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Title: Pricing the Permission of Pollution: Optimal Control-Based Simulation of Payments for the Initial Emission Allowance in China

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Keywords: pricing; payment; initial emission allowance; optimal control-based; chemical oxygen demand; ammoniacal nitrogen

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Abstract: China has modified its pollution control policy system with such price tools as the pollution charge (PC) policy and the payment for initial emission allowance (PIEA) policy. The aim of PC policy is to compensate for the environment damage caused by pollutants, while PIEA is in charge of the initial emission allowance (IEA) within the emission trading system (ETS). However, since the implementation of PIEA, it has been criticized as redundant because of the similar pricing scheme with the PC. In addition, the existing PIEA pricing approaches have ignored interactions with other policies, such as PC and total emission control (TEC) policies. In this research, we established an optimal control-based model with chemical oxygen demand (COD) and ammoniacal nitrogen (NH3-N), two independent pollutants variables, to simulate the water pollutants' PIEA price. Simulation results indicated that emission quantity and optimal social benefit in the PC-PIEA combination scenario was equal to the situation in the PIEA scenario. Under this design, PC compensated for the emission damage, and PIEA paid for the scarcity rent, while PIEA does not duplicate the PC policy. In addition, the PIEA policy has a complex effect on pollutant emission. Because PIEA policy increases the enterprises' discharging cost, most regions' COD emissions are less than the baseline, excepting Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, and Guangdong, in which emission quantities are greater than the baseline. The NH3-N emission shows an opposite trend. The simulation result is that excluding Inner Mongolia, Hubei, Hunan, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang, the NH3-N emissions in the rest of regions are increased. TEC policy has a significant effect on pollutant emissions and the PIEA price. The COD emission quantity with TEC is lower than that without the TEC policy, therefore, the TEC policy will be effective for pollutant emission control. The pollutant beyond the restricted target will be charged a payment for IEA at a higher price than without the TEC policy.

Dear editor and three anonymous reviewers,

We would like to thank for editor's hard work to find reviewers, and we would like to thank to reviewers who spend time reading our article carefully and presenting professional and detailed advices. We have revised the article according to reviewers' suggestions and response to questions one by one. The revised article is more readable by following the reviewers' advices. We would appreciate your help!

Yours sincerely,

Jin-Nan WANG

Reviewer #1:

1. Too little is described and defined social benefits.

A: The details of social benefit are described in P 11 Line 15.

2. No comparison of the method and model of the other.

A: Some comparisons are elaborate in P 9 Line 16 methodology part.

3. What are the penalties, ie. What value and what character.

A: The detail explanation of the penalty function in SI in the P S5 Line 23. The penalty function in this study is actually a method used in the algorithm to deal with constraints, rather than intuitive understanding of the environmental policy used to punish excessive means of discharge and its standards.

4. What is the practical aspect of the model and studies? Is it just the diagnosis or the use of theses and practical results-appropriate decisions / Case Study/.

A: The practical application of this study is the pricing method designed for China's implementation of the PIEA policy. The PIEA Policy is piloted in 12 regions, and each region choose pricing method by their own decision. The most of pilot regions take treatment cost as pricing method for convenience, but does not take into account the existing policies, so this study is promoted.

5. What about the computational complexity.

A: Computational process is complex indeed, since words limited, all details cannot be described excepting briefly calculated steps and algorithms listed in the article. In order to calculate coefficients and parameters required by pricing model, we also need to set up some auxiliary models. These calculations are listed in SI. After modeling, simulation and solution are also important parts of the work. Solution algorithm is shown in the article.

6. Is obtained optimal solution or sub-optimal / simulation /.

A: Due to various restrictions, the impact on the environment is temporarily only pollutant emissions; the health impact has not been included in the study. The reasons why health effects incorporating into the study are explained in research limitation section.

7. No information about the implementation of the model / environment, tools and solvers etc./

A: The calculation tool uses the MATLAB software, and the solution algorithm is listed in SI.

Reviewer #2:

The paper studies the design of payment for initial emission allowance pricing approach based on optimal control theory. It is an important and interesting piece of work, and is relevant to real word problems. Nevertheless, I do have some concerns:

1. The current introduction section does not pinpoint the theoretical problem of prior research, and fails to highlight the intended contribution of the study. I'd suggest the authors to clearly spell out why this study is important, what's the gap in this literature, also how this study intends to contribute to the literature.

A: We rewrote the introduction section in accordance with the reviewers ' recommendations, highlighting why the study was important, what the existing research was, and the contribution of this study.

2. This may be not easy without a meaningful comparison with similar research in the literature. The literature review should be extended. As far as my understanding, many relevant references are missing.

A: In previous version, the literature review focus on the topic of initial emission allowance pricing, and the content of the discussion was limited. Following the reviewers ' suggestions, we extended the topic literature review to relevant resource pricing. We try to modify the paper better, but do not know if follow the instruction of topic proposed by reviewers, if there is more detailed advice, please let us know.

3. In section 3 Case and data, the authors only outlining the data sources without much discussion of the case. More information about the case will useful here.

