper, a partial equilibrium model is constructed to explore the interaction between carbon pricing and renewable electricity subsidies. Based on this model, the following issues are explored: the conditions under which a single policy is optimal and the scenarios where a policy mix is necessary in the realisation of the outlined policy targets, and the means by which to coordinate different policy targets to reduce the negative effects of any potential conflicts, especially possible CO_2 price collapses. The optimal portfolio of the two policy targets is obtained, and the method of coordinating them to stablize CO_2 prices is delineated. Thereafter, an empirical study of China's case is conducted. The results show that with the policy targets set by the Chinese government for 2020, renewable energy power subsidies may lead to a collapse of CO_2 prices, and a tightening of the carbon emission budget is necessary to stablize the latter.

Keywords: policy mix; policy interaction; policy coordination; renewable energy policy; carbon pricing

1 Introduction

To mitigate the adverse impact of climate change, many countries have introduced a range of policies to reduce greenhouse gas (GHG) emissions, such as energy efficiency policies, subsidies for electricity production from renewable energy sources (RES-E), carbon pricing policies and so on (Zuluaga and Dyner, 2007; Zhu et al., 2014). For example, the European Union (EU) has agreed on two ambitious objectives for 2030; namely, a 40% reduction of carbon emissions from 1990 levels, and a bolstering of the market share held by renewable energy to 27% (Siitonen and Ahtila, 2010). Accordingly, the EU has implemented a variety of policy instruments, such as the EU Emission Trading Scheme (ETS) and the renewable energy subsidy policy, or the renewable portfolio standard (RPS). As the world's largest producer of CO_2 emissions, China has piloted emission trading scheme in seven provinces and cities, and a nationwide carbon market is planned to be implemented in 2017, with the aim of lowering the carbon emission intensity by 40-45% by 2020 and, further, to realise a carbon emission peak by 2030. Meanwhile, the country has also introduced a feed-in tariff (FIT) policy for renewable energy-based electricity, which will promote renewable energy development and increase the share held by green electricity to 15% by 2020 and 20% by 2030. With this in mind, it can be foreseen that carbon pricing and the FIT policy would coexist for a certain period.

The potential effects of interaction between the coexisting policy instruments are of notable concern for the policymakers (Goulder, 2013; Levinson, 2010). More specifically, the implementation of a carbon emission trading scheme would increase the emission costs of fossil fuel-based power plants and improve the relative competitiveness of renewable energy-derived electricity. As a side effect, the implementation of a carbon emission trading scheme may promote renewable energy development. In addition, the FIT policy for renewable energy could increase the electricity production from RES, promoting the substitution of fossil fuel-based electricity. In sum, the FIT policy for RES may promote carbon abatement. What we have outlined above is only one aspect of the interaction between different policy instruments, that is, the synergy effect; the other one is the possible conflict effect. Some previous studies have pointed out that too stringent a policy for supporting renewable energy may lower carbon prices by reducing the demand for carbon emission permits in the carbon market (Fankhauser et al., 2010; Fischer and Preonas, 2010; Greaker et al., 2008), which would undermine the effect of the emission trading scheme on emission abatement and, especially, on low carbon energy investment (Grubb and Neuhoff, 2006; Abadie and Chamorro, 2008; Blanco and Rodrigues, 2008; Nordhaus, 2011; Mo et al., 2012; Löfgren et al., 2013; Mo et al., 2016). For example, the carbon prices set out by the EU ETS are low for several reasons, including the generous allocation of allowances, the lavish use of credits from offsetting projects, the outbreak of the financial crisis and so on. Besides these factors, faster-than-expected growth in renewable energy as a result of the related supporting policy is also a critical reason (Mo and Zhu, 2014). Consequently, the FIT policy for RES may negatively affect the performance of the emission trading scheme. At that point, how to coordinate the different policy instruments to avoid the effects of possible conflict would become a challenging issue.

There have been a handful of relevant qualitative studies on the interaction and coordination between the coexisting policy instruments. The coevality of ETS and RES deployment targets creates a classic case of interaction effects. Amundsen and Mortensen (2001) applied a static equilibrium model to investigate both long- and short-term interactions between the renewable energy certificates (RECs) market and ETS in the context of the Danish power sector. The model considered price ceilings and floors of RECs, CO_2 prices and electricity imports. The results showed that under the condition of autarchy, tightening CO_2 emissions, together with a fixed share of renewable energy-based electricity, may lead to a reduction in green producers' profits and the RECs' price. However, an increasing share of renewable energy-derived electricity with a fixed carbon emission cap would lead to CO_2 price reductions. Abrell and Weigt (2008) simulated the interaction between the 20% CO_2 reduction target and the 20% renewable energy (RE) share target using a computable general equilibrium model of the German economy based on 2004 data, and found that achievement of the 20% RE share target made the CO_2 reduction target superfluous and thereby reduced the CO_2 price to zero. In addition to this theory, several simulation-based studies have also predicted that RES deployment may impose a strong downward pressure on CO_2 prices. For example, simulations by Van den Bergh et al. (2013) suggested that RES deployment reduced CO_2 prices by €46 in 2008 and more than €100 in 2010. Meanwhile, in the simulation by De Jonghe et al. (2009), the allowance price could even drop to zero, depending on the stringency of the targets (see also Unger and Ahlgren, 2005; Weigt et al., 2013). As mentioned above, many researchers argue that the interaction between the ETS and RES policies has a negative effect on CO_2 prices by reducing the demand for carbon permits in the electricity sector.

To address the possible effects of conflict between the coexisting policy instruments, especially the possible low CO_2 price, some researchers have considered the attainment of coordination between them. These authors believe that the long-term carbon emission cap target needs to be reconsidered to avoid a weakening of CO_2 prices (Gawel, 2014; Freitas, 2015; Fais, 2014). In fact, many countries have pondered reducing CO_2 emission allowances to stablize said prices. For example, the EU will establish a Market Stability Reserve (MSR) in 2018, while the placing of allowances within the reserve will come into operation from 1 January 2019. When CO_2 prices are too low in the eyes of the ETS, the MSR will absorb excess carbon emission allowances to avoid a possible collapse of such prices. Additionally, within the EU's framework for climate and energy targets by 2030, the CO_2 emissions cap will need to be lowered by 2.2% per year from 2021, compared with the current 1.74%.

Although there have been a few qualitative discussions on how one of the coexisting policy instruments affects the performance of the others, quantitative studies are scarce, and techniques for coordinating different policy targets and their corresponding instruments are little discussed.

In this work, therefore, we explore the potential interaction and coordination between carbon pricing and renewable subsidies within the context of a renewable energy power policy. To conduct a quantative analysis and highlight the interaction effect explicitly, a partial equilibrium model of the electricity market was built, incorporating the decision optimisation behaviour of fossil fuel power producers, renewable energy power producers and power grid firms. Based on this model, the portfolios of the carbon emission cap and renewable energy targets, under which one single policy is optimal and a policy mix is necessary, were obtained. In addition, we were able to determine the manner of coordinating different policy targets in order to reduce potential conflict between the varying instruments and, especially, to avoid possible CO_2 price collapses. These two points are the main contribution of our work. In addition, an empirical study of China's case was conducted. The results show that with the policy targets set by the Chinese government for 2020, a renewable energy power subsidy may lead to a collapse of CO_2 prices, and adjusting the carbon emission cap target is therefore necessary for stabilisation.

The remainder of this paper is organised as follows. Section 2 describes the model; analytical results are presented in Section 3; Section 4 undertakes an empirical study in China and Section 5 offers discussions and a conclusion.