A: We added information in the data collection section.

4.The simulation results Section is also weak. The authors only describe the results. No clear insights are drawn. I haven't learned anything from this manuscript from the environmental policy research viewpoint.

A: This study focuses on to establish a pricing method that is applicable to the implementation of the PIEA policy with the existing complex policies background. The previously version does not show the policy recommendations legible. Following the reviewers' suggestions, we reorganized the narrative of results, and list the viewpoints.

5. No policy implications are discussed. The conclusion should focus more on the practical implications and policy implications of your article. Although the main findings are summarized, what are the implications of these findings to the industrial firms or government policy makers? It is not entirely clear to me how the theory developed can be applied and used for policy evaluation.

A: As reviewer's suggestion, we add theory information about pricing method in theoretical analysis section to help understand how the theory can be applied and used for policy evaluation. Then we elaborate the implications of the research findings in discussion section.

6. The authors need to more critically discuss the research limitations and how these limitations inform further research in the future.

A: More information about research limitation is listed in discussion section.

7. There are some problems with grammar and sentence structure through the paper. Attention should be paid to avoid grammatical errors.

A: We try our best to correct grammatical errors and polish the article.

Reviewer #3:

This manuscript creatively established an optimal control-based model with two independent pollutants variables, chemical oxygen demand(COD) and ammoniacal nitrogen(NH3-N), to simulate water pollutants payment for initial emission allowance(PIEA). The model establishment is reasonable and feasible. The previous mistaken understanding of pollution charges(PC) and PIEA has been proposed and corrected, and the influence of other policies, PC and total emission control(TEC) for example, has been taken into consideration. Besides, the interaction between two pollutants index, COD and NH3-N, has been discussed, according to the simulation result. The conclusion of this manuscript has a critical reference value for the PIEA price setting in china.

A few major revisions are listed as follow:

1) As it is mentioned in P8 Line 26, maximum social benefit is the object of PIEA optimal model. But in the Formula (7) and (9), they are about the enterprise profits in different scenarios. It is kind of difficult to obtain the stimulated results about optimal social benefit, best pollution emission quantity and PIEA price based on the Formula (7) and (9) directly.

A: Thank you for your attention to the details of the model. Due to length limitation of the article, some details are omitted. Here is a more detailed explanation. Formula (6) represents the social benefit, and the formulas (8) and (10) represent the individual business benefits of Scenario 1 and Scenario 2 respectively. In formula (8), τ_C and τ_N represent initial payment price for COD and NH_3-N, and $g_C^i(x^i, K^i)$ and $g_N^i(x^i, K^i)$ represent firm COD and NH_3-N emissions. (The process of establishing the function of enterprise's profit function and the social benefit function, including the details how to establish the pollutant emissions function is described in SI, instead of describing in main text.) The section in P 10 Line 8 describes the process how to find the initial allowance price that achieves optimal social benefit. "In the **first stage**, the policy maker offers a series of PIEA prices according to an area with several enterprises. In the **second stage**, enterprises take countermeasures. Increasing costs will decrease the enterprises' profits after the PIEA policy has been implemented. Supposing that the enterprise is an 'economic man' who chases the maximum benefit; thus, the enterprise will take measures if the profit decrease is beyond the acceptable range. Two types of strategies are available to adopt by the enterprise: adjust the production output or raise the pollution reduction investment. The enterprise chooses the best suitable measure in accordance with the maximum profit principle. In the **third stage**, the policy maker decides which price will be taken for the benefits. The policy maker will measure the social benefit aimed at every price and choose the price that will maximize the social benefit." Following description is easier to understand, the optimal social benefit is the objective solution, the best pollution emission is the emission when achieving objective solution, and the initial allowance price is the condition when pollutants are controlled at the best emission.

Thus, the equations are available for obtaining the stimulated results about optimal social benefit, best pollution emission quantity and PIEA price.

2) It is noted that the Table 1 has not mentioned the information what is introduced in P11 Line 15-16.

A: It's our mistake in labeling, and we correct the mistake: the information about initial allowance price mentioned in P19 Line 10 is introduced in Fig 7 and Fig 8.

3) The relationship between PC and PIEA has been discussed many times in the whole manuscript. It would be better to be discussed in two aspects, in optimal social benefit and in PIEA price setting, separately.

A: Following the reviewer’s instruction, we make the paragraph clear organized.

4) The structure of the manuscript is not clearly. Results, discussions and conclusions part are not proper. Especially the conclusions, it is not listed by points, and it is not well matched what has mentioned in the abstract and introduction.

A: We arrange the narrative order by following the structure that results, discussions and conclusions. The results part shows the optimal social benefit, best pollution emission and initial allowance price. The discussions part includes policy implication and research limitation. The conclusion part summaries the results and lists them by points.