2 Model

Based on the characteristics of the Chinese electricity market, three representative participants were incorporated into our model: a power grid firm, a fossil fuel electricity producer and a renewable energy electricity producer. Their relationship was that the power grid firm purchased electricity from both types of producers at corresponding on-grid prices, and sold all of it to consumers at a consumer price. During this process, all participants pursued profit maximisation. The decision making of the three participants were as follows:

(1) The representative fossil fuel electricity producer has the flexibility to comply with CO_2 emission regulations by reducing his own carbon emissions, cutting his own production or purchasing emission permits from the markets, with the objective of maximising his profit π_F,

$$\begin{aligned}\max_{Q_F,A_F} \pi_F &= R_f\left(Q_F, P_f\right) - C_f(Q_F) - C_e(A_F) - C_c(\theta, Q_F, A_F) \\ &= P_f Q_F - C_f(Q_F) - C_e(A_F) - P_c(\theta Q_F - A_F) \qquad (1)\end{aligned}$$

where $R_f(\cdot)$ is the revenue from fossil fuel electricity sales, in other words, the fossil fuel power generation, Q_F multiplied by the on-grid price P_f for fossil fuel power. $C_f(\cdot)$ is the electricity production cost function, which is strictly monotonic, increasing in Q_F and convex; more specifically, $C_f'(\cdot)>0$, $C_f''(\cdot)>0$. $C_e(\cdot)$ is the carbon abatement cost function, and is similarly monotonic, increasing in abatement mount A_F and convex, $C_e'(\cdot)>0$, $C_e''(\cdot)>0$ (Lecuyer and Quirion, 2013). $C_c(\cdot)$ is the cost of purchasing carbon emission permits through auction or from the carbon market, which is the CO_2 price, P_c multiplied by the gap between the carbon emission amounts θQ_F and the abatement amount A_F, in which θ is the intensity of CO_2 emissions by the fossil fuel power producer. It should be noted that the carbon emission permits are allocated by auction method in this situation.

(2) There are N kinds of renewable energy sources, and for each kind, the producer maximises its profit π_{iR},

$$\max_{Q_{iR}} \pi_{iR} = R_{ir}(Q_{iR}, P_r) - C_{ir}(Q_{iR})$$

$$= P_r Q_{iR} - C_{ir}(Q_{iR}), i = 1,2,3 \ldots, N \tag{2}$$

where $R_{ir}(\cdot)$ is the revenue from electricity sales, which equals to the amount of electricity produced, Q_{iR}, multiplied by the on-grid price P_r for renewable energy power. The cost function $C_{ir}(\cdot)$ is assumed to be monotonic, increasing in the amount of electricity produced, and convex; and formally, it satisfies the following conditions: $\mathrm{C_{ir}}^{'}(\cdot)>0$, $\mathrm{C_{ir}}^{''}(\cdot)>0$. The electricity producer maximises its profit by optimising its production decision, Q_{iR}. Since the renewable energy power subsidy policy was introduced, the on-grid price for renewable energy power P_r is higher than that of the fossil fuel power, i.e. $P_r \geq P_f$, and the subsidy for the renewable energy power is $S = P_r - P_f$.

(3) The power grid firm maximises its profit π_G:

$$\max_{Q_{iR}} \pi_G = R_g(Q_T, P) - R_f\left(Q_F, P_f\right) - \sum_{i=1}^{N} R_{ir}(Q_{iR}, P_r)$$

$$= P(Q_T)Q_T - P_f Q_F - \textstyle\sum_{i=1}^{N} P_r Q_{iR}\, , i = 1,2,3 \ldots, N \tag{3}$$

where $R_g(\cdot)$ is the revenue from electricity sales to the consumer, $R_f(\cdot)$ and $\sum_{i=1}^{N} R_{ir}(\cdot)$ are electricity purchasing costs from the fossil fuel electricity producer and the renewable energy electricity producer, respectively. $P(\cdot)$ is the consumer price of electricity and Q_T is the total electricity from both energy producers, which is also the total electricity demand, as shown in Eq. (4),

$$Q_T = Q_F + Q_R = Q_F + \sum_{i=1}^{N} Q_{iR}\,, i = 1,2,3\ldots, N \tag{4}$$

There are two policy targets set by the government: the carbon abatement target or carbon emission cap, and the share of renewable energy electricity target, which constitute the main constraining conditions. To be specific, the carbon emission constraint is expressed as follows:

$$\theta Q_F - A_F + E_N - A_N = \bar{E} \tag{5}$$

where θQ_F and E_N are the carbon emissions in the baseline scenario for the electricity and non-electricity sectors respectively, and similarly, A_F and A_N are carbon emission abatements for the same two sectors. Eq. (5) denotes that the net carbon emission from the electricity sector, $\theta Q_F - A_F$ and that from the non-electricity sector, $E_N - A_N$, should be equal to the carbon emission cap $\bar{E}$.

In Eq. (5), it is critical to determine the carbon emission abatement for the non-electricity sector, A_N. In this work, we used the carbon emission abatement cost curve $C_n(A_N)$ for this purpose. More specifically, the marginal abatement cost of the non-electricity sector should be equal to the CO_2 price under the carbon market equilibrium condition:

$$C_n{}'(A_N) = P_c. \tag{6}$$

The constraint condition for the renewable energy target is as follows:

$$Q_R = \alpha Q_T \tag{7}$$

where α is the share of the renewable electricity.

Finally, the electricity demand function $P(\cdot)$ is defined as follows, based on Lecuyer and Quirion (2013):

$$P(Q_T) = a - bQ_T. \tag{8}$$

To conduct further analysis, we are required to make certain assumptions about the form of the production and carbon abatement cost functions. To be precise, the marginal costs are assumed to have a classical linear-quadratic form, as per Jensen and Skytte (2002) and Lecuyer and Quirion (2013):

$$C_f(Q_F) = \frac{1}{2} c_1^f {Q_F}^2 + c_2^f Q_F, \tag{9}$$

$$C_r(Q_{iR}) = \frac{1}{2} c_{i1}^f {Q_{iR}}^2 + c_{i2}^f Q_{iR}, i = 1,2, \dots, N, \tag{10}$$

$$C_e(A_F) = \frac{1}{2} c_1^e {A_F}^2 + c_2^e A_F, \tag{11}$$

$$C_n(A_N) = \frac{1}{2} c_1^n {A_N}^2 + c_2^n A_N. \tag{12}$$

Based on the above model, we will conduct further analysis of our main concerns in the following section.

3 Analytical results

In this section, we will analyse under what conditions a policy mix should be employed to achieve the carbon emission cap and the share of renewable energy electricity targets, before discussing the potential effects of interaction and coordination between the carbon pricing and renewable energy power subsidy policies.

To realise the carbon emission cap and the share of renewable energy electricity targets, the policy makers can employ one of three kinds of policy; that is, a single carbon pricing policy, a single renewable energy power subsidy policy or a policy mix. The optimal policy would differ for the target portfolios for each of these scenarios. To be more specific, the overall portfolio would be divided into three subsets. In the first subset, Ω_{CP}, it would be key to implement a single carbon pricing policy to realise both policy targets. In this subset, once the the carbon pricing policy is applied, the competitiveness of the fossil fuel electricity is undermined as a result of the increasing carbon cost (or opportunity cost), and the share of the renewable energy electricity target would be achieved simultaneously through the sustitution of fossil fuel electricity with renewable electricity.

Meanwhile, in the second subset, Ω_S, it would be optimal to implement a single renewable energy power subsidy policy to realise both targets. In this subset, once the renewable energy power subsidy policy is implemented, the cost competitiveness of the renewable electricity, relative to the fossil-fuel electricity, would be improved as a result of the subsidy. Thereafter, the renewable electricity would replace its fossil fuel counterpart, and the CO_2 emissions would be reduced simultaneously as a result of the reduction of fossil fuel electricity production.

In the third subset, $\Omega_{CP\&S}$, a policy mix would be implemented. In this subset, although the implementation of the carbon pricing (or renewable energy power subsidy) can promote the substitution of the fossil fuel electricity (or carbon emission cap), single carbon pricing (or the renewable energy power subsidy) is not enough to achieve the share of the renewable energy electricity target (or carbon emission cap target), and a policy mix is therefore necessary.

To illustrate the above idea more explicitly, we created a graph. As shown in Figure 1, the horizontal axis represents the share of the renewable energy electricity target, while the vertical axis is the carbon emission cap target. The entire area is divided into three parts by two boundary curves: AB and CD. These three areas correspond to the three subsets referred to above. To be precise, Area 1 corresponds to the subset Ω_S, in which both policy targets can be achieved by the single renewable energy power subsidy policy, and the CO_2 price would be zero; similarly, Area 2 corresponds to the subset Ω_{CP}, in which both targets can be achieved by the single carbon pricing policy and the renewable energy power subsidy is zero. Finally, Area 3 corresponds to the subset $\Omega_{CP\&S}$, in which area a policy mix should be employed to realise the two policy targets.

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Figure 1 The coordination between carbon emission cap and share of renewable electricity targets

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The boundary curve AB can be obtained by letting the CO_2 price equal zero, while similarly, the boundary curve CD can be obtained by letting the renewable energy power subsidy equal zero.

To obtain the three subsets of the policy target portfolio, the key point is to find the boundary curves, AB and CD. In Proposition 1, we try to drive the function of the two curves.

Proposition 1. There are boundaries such that, the first subset of the target portfolio, in which the carbon emission cap and the share of renewable energy electricity targets can be achieved by single carbon pricing policy, is represented as follow,

$$\Omega_{CP} = \{(\alpha, \bar{E}) |\ 0 < \alpha < \alpha_{CP}(\bar{E})\}$$

$\alpha_{CP}(\bar{E})$ represents the boundary curve CD and α_{CP} is the maximum share of renewable energy electricity that can be achieved by the carbon pricing policy with the carbon emission cap target ($\bar{E}$) set by the government.

The second subset of the target portfolio, in which the carbon emission cap and the share of renewable energy electricity targets can be achieved by single renewable energy power subsidy policy, is represented as follow,

$$\Omega_S = \{(\alpha, \bar{E}) | \bar{E} \geq \bar{E}_S(\alpha)\}$$

$\bar{E}_S(\alpha)$ represents the boundary curve AB and $\bar{E}_S$ is the minimum carbon emissions that can be achieved by the renewable energy power subsidy policy with the share of the renewable energy electricity target (α) set by the government.

The third subset of the target portfolio, in which the policy mix of the carbon pricing and renewable energy power subsidy policies should be implemented to realise the two targets, is represented as,

$$\Omega_{CP\&S} = \left\{(\alpha, \bar{E}) \middle| \alpha_{CP}(\bar{E}) \leq \alpha \leq 1 \text{ , } 0 \leq \bar{E} \leq \bar{E}_S(\alpha)\right\}$$

Proof: See Appendix A.

Next, we will analyse the effect of interaction between the coexisting carbon pricing and renewable energy power subsidy policies in the subset $\Omega_{CP\&S}$, an area of concern for many researchers (Goulder, 2013; Levinson, 2010).

Proposition 2. In the subset $\Omega_{CP\&S}$, tightening the carbon emission cap, together with a fixed share of the renewable energy electricity target, will lead to an increase (decrease) in the CO_2 price (renewable energy power subsidy); on the other hand, a higher share of the renewable energy electricity target together with a fixed carbon emission cap may lead to a decrease (increase) in CO_2 price (renewable energy power subsidy).

Proof: See Appendix A.

Remark: Proposition 2 indicates that there is a potential synergistic effect, as well as a conflict effect, between the carbon pricing and renewable energy power subsidy policies. More specifically, tightening the carbon emission cap will lower the renewable energy power subsidy needed to realise the share of the renewable electricity target; this is the synergistic effect. In contrast, increasing the share of renewable energy electricity will promote the substitution of fossil fuel power with renewable energy power, which in turn exerts downward pressure on the CO_2 permit demand, thereby driving down the CO_2 price and potentially undermining the effectiveness of the carbon pricing policy. This is the possible conflict effect, which has been pointed out in much relevant research (Amundsen and Mortensen, 2001; De Jonghe, 2009; Jensen and Skytte, 2003; Tsao et al., 2011).

Due to this effect, the renewable energy subsidy may lead to a collapse of CO_2 prices (Clo et al., 2013; Koch et al., 2014), and it cannot provide an effective incentive for low-carbon technology investment (Blanco and Rodrigues, 2008; Grubb and Neuhoff, 2006), which may increase the risk of carbon lock-in (Clò et al., 2013). Accordingly, with the share of the renewable energy electricity target fixed, the carbon emission cap should be reduced to stablize the CO_2 price (Gawel, 2014; Freitas, 2015; Fais, 2014). Thereafter, we can obtain the relationship between the carbon emission cap and the share of the renewable energy electricity target under a certain CO_2 price, as stated in Proposition 3.

Proposition 3. In order to keep the CO_2 price at a certain level, i.e. *P*, the carbon emission cap should be adjusted with a varying share of the renewable energy electricity target, and this relationship is as follow,

$$\bar{E} = \frac{\theta c_1^f (1-\alpha)(\mathrm{a}C_{R1}-\alpha C_{R2}) + \xi(\alpha)\theta c_2^f - P(\,\xi(\alpha)(c_1^f W-\theta^2)+U(\alpha)W\big)}{\left(c_1^f\,\xi(\alpha)+U(\alpha)\right)} + M. \tag{13}$$

In addition, based on Eq. (17), the iso-carbon price curve, i.e. *P*, can be expressed as:

$$P = \frac{c_1^f (1-\alpha)(\mathrm{a}C_{R1}-\alpha C_{R2}) + \xi(\alpha)\theta c_2^f - \left(c_1^f\,\xi(\alpha)+U(\alpha)\right)(\bar{E}-M)}{\xi(\alpha)\left(c_1^f W-\theta^2\right)+U(\alpha)W}, \tag{14}$$

where $C_{R1} = \sum_{i=1}^{N} \frac{1}{c_{i2}^r}$, $C_{R2} = \sum_{i=1}^{N} \frac{c_{i2}^r}{c_{i1}^r}$, $M = E_N + \frac{c_2^e}{c_1^e} + \frac{c_2^n}{c_1^n} - \frac{\theta c_2^f}{c_1^f}$, $W = \frac{\theta^2}{c_1^f} + \frac{1}{c_1^e} + \frac{1}{c_1^n}$, $U(\alpha) = \left(c_1^f\right)^2 C_{R1}(1-\alpha)^2$, $\xi(\alpha) = 2bC_{R1} + \alpha^2$.

Proof: See Appendix A.

As shown in Figure 1, in Area 3, an iso-carbon price curve can be obtained, e.g. FG, in which the CO_2 price is equal to P. According to Proposition 3, to keep the CO_2 price at a certain level, e.g. P, the carbon emission cap should be adjusted from $\bar{E}_1$ to $\bar{E}_2$ with the share of the renewable energy electricity target correspondingly increasing from α_1 to α_2, i.e. from point H to point I.

4 An empirical study of China’s energy and climate targets for 2020

China is the largest emitter of greenhouse gases in the world, and therefore has a crucial role to play in mitigating global climate change. China set its targets for carbon intensity reduction and increasing its share of renewable energy-based electricity as part of the 13th Five-Year Plan (2016-2020), and accordingly, its carbon pricing and renewable energy power subsidy policies have been implemented. In this section, an empirical study on the interaction and coordination between these two policies is conducted, based on the model and propositions referred to above. Initially, we will present our estimation of the key parameters of the model in Section 4.1, before the empirical results are laid out in Section 4.2.