Amount of words：9547

Pricing the Permission of Pollution: Optimal Control-Based Simulation of Payments for the Initial Emission Allowance in China

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Abstract

China has modified its pollution control policy system with such price tools as the pollution charge (PC) policy and the payment for initial emission allowance (PIEA) policy. The aim of PC policy is to compensate for the environment damage caused by pollutants, while PIEA is in charge of the initial emission allowance (IEA) within the emission trading system (ETS). However, since the implementation of PIEA, it has been criticized as redundant because of the similar pricing scheme with the PC. In addition, the existing PIEA pricing approaches have ignored interactions with other policies, such as PC and total emission control (TEC) policies. In this research, we established an optimal control-based model with chemical oxygen demand (COD) and ammoniacal nitrogen (NH_3-N), two independent pollutants variables, to simulate the water pollutants' PIEA price. Simulation results indicated that emission quantity and optimal social benefit in the PC–PIEA combination scenario was equal to the situation in the PIEA scenario. Under this design, PC compensated for the emission damage, and PIEA paid for the scarcity rent, while PIEA does not duplicate the PC policy. In addition, the PIEA policy has a complex effect on pollutant emission. Because PIEA policy increases the enterprises' discharging cost, most regions' COD emissions are less than the

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baseline, excepting Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, and Guangdong, in which emission quantities are greater than the baseline. The NH_3-N emission shows an opposite trend. The simulation result is that excluding Inner Mongolia, Hubei, Hunan, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang, the NH_3-N emissions in the rest of regions are increased. TEC policy has a significant effect on pollutant emissions and the PIEA price. The COD emission quantity with TEC is lower than that without the TEC policy, therefore, the TEC policy will be effective for pollutant emission control. The pollutant beyond the restricted target will be charged a payment for IEA at a higher price than without the TEC policy.

Keywords: **pricing; payment; initial emission allowance; optimal control-based; chemical oxygen demand; ammoniacal nitrogen**

1. Introduction

The natural environment not only provides human beings with a habitat for survival but is also involved in manufacturing processes as a factor of production. In addition to providing natural resources, the environment receives pollution produced by manufacturing processes. It is well-known that environmental capacity to receive pollutant emissions is a type of natural resource. Environmental capacity resources are limited, while the demand for it is growing; therefore, people need to measure the cost and benefits to use resources efficiently. The cost of using environmental capacity resources is primarily caused by its external damage, but the government employs a methodology to internalize externalities to make the beneficiaries undertake the real environmental costs. When calculating the benefits of environmental resources, the scarcity rents are often overlooked. The Chinese government implemented the payment for initial emission allowance (PIEA) policy to capture scarcity rents for environmental capacity resources.

The PIEA policy arises from the actual demand of the emission trading policy. In the initial stage of emission trading, the manager allocated the allowance to enterprises by some rules for free. Free allocation causes a lot of problems. Unpaid emission allowances are for existing enterprises, and new entrants are required to purchase allowances from the emissions trading market. Compared to the new entrants that have to pay for the allowance, the enterprises that receive the allowance for free are basically receiving a subsidy(Bovenberg et al., 2005). In addition, with free allowances, the enterprises lack incentives and pressure to reduce emissions(Goulder et al., 2010). Unpaid allowances make enterprises using environmental capacity resources inefficient, and the enterprises tend to use more allowances than they need. Furthermore, allocating allowances for free promotes manager power rent-seeking, that is, enterprises will attempt to obtain special approval for allowances(Gu, 2007).

To avoid the free allowance as a subsidy for enterprises, to improve the efficiency of resource allocation and to avoid rent-seeking behavior in allocating, the Chinese government launched the PIEA policy in 2008. The policy stipulates that for chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), sulfur dioxide (SO_2) and nitrogen oxide (NO_X) four pollutants, enterprises should pay for the emission allowance that they obtained(General Office of the State Council, 2014).

The practical significance of the PIEA policy is to meet the needs for an initial allowance allocation in the first stage of the emissions trading market, since managers gradually realized that if the demands for allowances are adequate, unrestricted rights to use them will lead to an overextension of resources, and the scarcity rents of resources are wasted. Therefore, additional policies are needed to ensure the sustainable use of resources. Since charging appropriate scarcity rents for depleted resources can keep resource consumption at a sustainable level (Hartwick, 1977), the PIEA policy has been implemented.

The initial emission allowance price as results of this study could be in support of the policy implementation. In addition, the price is not only for the initial emission allowance but also actually shows the scarcity rents for environmental capacity resources, meaning that the price calculation method in this study could be implemented in resource value accounting.