4.1 Parameter estimation

The key parameters of the model for the case of China are estimated, including those of the cost function for the fossil fuel and renewable energy power production, the carbon emission abatement cost function for fossil fuel power and the non-electricity sector, and the electricity demand function.

4.1.1 Cost function of power generation

We fit the marginal production cost function of a Chinese fossil fuel power producer with a linear-quadratic form function, shown in Eq. (9). As the production cost of fossil fuel-based electricity varies significantly between different regions of China, we used the data on fossil fuel power generation amounts and the corresponding on-grid prices in various regions to estimate the key parameters c_1^f and c_2^f. The data on the production amounts and costs were taken from the Chinese Electric Power Statistics Yearbook (2013) and the National Development and Reform Commission (NDRC, 2014a). The results are shown in Table 1.

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Table 1 The estimation results of the marginal cost function for fossil fuel electricity production

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Similarly, we used the data on renewable energy power generation amounts and the corresponding levelized cost of electricity (LCOE) of different technologies to fit the marginal cost function of the renewable power production with a linear-quadratic form function, shown in Eq. (10). The data on the production amounts came from the National Bureau of Statistics (NBS, 2015) and NDRC (2014b, 2014c), while those on the LCOE in different technologies were from the International Energy Agency (IEA) (2010), Ouyang and Lin (2014) and the China Electric Power Statistical Yearbook (2013). The results are shown in Table 2.

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Table 2 The estimation results of the marginal cost functions for renewable electricity production

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4.1.2 The estimation of carbon abatement cost function

Many existing research use a multi-sector computable general equilibrium (CGE) model to estimate the marginal abatement cost for different sectors. Specifically, after calibrating the model in the BAU scenario, the carbon tax was introduced as a shock to model, and in the new equilibrium state, the new carbon emission amount for each sector can be obtained, and the carbon abatement amount can be obtained accordingly. Following the same way, shocking the model using different carbon tax, the corresponding carbon emission abatement data can be obtained. In addition, these data can also be obtained by another way. In specific, the model can be shocked using different carbon emission cap, and then the implied carbon price or shadow value of the carbon constraint and carbon emission amount for each sector can be obtained in the new equilibrium. Using these carbon tax (price) and carbon abatement data, the marginal abatement cost function can be fitted and estimated. Bi (2012) obtained the data of carbon tax rate and the corresponding carbon emission (abatement) data for different sectors in China using the China Dynamic Energy Computable General Equilibrium model. We divided all sectors of the economy into two groups – that is, the electricity sector and the non-electricity sector – before fitting the carbon abatement cost function of the fossil fuel electricity sector and non-electricity sector with a linear-quadratic form function, as shown in Eq. (11) and Eq. (12), respectively. The estimation results are shown in Table 3.

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Table 3 The estimation of marginal abatement cost curve for fossil fuel electricity sector and non-electricity sector

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4.1.3 The estimation of electricity demand function

We estimated the electricity demand function parameters as per the linear function (a and b) shown in Eq. (8), using the consumer electricity price (NEA, 2014a) and the electricity consumption data from NBS (2013; 2014). The results are shown in Table 4, and the details of the estimation can be found in Appendix B.

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Table 4 The estimation of electricity demand function

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4.2 Empirical results analysis

In this section, we make an empirical analysis of the policy interaction and coordination in China’s case based on the three propositions in analytical results (Section 3). Firstly, we verify the validity of the model and parameters by comparing the simulation results and the real data. Thereafter, the effect of interaction between the carbon pricing and renewable energy power subsidy policies is explored, and the method of coordinating the carbon emission cap and the share of renewable energy electricity targets by 2020 is determined.

4.2.1 Validity verification of the model

With China's carbon emission intensity and the share of renewable energy electricity targets in 2014 as the input for the model, we were able to calculate the electricity production, electricity price, carbon abatement and CO_2 price for that year. Then, by comparing the simulation results with the real data for 2014, the validity of the model could be verified. China's CO_2 emissions in 2014 are 9.76Gt (BP statistical review of world energy, 2015) and its share of renewable energy power was 3.5%, according to the China Statistical Yearbook (NBS, 2015). Accordingly, the policy target portfolio can be expressed as $\bar{E} = 9.76$Gt, $\alpha = 3.5\%$, which is included in the subset of the policy mix, $\Omega_{CP\&S} = \{\alpha = 3.5\%, 6.6Gt \leq \bar{E} \leq 10.1Gt\}$. The detailed simulation results, as well as those for the real data, are shown in Table 5.

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Table 5 Comparison between the simulation results and real data in 2014

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In Table 5, we compare the key simulation results with the real data, such as fossil fuel and renewable energy electricity generation, the on-grid prices for fossil fuel and renewable energy power, and the CO_2 price. In 2014, the fossil fuel and renewable generation were 4233.7 TWh and 156.3 TWh according to the China Statistical Yearbook (NBS, 2015), and the simulation results were 4278 and 155.2TWh, with the relative errors being 1% and 0.7% respectively. The on-grid power price for fossil fuel and wind power were 0.46 and 0.61 RMB/KWh, and the simulation results were 0.49 and 0.67 RMB/KWh respectively, with the relative errors being 6.5% and 9.8%. Finally, the CO_2 price in the Chinese carbon trading pilots was 31.2 RMB/t CO_2 and 31.6 RMB/t CO_2 in the simulation result, with the relative error being 1.3%. In summary, the relative errors between the simulation results and the real data are acceptable, and our model and its parameters are proven to be valid.

4.2.2 The interaction between carbon pricing and renewable electricity subsidy policies

According to Proposition 2, there is a potential synergistic effect, as well as a conflict effect, between the carbon pricing and renewable energy power subsidy policies. More specifically, the decreasing carbon emission cap may lower the renewable energy power subsidy needed to realise the renewable electricity share target. In contrast, an increase of the renewable energy power electricity target may result in a different generation mixt, reduce the total emission, and lower the CO_2 prices. In this section, we discuss this interaction effect between the carbon pricing and renewable energy power subsidy policies in China based on empirical analysis, as shown in Figure 2.

The left pane of the Figure 2 shows the CO_2 price with varying shares of the renewable energy electricity target in different scenarios of carbon budgeting or levels of the carbon emission cap. As expected, as the latter increases, the CO_2 price lowers, in line with a given share of the renewable energy electricity target. More specifically, when keeping the share of renewable energy-based electricity at a certain level in 2014, such as 3.5%, the CO_2 price would decrease from 40 RMB/t CO_2 to 31.6 RMB/t CO_2, and further to 23.3 RMB/t CO_2, when the carbon emission cap increases from 9.6Gt CO_2 to 9.7Gt CO_2 and to 9.8Gt CO_2. What is really of interest is that, with a given carbon emission cap, the CO_2 price would be lower, with the share of the renewable energy-based electricity target becoming more stringent. For example, with the carbon emission cap given as the current emission level – that is, 9.7Gt CO_2 – the CO_2 price decreases from 35RMB/tCO_2 to 26RMB/tCO_2 with the share of the renewable energy electricity target increasing from 2.5% to 4.5%. This is the conflict effect between the carbon pricing and renewable energy policies; to keep the CO_2 price at the initial level, i.e. 35RMB/tCO_2, the carbon emission cap should be more stringent, that is between 9.7Gt CO_2 and 9.6Gt CO_2.

The right pane of Figure 2 shows how the renewable energy power subsidy changes with the carbon emission cap adjustment in different scenarios regarding the share of the renewable energy electricity target. Similarly, with a given carbon emission cap, the renewable energy power subsidy increases, with the share of the renewable energy power energy electricity target becoming stringent. What is more, with the carbon emission cap becoming stringent – in other words, a lower carbon emission budget – the renewable energy power subsidy required to realise a given share of the renewable energy power energy electricity target would decrease. This is the synergy effect between the carbon pricing and renewable energy policies, in which the share of the renewable energy electricity target can be realised with a lower renewable energy power subsidy when carbon pricing is introduced. To be precise, to realise a share of the renewable energy-based electricity target of 4.5%, the renewable energy power subsidy needed decreases from 0.22 RMB/kWh to 0.21 RMB/kWh.

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Figure 2 The interaction effect between carbon pricing and renewable energy power subsidy policies

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4.2.3 The coordination between the carbon emission cap and share of renewable energy electricity targets by 2020

In the analytical results in Section 3, the three subsets of the policy target portfolio have been obtained in proposition 1, and the coordination between the carbon emission cap and the renewable electricity share targets to alleviate the negative/conflict effect between the coexisting policies have been proposed in Proposition 3. To make the empirical analysis of Proposition 1 and 3 in China's case, we will attempt to identify the policy that should be employed to realise the carbon emission cap and the share of renewable energy-based electricity targets by 2020, and how to coordinate the two policy targets to mitigate potential policy conflicts in China.

In any such attempt, the carbon emission cap and the share of renewable energy electricity targets in 2020 should first be determined. For the latter, the share of non-hydro renewables should reach 9%, according to the National Energy Development Strategy Action Plan (2014-2020) (NEA, 2014b). The carbon emission cap for 2020 can be calculated as follows. The economic output (nominal GDP) and carbon emissions in 2005 were 18.59 Trillion RMB and 6.3Gt (NBS, 2006; BP statistical review of world energy, 2015), while the carbon intensity in the same year was 0.0034 kg CO_2/RMB. The Chinese government has promised to reduce carbon emissions' intensity by 40%-45% from 2005 levels by 2020. Based on such a pledge, said intensity in 2020 in China would be 0.0018 CO_2/RMB. Based on the economic output (GDP from 2005-2015), GDP index (2005-2015) (NBS, 2015) and the expected GDP growth rate (2015-2020) (NDRC 2016), we can calculate the GDP in 2020 (with 2005 as the base year) as 64.41 Trillion RMB. Thereafter, the carbon emission cap for the same year can be obtained by multiplying the GDP by the carbon intensity, which is about 12Gt CO_2.

Besides the outlined targets referred to above, some relevant parameters should be updated for 2020, including the carbon emission intensity of the fossil fuel-based electricity sector (θ) and the emission amount for the non-electricity sector (E_N) in the baseline scenario. According to the National Energy Development Strategy Action Plan (2014-2020) (NEA, 2014), the standard coal consumption for power generation should be less than 300gce/kWh. The emission factor of standard coal is 2.46tCO_2/tce (IPCC, 2006). The carbon emission intensity of coal power generation in 2020 can be obtained by multiplying the standard coal consumption for power generation with the emission factor of standard coal; giving a result of 738g CO_2/kWh.

In addition, non-electricity CO_2 emissions were 66Gt in 2014 (NBS, 2015), and their average annual growth rate is expected to be 1.6% during the 13th Five-Year Plan (2016-2020), according to He (2015). Based on this, the non-electricity CO_2 emissions for 2020 can be calculated as 71 Gt.

Based on the new parameter settings, the entire set of the policy target portfolio can be divided into three subsets, as stated in Proposition 1, which is shown in Figure 3. In Area 2 ($\Omega_{CP} = \{\alpha = 9\%, 0 \le \bar{E} \le 5.4Gt\}$) the single carbon pricing policy is optimal; in Area 1 ($\Omega_S = \{\alpha = 9\%, \bar{E} \ge 10.2Gt\}$), the single renewable energy power subsidy policy is optimal and in Area 3 ($\Omega_{CP\&S} = \{\alpha = 9\%, 5.4Gt \le \bar{E} \le 10.2Gt\}$), the policy mix is necessary. The policy target portfolio in 2020 is ($\alpha = 9\%, \bar{E} = 9.76Gt$) and is included in Area 1. This means that a single renewable energy power subsidy policy is sufficient to achieve the carbon emission abatement target and the share of renewable energy-based electricity target. In addition, the CO_2 price will be reduced to zero, and the carbon pricing policy may have little effect on the carbon abatement and cannot effectively promote the investment of low-carbon technology. This is the policy conflict shown in Proposition 2. To stablize the CO_2 price, the carbon emissions cap in 2020 needs to be adjusted according to Proposition 3. More specifically, to keep the CO_2 price at the level of the simulation results for 2014, i.e. 31.6 RMB/t CO_2, the carbon emission budget should be reduced to 9.83Gt, as shown in Fig. 3; and accordingly, the carbon emissions intensity for 2020 should be reduced by 50% compared to that in 2005, based on the simulation results.

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Figure 3 The coordination between the carbon emission cap and share of renewable energy targets in 2020

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In addition, to promote low-carbon technology investment to good effect, it is necessary to increase the CO_2 price even further to between 140 RMB/t CO_2 and 300 RMB/t CO_2 in China, according to many relevant studies (McKinsey Company, 2009; Mo and Zhu, 2014), and the carbon emission cap should be further adjusted accordingly. Based on the simulation result, the carbon emissions cap should be reduced to 8.6Gt and further to 7.1Gt, to bolster the CO_2 price from the current level to 140 RMB/t CO_2 and, further, to 280 RMB/t CO_2.

5. Conclusion

In this paper, a partial equilibrium model was built to explore the interaction between the carbon pricing policy and the renewable energy power subsidy. Based on this model, the following issues were explored: under what conditions a single or policy mix is optimal to realise the given policy targets, and how to coordinate different policy target settings to reduce the potential conflict between policy instruments, especially in terms of possible CO_2 price collapses. The optimal portfolio of the two policy targets is obtained and, notably, the means to coordinate the two policy targets to stablize the CO_2 price is derived.

The analytical resutls show that the whole set of carbon abatemwnt and renewable energy target portfolio can be divided into three subsets, in which the carbon emission cap and the renewable electricity share targets can be achieved by the single carbon pricing policy, single renewable energy power subsidy policy or policy mix, respectively. In the case of the policy mix, there exists policy interaction effect between carbon pricing and renewable energy power subsidy. In specific, there is a potential synergistic effect, as well as a conflict effect, between the carbon pricing and renewable energy power subsidy policies. More specifically, tightening the carbon emission cap will lower the renewable energy power subsidy needed to realise the share of the renewable electricity target; this is the synergistic effect. In contrast, increasing the share of renewable energy electricity will promote the substitution of fossil fuel power with renewable energy power, which in turn exerts downward pressure on the CO_2 permit demand, thereby driving down the CO_2 price and potentially undermining the effectiveness of the carbon pricing policy. This is the possible conflict effect. In order to alleviating the policy conflict effect, the adjustment path of carbon emission cap target with a varying share of the renewable energy electricity target, to maintain the CO_2 price at a certain level was proposeed.

Corresponding with propositions in analytical results, an empirical study of China’s case was conducted. The empirical results show that the single renewable energy power subsidy policy can serve to achieve the carbon emission reduction and share of renewable energy electricity targets in 2020 by itself, but the CO_2 price may drop to zero, with the carbon pricing policy having little effect on the carbon abatement and the low-carbon technology investment. That is the conflict effect between the coexisting policies. Therefore, to address the potential effect of policy conflict between the carbon pricing and renewable energy power subsidy policy, it may be necessary to adjust the carbon emission cap. More specific, the carbon emission cap should be decreased to 9.8Gt to stablize the CO_2 price at the current level in the pilot ETSs; i.e., 31.6 RMB/t. In such case, the carbon emissions intensity in 2020 should be reduced by 50% relative to that in 2005.