2. Literature Review

In the PIEA policy, the allowance price is the key factor; thus, how to price allowances is a concern of researchers. Many researchers studied methods for pricing initial emission allowances. The market price method is conveniently used in pricing allowance. Several researchers employed an auction to pricing emission allowance, such as the CO_2 emission allowance within the EU emissions trading system (EU ETS)(Watanabe and Robinson, 2005), carbon monoxide (CO), volatile organic compounds (VOC), sulfur dioxide (SO_2)(Karl, 1992), and nitrogen oxides (NO_X)(Napolitano et al., 2007) in the United States Clean Air Act (CAA)(McCarthy et al., 2007) and COD, NH_3-N, SO_2 and NO_X in the China PIEA policy(Xiao et al., 2001). The auction method has advantages for pricing allowance. Compared to the free allocation method, the auction method will generate income, thereby reducing the government's dependence on ordinary taxes (Andrew Muller et al., 2002; Parry, 1997). Auction revenue also leads to a revenue-recycling effect that reduces tax distortions (Goulder et al., 1999; Muller et al., 2002; Parry, 1997). In the carbon emissions trading market, the allocation of initial allowance has significant impacts on price and allocation efficiency, and auctions tend to reduce price and marginal cost differences, while free allocation tends to amplify the differences (Burtraw et al., 2001). The auctions will encourage companies to implement effective technical innovations(Milliman and Prince, 1989; Popp, 2003). However, the auction method has several drawbacks. As a market-based mechanism, an auction is considered to be able to allocate resources efficiency and generate income, but when the auction is applied to negative externality products, the effect on consumer welfare and social welfare is uncertain (Li, 2015). In addition, in the EPA's emissions trading market, auction settings may cause both buyers and sellers to underestimate the allowance value, leading to lower efficiency in the emission trading market (Cason, 1993), and when the seller can set the bid price, it will distort the market efficiency (Dijkstra and Haan, 2001). Thus, researchers seek pricing methods other than auctions.

PIEA is charging for the environmental capacity to collect scarcity rent, which means "missing money"(Fullertona and Metcalf, 2001; Zöttl, 2011); therefore, several researchers adopted a pricing approach for natural resources. In the US SO_2 emission trading, the shadow price of the SO_2 emission reduction is estimated using the output distance function, which is considered to be the allowance price (Coggins and Swinton, 1996; Fare et al., 2007). Several researchers believe that the initial emission allowance price is related to the cost of using the environmental capacity resources. The environmental self-purification capacity is regarded as environmental capacity resource, and its price is equivalent to its marginal opportunity cost (Zhang, 1996). The cost recovery method was used to assess the price of environmental capacity and took the price as the reference for the initial emission allowance price (Bi et al., 2007). Similarly, it is believed that the price paid for the initial emission allowance is based on the value of the environmental capacity resources; therefore, pollution control costs could be used as a reference for pricing (Ye et al., 2011).

Other researchers believe that the price of the initial emissions allowance from the costs and benefits of using environmental capacity should be considered, especially the damage caused by the pollution emitted to the environment. The costs and benefits were took as a consideration for the initial emissions allowance price model (Huang and Wu, 2004). An initial allowance pricing strategy was established based on the value of water environmental capacity, and the pricing strategy considered the economic value and ecological value of water environmental capacity, as well as the differences between regions and industries (Yu et al., 2012).

In the abovementioned studies, only the manager participates in pricing. However, when manager and enterprises are involved in the pricing process, the pricing process becomes a game process. From the perspective of a dynamic game, the evolution of the strategy of the manager and enterprises in the formulation of the allowance price were analyzed, which provides a reference for the government to formulate a fair and effective pricing model of the initial allowance (Xia et al., 2010). The cooperative game theory was employed to construct the Nash-Bargaining pricing model for the initial allowance of the Tai lake industry based on multi-stakeholder cooperation (Liu et al., 2012).

Researchers discussed varied kinds of pricing approaches, several methods have been applied in practice, and others remained at the theoretical stage. Observing these approaches from an independent perspective, each approach has different considerations. However, when the Chinese environmental policy framework is taken into account, certain approaches ignore the interaction with existing policies (del Río González, 2007).

Prior to the PIEA policy, China embarked on policies related to environmental capacity resources such as the pollution charge (PC) policy and the total emission control (TEC) policy. Next, we focus on the following questions: the pollution charges paid by enterprises in the PC policy as compensation for environmental damage is a part of the value for environmental capacity resources. The payment for the initial allowance is also for environmental capacity resources. The interaction between the PIEA and PC was not considered in the pricing approach mentioned above. Does the payment for compensation affect the allowance price in the PIEA policy? In the PC policy, the industrial average treatment cost was used in calculating the payment of pollution charge calculation(Wang, 2005). In the abovementioned initial allowance pricing approaches, some methods involved using the average treatment cost, therefore the pricing approach had been criticized as being redundant because the same pricing approach was adopted with the pollution charges (PC)(Zhang et al., 2015).

The allowance price is relative to the allowance quantity, and the allowance quantity for one region is determined by this region's total emission control (TEC) cap(Goulder, 2013). The effect of the TEC policy on the PIEA price is ignored. Does this emission restriction affect the allowance price?

The PIEA policy for water pollutants refer to chemical oxygen demand (COD) and ammoniacal nitrogen (NH_3-N) pollutants, and the two pollutants have a synergistic effect in the treatment process (Eddy et al., 2014; Loosdrecht et al., 2016).When the enterprise attempts to reduce one pollutant, the other pollutant is also reduced accordingly(Patwardhan, 2008). In previous studies, all approaches calculated the COD and NH_3-N pollutant price individually without considering the synergistic effect on the pollutant treatment process. Therefore, when pricing the initial emission allowance, the synergistic effect should be considered.