There are some limitations worth noting in this work. In the equilibrium model employed, a completely competitive electricity market is assumed, and the market regulation by the government is ignored. In fact, the market intervention may lead to a distortionary price, and the simplification of the model may overestimate the pass through of the carbon price in our model. In addition, the transaction costs are not considered in current model, which may affect the ultimate equilibrium results of the model and the coordination between carbon pricing and renewable energy power subsidy policy. It should also be pointed out that the empirical results of the China case study were obtained based on certain relevant assumptions, such as cost parameters, which may affect the optimal policy choice. To be specific, the lower abatement cost in the power sector can improve the competitiveness of the fossil fuel sector and increase the power generation from fossil fuel, and to increase the share of renewables generation, a single renewable energy power subsidy policy may not ensure the achievement of both policy targets. In addition, with the cost of renewable generation decreasing due to the learning effect, the single subsidy policy may have a more significant effect on renewable development and may be sufficient to achieve both policy targets. However, the subsidy level for renewable energy in China may become lower in future, given that the deficit of the renewable development fund is becoming a grave concern; and in this case, the single subsidy policy may not be sufficient to achieve both policy targets. Finally, if the carbon abatement target becomes more stringent in future, carbon pricing may also be necessary in addition to the subsidy policy. Therefore, the development of renewable energy technology and a policy adjustment may affect the empirical results of our study, which should be further explored in future.

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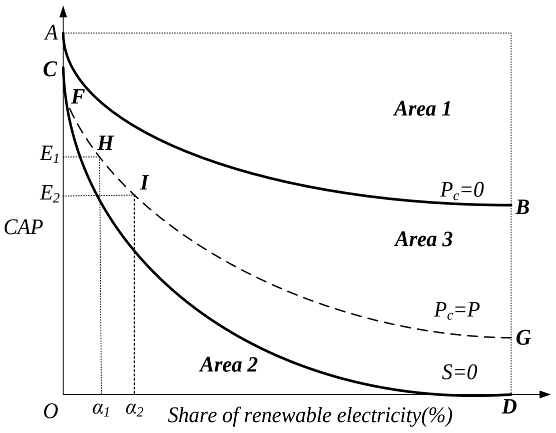

Fig. 1 The coordination between carbon emission cap and share of renewable electricity targets

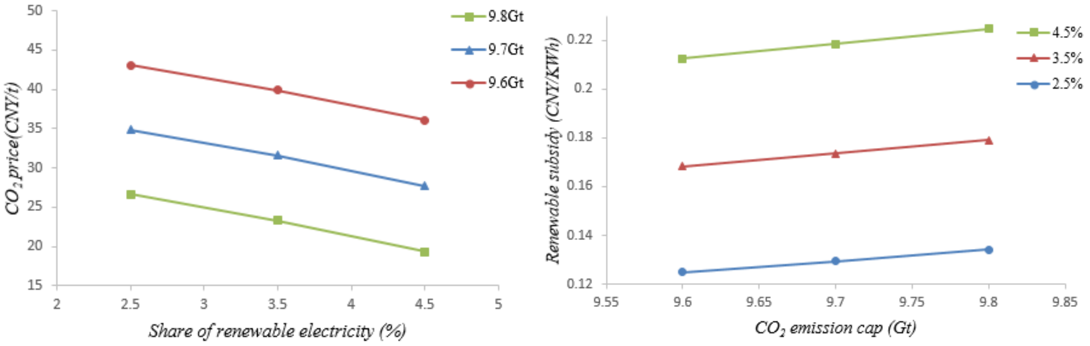

Fig. 2 The interaction effect between carbon pricing and renewable energy power subsidy policies

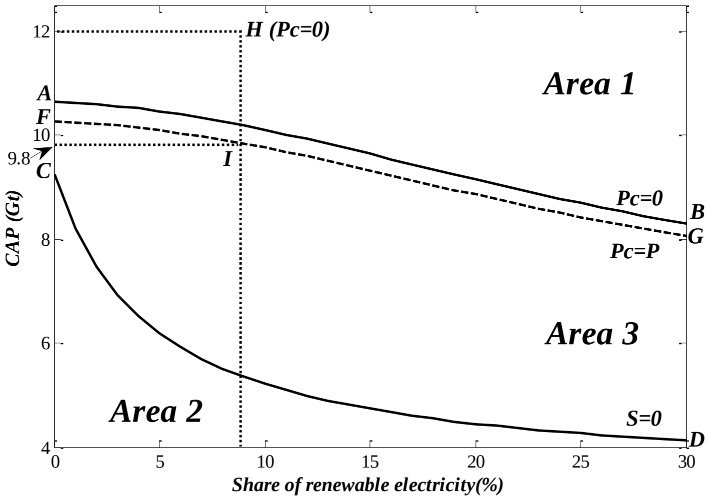

Fig. 3 The coordination between the carbon emission cap and share of renewable energy targets in 2020

Table 1 The estimation results of the marginal cost function for fossil fuel electricity production

Description	Parameter	Value	Units
Slope of the marginal cost curve	c_1^f	$4.56*10^{-14**}$	（RMB/KWh^2）
Intercept of the marginal cost curve	c_2^f	0.26^{**}	（RMB/KWh）
Goodness of fit	R^2 adjusted	87.70	(%)
	R^2 predicted	85.96	(%)

**P<0.1, Significant coefficient.

Table 2 The estimation results of the marginal cost functions for renewable electricity production

Description		Parameter	Value	Units
Slope of the marginal cost curve	Wind	c_{11}^{r}	$9*10^{-13}$***	(RMB/KWh^2)
	Biomass	c_{21}^{r}	$1*10^{-10}$***	(RMB/KWh^2）
	Solar	c_{31}^{r}	$2*10^{-11}$***	(RMB/KWh^2)
Intercept of the marginal cost curve	Wind	c_{12}^{r}	0.53***	(RMB/KWh)
	Biomass	c_{22}^{r}	0.62***	(RMB/KWh)
	Solar	c_{32}^{r}	0.82***	(RMB/KWh)
Goodness of fit	Wind	R^2 adjusted	91.70	(%)
		R^2 predicted	90.72	(%)
	Biomass	R^2 adjusted	91.76	(%)
		R^2 predicted	89.17	(%)
	Solar	R^2 adjusted	92.32	(%)
		R^2 predicted	91.38	(%)

***$P<0.05$, Significant coefficient.

Table 3 The estimation of marginal abatement cost curve for fossil fuel electricity sector and non-electricity sector

Description		Parameter	Value	Units
Slope of the marginal cost curve	fossil fuel electricity sector	c_1^e	$4*10^{-7}$***	(RMB/t^2 CO_2)
	non-electricity sector	c_1^n	$3.5*10^{-7}$***	(RMB/t^2 CO_2)
Intercept of the marginal cost curve	fossil fuel electricity sector	c_2^e	0	(RMB/t CO_2)
	non-electricity sector	c_2^n	0	(RMB/t CO_2)
Goodness of fit	fossil fuel electricity sector	R^2 adjusted	85.30	(%)
		R^2 predicted	83.15	(%)
	non-electricity sector	R^2 adjusted	86.39	(%)
		R^2 predicted	84.54	(%)

***P<0.05, Significant coefficient.

Table 4 The estimation of electricity demand function

Description	Units	Parameter	Value
Power price demand elasticity	-	E_d	-5.54
Intercept of demand function	（RMB/KWh）	a	0.70
Slope of demand function	（RMB/KWh^2）	b	$2*10^{-14}$

Table 5 Comparison between the simulation results and real data in 2014

	Total electricity production (TWh)	Fossil fuel electricity production (TWh)	Renewable electricity production (TWh)	On-grid price of fossil-fuel electricity （RMB/kWh）	On-grid price of renewable electricity （RMB/kWh）	CO_2 price （RMB/tCO_2）
Simulation results	4433.2	4278.0	155.2	0.49	0.67	31.6
Data in reality	4453.4 [a]	4233.7 [a]	156.3 [a]	0.46 [b]	0.61[b]	31.2 [c]
Relative Error (%)	0.5	1	0.7	6.5	9.8	1.3

Notes: [a] Data sources: NBS (2015);

[b] Data source: NDRC (2014a; 2014b);

[c] Data sources: Liu et al. (2015).

Appendix A

Proof of Proposition 1:

To obtain the three areas referred to in Proposition 1 of Section 3, the critical issue is to find the two boundary curves that separate the entire set of the policy target portfolio into the three subsets.

A.1 Single carbon pricing policy model:

In the market equilibrium state, all the participants optimise their decision to maximise their profits, and first-order conditions can be obtained. Concretely, the fossil fuel electricity producer maximises its profit $\pi_F(\cdot)$ by optimising its electricity production and carbon abatement (Q_F, A_F) simultaneously, which yields the following first-order conditions:

$$C_f{}'(Q_F) = P_f - \theta P_c, \tag{A.1}$$

$$C_e{}'(A_F) = P_c. \tag{A.2}$$

Eqs. (A.1) and (A.2) show that the on-grid power price is equal to the sum of the marginal production costs of fossil fuel power and the carbon emission cost, and the CO_2 price is determined by the marginal cost of the carbon emission abatement.

For the renewable energy electricity producer, the on-grid price is equal to the marginal cost of the renewable energy electricity production:

$$C_r{}'(Q_{iR}) = P_r. \tag{A.3}$$

Similarly, for the power grid firm, the first-order condition is as follows:

$$P(Q_T) + P'(Q_T) \cdot Q_T = (1-\alpha)P_f + \alpha P_r, \tag{A.4}$$

which depicts the relationship between the electricity sales price, i.e. consumer price, and the on-grid prices of fossil fuel power and renewable energy power.

With the assumption of a single carbon pricing policy, the on-grid price of renewable energy-based electricity is equal to the on-grid price of fossil fuel, and the subsidy is zero, which can be expressed as:

$$S = P_r - P_f = 0, \tag{A.5}$$

Additionally, the share of renewable energy-derived electricity is as follows:

$$\alpha = \frac{\sum_{i=1}^{N} Q_{iR}}{Q_F + \sum_{i=1}^{N} Q_{iR}}. \tag{A.6}$$

There is also a carbon emission cap target set by the government, which constitutes the main constrained conditions and is expressed as follows:

$$\theta Q_F - A_F + E_N - A_N = \bar{E}, \tag{A.7}$$

Then, we substitute the cost function and demand function, i.e. Eqs. (8)-(12) in Section 2 into these equations above, allowing us to obtain the share of the renewable electricity (α_{CP}) as a function of the carbon emission cap ($\bar{E}$):

$$\alpha_{CP}(\bar{E}) = \frac{-\epsilon(\bar{E}) + \sqrt{\epsilon^2(\bar{E}) - 4\gamma(\bar{E})\vartheta(\bar{E})}}{2\gamma(\bar{E})}, \tag{A.8}$$

in which $C_{R1} = \sum_{i=1}^{N} \frac{1}{c_{i2}^{r}}$, $C_{R2} = \sum_{i=1}^{N} \frac{c_{i2}^{r}}{c_{i1}^{r}}$, $\gamma(\bar{E}) = \bar{E} - E_N - \theta C_{R2} + c_1^f C_{R1}(\bar{E} - E_N) + \theta c_2^f C_{R1}$, $\epsilon(\bar{E}) = \left(\theta a C_{R1} + \theta C_{R2} - c_2^f C_{R1} - c_1^f C_{R1}(\bar{E} - E_N)\right)$, $\vartheta(\bar{E}) = \left(c_1^f C_{R1}(\bar{E} - E_N) + \theta c_2^f C_{R1} + 2bC_{R1}(\bar{E} - E_N) - \theta a C_{R1}\right)$.

$\alpha_{CP}(\bar{E})$ represents the boundary curve, which is the maximum share of renewable energy-based electricity achieved by the carbon pricing policy with the carbon emission cap target ($\bar{E}$). Then, the subset of the target portfolio that can be achieved by the single carbon pricing policy is expressed as follows:

$$\Omega_{CP} = \{(\alpha, \bar{E}) \mid 0 < \alpha < \alpha_{CP}(\bar{E})\}$$

A.2 Single renewable energy power subsidy policy model:

With the assumption of the single renewable energy power subsidy policy, the equilibrium carbon price is zero:

$$P_c = 0. \tag{A.9}$$

Similarly, the representative fossil fuel electricity producer and renewable energy electricity producer maximise their profits by optimising their electricity production (Q_F, Q_{iR}) simultaneously, which yields the following first-order conditions:

$$C_f'(Q_F) = P_f, \tag{A.10}$$

$$C_r'(Q_{iR}) = P_r. \tag{A.11}$$

While for the power grid firm, the first-order condition is as follows:

$$P(Q_T) + P'(Q_T) \cdot Q_T = (1-\alpha)P_f + \alpha P_r \tag{A.12}$$

There is a policy target set by the government that constitutes the main constraint conditions. More specifically, the share of renewable energy electricity's constraint is expressed as follows:

$$Q_R = \alpha\left(Q_F + \sum_{i=1}^{N} Q_{iR}\right). \tag{A.13}$$

With the assumption of a single renewable energy power subsidy policy, the on-grid price of renewable energy-based electricity is greater than the on-grid price of fossil fuel, which can be expressed as:

$$S = P_r - P_f \geq 0. \tag{A.14}$$

While the carbon emission is as follows:

$$\bar{E} = \theta Q_F + E_N. \tag{A.15}$$

Similarly, we substitute the cost function and demand function, i.e. Eqs. (8)-(12), in Section 2.2 into these equations above, and can thereby obtain the carbon emission cap ($\bar{E}_S$) as a function of the share of the renewable electricity (α):

$$\bar{E}_S(\alpha) = \frac{L\left(\frac{\alpha}{c_1^f}-(1-\alpha)C_{R1}\right)\left(a+2b(\frac{c_2^f}{c_1^f}+C_{R2})\right)-\left(2b\frac{\theta^2}{(c_1^f)^2}-L\left(1+2b\left(\frac{1}{c_1^f}+C_{R1}\right)\right)\right)\left((1-\alpha)\frac{c_2^f}{c_1^f}-\alpha C_{R2}\right)}{J} \quad \text{(A.16)}$$

in which $C_{R1} = \sum_{i=1}^{N}\frac{1}{c_{i2}^r}$, $C_{R2} = \sum_{i=1}^{N}\frac{c_{i2}^r}{c_{i1}^r}$, $J = 2b\frac{\theta}{c_1^f}\left(\frac{\alpha}{c_1^f} - (1-\alpha)C_{R1}\right)$, $L = \frac{\theta^2}{c_1^f} + \frac{1}{c_1^e} + \frac{1}{c_1^n}$.