In addition to pricing, the policy maker pays close attention to the influence after policy is implemented. There are few studies on effect of PIEA policy implementation and the changes in pollutant emission quantity. Because it is difficult to separate the PIEA policy effect from other policies such as TEC and PC, it is difficult to quantify the environmental benefit from the PIEA policy(Ye et al., 2011).

This research design utilizes the PIEA pricing approach based on optimal control theory. With this pricing approach, the PIEA policy avoids duplicating the PC policy and takes other relative policy interactions into consideration. Additionally, we clarify the effect of PIEA policy implementation and whether the PIEA price is affected by other relative policies. The result shows the prices in different policy-assembled scenarios. The findings also suggest similar best emission quantities in different PC–PIEA policy-assembled scenarios. Finally, we summarize the study and provide subjects for future research.

3. Theoretical Analysis

The pollution discharge from humans and business will affect the environment or even harm the environment, but the implementation of zero emissions is also irrational according to the cost-benefit analysis. In fact, the natural environment can absorb a certain amount of pollution, and managers should control the pollutant emissions to an acceptable limitation. Therefore, the problem of how to measure the acceptable level of pollution needs to be solved by policy designers.

There are two methods to set the acceptable pollutant emission level: one is setting the environmental exposure concentration of pollutants corresponding to the degree of acceptable risk that affects human health and calculating the regional environmental capacity based on the environmental quality criteria for the region; the other is the "best pollutant emission" after the cost-benefit analysis (Tietenberg and Lewis, 2016).

Pollution discharge is known to produce benefits and damages; the effective emission level is to maximize the net benefit in a simple static pollutant model. The emission level when achieving the max net benefit is equivalent to the emission level when the externalities are fully internalized. According to the optimal condition, we can observe that the net benefit of pollution can only be maximized when the marginal benefit of pollution is equal to the marginal damage. As shown in Fig 1, when the pollution marginal damage curve and pollution marginal cost curve intersect at point E, then the marginal cost of pollution at that point is equal to the marginal damage. In an ideal state, the pollution marginal damage curve and pollution marginal reduction curve will intersect at one point, and this point is the best emission quantity and the best emission charge point, as illustrated in Figure 1(Tietenberg and Lewis, 2016). Then, the corresponding amount of pollutant emissions is the best pollutant emissions. With the best emission target, the managers need to choose the appropriate method to keep the amount of emissions at the best emissions.

This research focus on the PIEA policy and takes the existing PC policy into account, payment for initial emission allowance and pollution charge, both of which are costs that enterprises need to pay for discharging pollutant. In the current total emission control policy, the amount of emissions set by the government is based on the target quantity that is not linked with the environmental capacity to date. Therefore, we believe that in this study, the PIEA policy and PC policy keep pollution at the best emission and that the total emission control policy exists as an additional condition for limiting pollutant emissions.

As shown in Fig 1, when the emission reaches the best emission point W, the polluter paid price at t, total fee is W×t, which is composed of areas B and C. Area B lies below the marginal damage cost curve, meaning that the polluter pays compensation for the damage caused by the emission. Area C lies over the marginal damage cost curve, so the polluter pays scarcity rent for acquiring the environmental capacity property resource. Therefore, the payment from the polluter includes two parts: compensation for pollution damage and scarcity rent, corresponding to the PC policy and PIEA policy in reality.

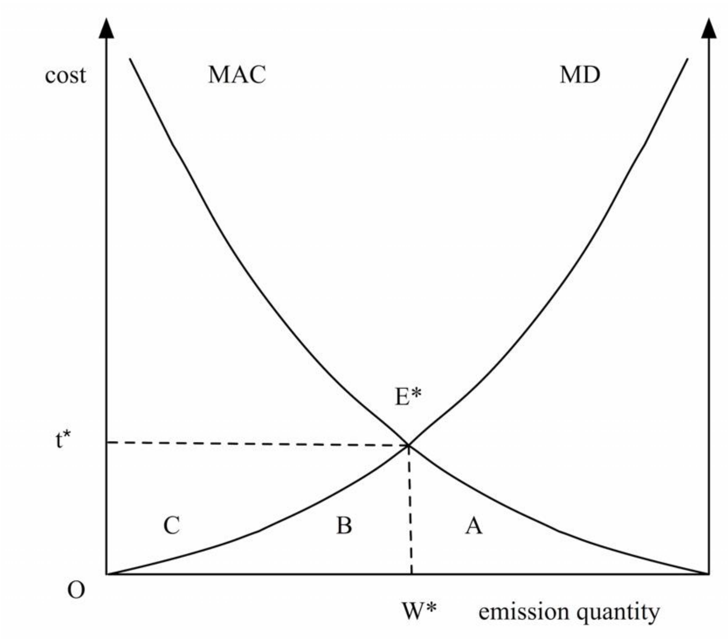

Fig 1 Emission charge for the best emission quantity

4. Methodology and Scenarios

4.1. Methodology

This research intends to solve the pricing problem of initial emission allowance and simulates what will occur when the policy is implemented. After identifying the best pollutant emission targets to achieve maximum net social benefits, it is necessary to build models to describe the best pollutant emission, the costs that polluters should pay, and the maximum net social benefits between these key variables relationships.

In the process of modeling, it is necessary to describe the relationships involved in the micro and macro levels individually: one of the relationships is each enterprise's response to the allowance price at the micro-level. The enterprise will account for changes in its earning after paying for the initial allowance. If the benefit decrease is unacceptable, the enterprise will adjust its strategy, including adjustment of their product amounts and additional pollution reduction investment. Another relationship is net social benefits after all enterprises implement response strategies. Instead of focusing on the benefits of individual enterprises, policy makers only focus on the net social benefits.

After receiving feedback that the net society benefits have changed, the policy makers will adjust the initial emission allowance price according to the feedback. This process "pricing

— strategy — feedback — price" is constantly cycling until it reaches the optimal goals set by the policy makers, which is the maximum net social benefit.

According to the research idea, it is necessary to establish a model that describes the individual enterprise behavior and link the enterprise model with the net social benefits model. Additionally, the relationships need to be described in the model, including the micro and macro levels, the long policy implementation time, and the many variables that change during the execution since the socioeconomic and environmental systems are dynamic. Therefore, the optimal goal at the beginning of the policy design may become non-optimal goal in the implementation process. Therefore, the dynamic characteristics of economic systems and environmental systems should be considered when formulating policy.

In this research, we employ the dynamic optimization model to find the optimal policy according to the manager's objectives and realistic conditions, and analyze the impact on the economy and environment. The dynamic optimal control is a given objective function and constraint condition, which includes the state that must be achieved at a given time and to select an optimal time path to achieve the optimal goal, which is actually a multi-stage decision process in a discrete and continuous time. There are other ways to assess the policy impact, such as the Input-Output (IO) model and Computable general equilibrium (CGE), but those methods have limitations. IO can only address linear relationships, non-linear relationships are not applicable (the relationship between pollutant emissions and amount of products is not linear in this research); CGE is applicable to non-linearity, but it requires a number of empirical parameters that are not easily obtained in this research. Finally, the two methods cannot be applied at the enterprise-level but only in macro industries.

4.2 Modeling process

According to the efficient allocation of pollution theory, efficiency is achieved when the marginal cost of control is equal to the marginal damage(Tietenberg and Lewis, 2016). Corresponding to optimal emission quantity, the manager charges the polluter for fixing the emission on the optimal quantity. The payments from polluters include two parts: compensation for pollution damage and scarcity rent, corresponding to PC policy and PIEA policy. For more details, see SI.

An optimal control-based model, has been widely applied in dynamic pollution regulation (Biglaiser et al., 1995; Moledina et al., 2003). This method could account for the optimal objective under a dynamic equilibrium situation. We consider the policy maker and enterprises as two types of players in the modeling process. The policy maker focuses on the entire social benefit. In this study, the social benefit is the total benefit for the study area from producing goods plus the environmental value. The environment value shall cover damages caused by pollution and services provided by the environment(Tietenberg and Lewis, 2016). Enterprises only focus on their own profits and do not want to take the external cost caused by discharging pollution to the environment voluntarily. Thus, policy the maker must take action to internalize the externality caused by pollution damage to the environment.

The approach follows three-stage games of incomplete information. In the **first stage**, the policy maker offers a series of PIEA prices according to an area with several enterprises. In the **second stage**, enterprises take countermeasures. Increasing costs will decrease the enterprises' profits after the PIEA policy has been implemented. Supposing that the enterprise is an 'economic man' who chases the maximum benefit; thus, the enterprise will take measures if the profit decrease is beyond the acceptable range. Two types of strategies are available to adopt by the enterprise: adjust the production output or raise the pollution reduction investment. The enterprise chooses the best suitable measure in accordance with the maximum profit principle. In the **third stage**, the policy maker decides which price will be taken for the benefits. The policy maker will measure the social benefit aimed at every price and choose the price that will maximize the social benefit. The detailed process is shown in Fig 2.