$\bar{E}_S(\alpha)$ represents the boundary curve, which is the minimum carbon emission cap achieved by the renewable energy power subsidy policy with the share of the renewable energy electricity target (α). Then, the subset of the target portfolio, which can be achieved by a single renewable energy power subsidy policy, is represented as follows:

$$\Omega_S = \left\{(\alpha, \bar{E}) \middle| \, 0 \le \alpha \le 1, \bar{E} \ge \bar{E}_S(\alpha)\right\};$$

Finally, the middle area between Ω_{CP} and Ω_S is the subset of the target portfolio, which should be achieved by a policy mix:

$$\Omega_{CP\&S} = \left\{(\alpha, \bar{E}) \middle| \, \alpha_{CP}(\bar{E}) \le \alpha \le 1, \; 0 \le \bar{E} \le \bar{E}_S(\alpha)\right\}$$

In the subset $\Omega_{CP\&S}$, although the implementation of the carbon pricing (renewable energy power subsidy) can promote the substitution of the fossil fuel electricity (carbon emission abatement), single carbon pricing (renewable energy power subsidy) is not enough to achieve the share of the renewable energy-based electricity target (carbon abatement target), and the policy mix is necessary.

Proof of Proposition 2:

First, we can obtain CO$_2$ price P_c and the renewable energy power subsidy as a function of the carbon emission cap and the share of renewable energy electricity targets in Section 2, based on the first-order conditions Eqs. (A.1)-(A.4), the constraint conditions Eqs. (5)-(8) and the cost functions Eqs. (9)-(12), as shown by Eq. (A.17) and Eq. (A.18).

$$P_c = \frac{c_1^f(1-\alpha)(aC_{R1}-\alpha C_{R2})+(2bC_{R1}+\alpha^2)\theta c_2^f-\left(c_1^f(2bC_{R1}+\alpha^2)+C_{R1}\left(c_1^f\right)^2(1-\alpha)^2\right)(\bar{E}-M)}{(2bC_{R1}+\alpha^2)\left(c_1^f\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)-\theta^2\right)+C_{R1}\left(c_1^f\right)^2(1-\alpha)^2\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)} \quad \text{(A.17)}$$

$$S=\frac{\left(\alpha\frac{1}{c_1^f}\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)-\alpha\left(\frac{\theta}{c_1^f}\right)^2-C_{R1}(1-\alpha)\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)\right)P_c+\left(\alpha\frac{1}{c_1^f}-(1-\alpha)C_{R1}\right)(\bar{E}-M)-\alpha\frac{\theta\, c_2^f}{c_1^f c_1^f}+(1-\alpha)\frac{\theta}{c_1^f}C_{R2}}{(1-\alpha)\frac{\theta}{c_1^f}C_{R1}} \tag{A.18}$$

where $C_{R1}=\sum_{i=1}^{N}\frac{1}{c_{i2}^r},\ C_{R2}=\sum_{i=1}^{N}\frac{c_{i2}^r}{c_{i1}^r},\ M=E_N+\frac{c_2^e}{c_1^e}+\frac{c_2^n}{c_1^n}-\frac{\theta c_2^f}{c_1^f}.$

Next, we analyse the effect of interaction between the coexisting carbon pricing and renewable energy power subsidy policies. We can differentiate the CO$_2$ price shown in Eq. (A.17) with respect to the share of renewable energy-based electricity (α). We can determine that $\frac{\partial P_c}{\partial \alpha}<0$ and a higher share of a renewable energy-derived electricity target will lead to a lower CO$_2$ price.

In addition, we can differentiate the CO$_2$ price shown in Eq. (A.17) with respect to the carbon emission cap ($\bar{E}$), to obtain:

$$\frac{\partial P_c}{\partial \bar{E}}=-\frac{c_1^f(2bC_{R1}+\alpha^2)}{(2bC_{R1}+\alpha^2)\left(c_1^f\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)-\theta^2\right)+C_{R1}\left(c_1^f\right)^2(1-\alpha)^2\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)}<0 \tag{A.19}$$

Therefore, tightening the carbon emission cap will lead to a higher CO$_2$ price.

Next, we can differentiate the renewable energy power subsidy shown in Eq. (A.18) with respect to the carbon emission cap $\bar{E}$, to obtain:

$$\frac{\partial S}{\partial \bar{E}}=\frac{\alpha\left(\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)-C_{R1}c_1^f(1-\alpha)\left(\frac{\theta^2}{c_1^f}+\frac{1}{c_1^e}+\frac{1}{c_1^n}\right)}{\theta C_{R1}(1-\alpha)}\cdot\frac{\partial P_c}{\partial \bar{E}}+\frac{\alpha-C_{R1}c_1^f(1-\alpha)}{\theta C_{R1}(1-\alpha)}$$

$$=c_1^f\theta(2bC_{R1}+\alpha^2)+\alpha\theta c_1^f(1-\alpha)>0 \tag{A.20}$$

Accordingly, we can obtain $\frac{\partial S}{\partial \bar{E}}>0$, and tightening the carbon emission cap will lead to a lower renewable energy power subsidy.

In addition, we can differentiate the renewable energy power subsidy shown in Eq. (A.18) with respect to the share of renewable energy electricity (α), to obtain $\frac{\partial S}{\partial \alpha}>0$, and a higher share of a renewable energy electricity target will lead to a higher subsidy.

Proof of Proposition 3:

Based on Eq. (A.17), we can obtain the relationship between the CO_2 emission cap target and the share of the renewable energy-based electricity target with a certain CO_2 price. That is:

$$\bar{E} = \frac{\theta c_1^f (1-\alpha)(\mathrm{a}C_{R1} - \alpha C_{R2}) + \xi(\alpha)\theta c_2^f - P(\xi(\alpha)(c_1^f W - \theta^2) + U(\alpha)W\big)}{\left(c_1^f\, \xi(\alpha) + U(\alpha)\right)} + M. \tag{A.21}$$

while the iso-carbon price curve can be obtained as follows:

$$P = \frac{c_1^f (1-\alpha)(\mathrm{a}C_{R1} - \alpha C_{R2}) + \xi(\alpha)\theta c_2^f - \left(c_1^f\, \xi(\alpha) + U(\alpha)\right)(\bar{E} - M)}{\xi(\alpha)\left(c_1^f W - \theta^2\right) + U(\alpha)W}, \tag{A.22}$$

where $C_{R1} = \sum_{i=1}^{N} \frac{1}{c_{i2}^r}$, $C_{R2} = \sum_{i=1}^{N} \frac{c_{i2}^r}{c_{i1}^r}$, $M = E_N + \frac{c_2^e}{c_1^e} + \frac{c_2^n}{c_1^n} - \frac{\theta c_2^f}{c_1^f}$, $W = \frac{\theta^2}{c_1^f} + \frac{1}{c_1^e} + \frac{1}{c_1^n}$, $U(\alpha) = \left(c_1^f\right)^2 C_{R1}(1-\alpha)^2$, $\xi(\alpha) = 2bC_{R1} + \alpha^2$.

Appendix B

The electricity demand function is assumed as follows,

$$Q = f(p) \tag{B.1}$$

And then, using the consumer electricity price and the electricity consumption data for 2013 and 2014, the electricity generation in 2014 with Taylor series expansions shown as,

$$Q_{2014} = Q_{2013} - |E_d| \cdot \frac{Q_{2013}}{P_{2013}} \cdot (P_{2014} - P_{2013}) \tag{B.2}$$

And then, the power price demand elasticity, E_d can be calculated.

In this paper, we assume the power price demand elasticity will not change from 2014. So, based on this power price demand elasticity, E_d, the electricity demand function as base year 2014 can be expressed,

$$Q = Q_{2014} - |E_d| \cdot \frac{Q_{2013}}{P_{2013}} \cdot (P - P_{2013}) \tag{B.3}$$

Therefore, the parameters a and b of electricity demand function shown in Eq. (8) can be estimated as,

$$a = \frac{(|E_d| - 1)}{|E_d|} \cdot P_{2014}, b = \frac{P_{2014}}{|E_d| \cdot Q_{2014}} \tag{B.4}$$