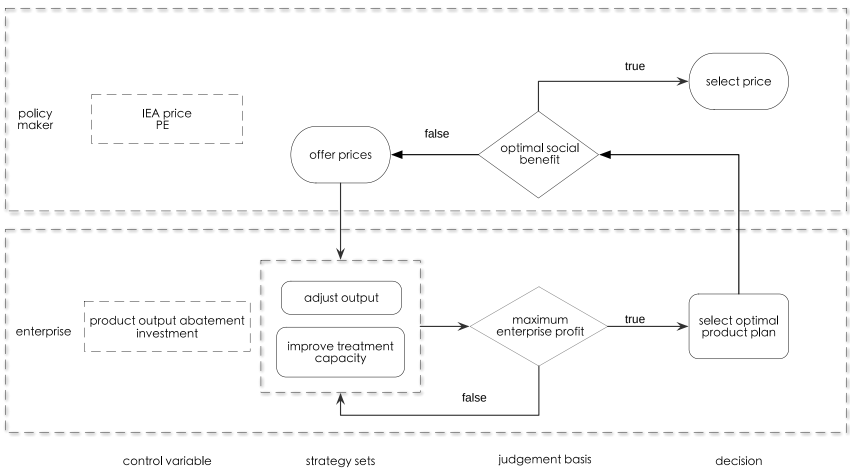

Fig 2 Modeling process of IEA pricing

The price model is based on the dynamic optimal control theory(Chiang, 2000). The modeling process refers to Biglaiser's research(Biglaiser et al., 1995) and modifies several of the items to be applicable to a realistic situation. The process can be expressed with an enterprise with two control variables, which are the production output $x^i(t)$ and the pollution reduction investment I^i, and one state variable, which is the facility running fee $K^i(t)$. The enterprise's optimal objective is to maximum enterprise profit. The policy maker has one control variable, which is the PIEA price $\tau(t)$.

The enterprise profit is equal to sales income deducted by production cost, pollution treatment cost, and possible expenditure additional pollution reduction investment.

$$enterprise\ profit = enterprise\ income - production\ cost - treatment\ c - investment \tag{1}$$

For the period from *0* to *T*, the discount rate is $\rho(\rho \geq 0)$. Assuming that the capital depreciation rate will not affect the result, the enterprise profit for a given time path is

$$\Pi^i = \int_0^T \{e^{-\rho t}[p^{\mathrm{i}}x^i - w^{\mathrm{i}}x^i - Mg^i(x^i, K^i) - I^i]dt \tag{2}$$

$(i = 1, \ldots, n)$

St. $x^i(t), I^i(t) \geq 0.$

In this equation, M is the PC price r, the PIEA price τ or $\mathrm{r} + \tau$.

According to optimal control theory, the enterprise profit Hamiltonian function is

$$H^i = e^{-\rho t}[p^{\mathrm{i}}x^i - w^{\mathrm{i}}x^i - Mg^i(x^i, K^i) - I^i] + \lambda I^i \tag{3}$$

The optimal objective is maximum social benefit. The existing study defines social benefits as the income minus damages caused by emissions (Perman et al., 2003). The social benefit function considers the following parts:

$$social\ benefit = social\ total\ income - total\ product\ cost - investment - pollution\ damage \tag{4}$$

Given a perfect competition market, social benefit can be presented as the sum of discounted enterprises' benefit minus the pollution damage, exclusive of emission taxes or profit from emission trading, since these represent only transfers between enterprises or between enterprises and the government (Biglaiser et al., 1995).

Under a perfectly competitive market, the social benefit could be presented as the sum of the enterprise discount profit subtracted by the pollution damage. The revenue from PIEA is not calculated because this part is the transfer payment from the enterprise and government. At the same time, the social benefit cost function is $D(\sum_i g^i(x^i, K^i))$. Assuming pollution damage to environment is linear:

$$D\left(\sum_i g^i(x^i, K^i)\right) = \delta \sum_i g^i(x^i, K^i) \quad (5)$$

In this equation, δ is the marginal emission damage coefficient.

For a period from *0* to *T*, the social benefit is

$$W = \int_0^T e^{-\rho t}\{\sum_i \left[p^{\mathrm{i}}x^i - w^{\mathrm{i}}x^i - I^i\right] - \delta \sum_i g^i(x^i, K^i)\}dt \quad (6)$$

The social benefit Hamiltonian function is

$$H^w = e^{-\rho t}\{p^{\mathrm{i}}x^i - w^{\mathrm{i}}x^i - I^i - \delta g^i(x^i, K^i)\} + \mu I^i \quad (7)$$

In this study, the COD and NH_3-N PIEA prices are set as two independent variables, which are all calculated in the emission cost. We use a subscript to distinguish COD and NH_3-N. The bivariate pollutant extended model and the details of multiple polluters extending the model process are presented in SI. Further details are provided in SI.

4.3 Scenarios

In this study, we focus on three policies: the payment for initial emission allowance (PIEA) policy, pollution charge (PC) policy and total emission control (TEC) policy. The previous theory analysis has clarified the difference between PC and PIEA. PC means the polluter pays to compensate for the damage caused by the emissions. PIEA means the polluter pays scarcity rent for acquiring the environmental capacity property resource. For enterprises, both PIEA and PC are expenditures that have no difference. Both costs are also calculated as emission costs. The TEC policy is implemented as a penalty function(Weitzman, 1978), see in SI.

We take a realistic situation as the baseline and set four scenarios. In scenario 1 (S1), only the PIEA policy is implemented. The scenario 1 setting is used to compare with the scenarios when PIEA is combined with PC. In scenario 2 (S2), PIEA and PC are implemented simultaneously, which is the simulation mimicking reality. The previous theory analysis discussed that PC requires compensation for the damage by emissions to the environment and PIEA requires scarcity rent to be paid for acquiring environmental capacity property resources. However, it is difficult to distinguish because it is an emission discharge cost expenditure for the enterprise. The charge for the best emission amount is consistent with the compensation for emission damage and scarcity rent. The remaining part is the scarcity rent if the existing pollution charge is deducted. In scenarios 3 and 4 (S3, S4), the TEC policy is added based on scenarios 1 and 2 separately. The equations for the scenarios are as follows:

Scenario 1: PIEA

According to Equation (2), enterprise i profit is:

$$\Pi = \int_0^T \{e^{-\rho t}[p^i x^i - w^i x^i - \tau_C g_C^i(x^i, K^i) - \tau_N g_N^i(x^i, K^i) - I^i]\}dt \tag{8}$$

The Hamiltonian function is:

$$H^i = e^{-\rho t}[p^i x^i - w^i x^i - \tau_C g_C^i(x^i, K^i) - \tau_N g_N^i(x^i, K^i) - I^i] + \lambda I^i \tag{9}$$

Scenario 2: PIEA+PC

According to Equation (2), enterprise i profit is:

$$\Pi = \int_0^T \{e^{-\rho t}[p^i x^i - w^i x^i - r_C g_C^i(x^i, K^i) - r_N g_N^i(x^i, K^i) - \tau_C g_C^i(x^i, K^i) - \tau_N g_N^i(x^i, K^i) - I^i]\}dt \tag{10}$$

The Hamiltonian function is:

$$H^i = e^{-\rho t}[p^i x^i - w^i x^i - r_C g_C^i(x^i, K^i) - r_N g_N^i(x^i, K^i) - \tau_C g_C^i(x^i, K^i) - \tau_N g_N^i(x^i, K^i) - I^i] + \lambda I^i \tag{11}$$

Scenario 3: PIEA+TEC

The function is the same as in scenario 1, and the TEC policy is implemented as a penalty function.

Scenario 4: PIEA+PC+TEC

The function is similar to scenario 2, and the TEC policy is implemented as a penalty function.

4.4 Implementation algorithm

The preceding paragraph describes the process of establishing an initial emission allowance pricing model and to develop the theoretical general model into the model is applicable for two pollutants based on realistic needs. The maximum value principle is the first-order necessary condition in the optimal control theory to obtain the optimal value, which is used to solve a constrained pan-extremes problem. In the theoretical model, we determine the analytical solution based on the maximum principle.

According to formula A, the x^i value is determined by λ^i. The expression of λ^i is non-linear, therefore there is no analytical solution for x^i. This means that the maximum value principle becomes no longer applicable to solve the partial differential equations. Although there is no analytical solution, we attempt to use software tools and algorithms to achieve its numerical solution.

In this research, we employed the BFGS-PSO[†] two-layer nestification algorithm to obtain the optimal object numerical solution(Møller, 1993; Poli et al., 2007) and take MATLAB software as the computational tool. We determine which PIEA price combination by τ_C and τ_N can achieve the optimal social benefit. We employed a two-layer nestification algorithm to solve the two optimal problems.

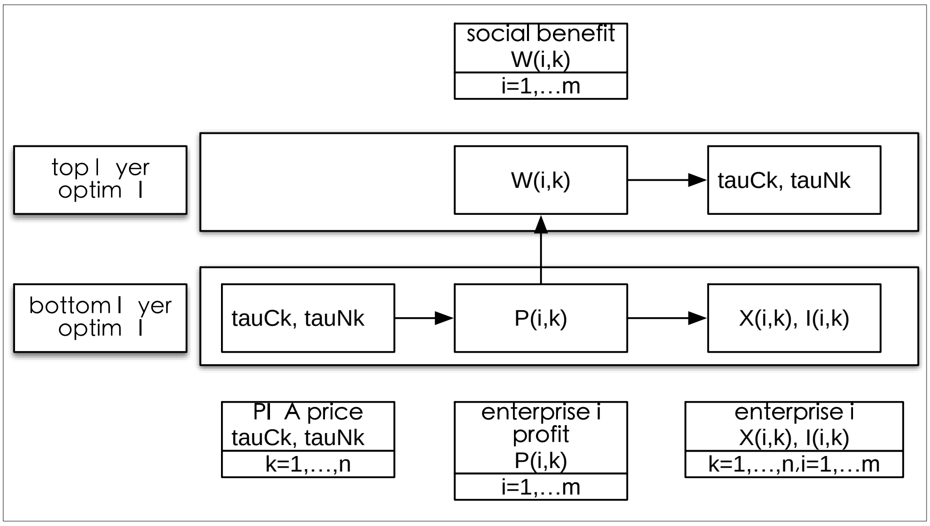

Fig 3 Two-layer nestification algorithm

As seen in Fig 3, the two-layer nestification algorithm is comprised of the optimal bottom layer and optimal top layer. We used the PIEA price τ_C and τ_N in the bottom layer to determine product quantity x^i and abatement investment I^i, which can achieve the enterprise optimal profit using the optimal pollutant discharging function. Next, we identified the top optimal PIEA price combination τ_C and τ_N, which can achieve the social benefit using the optimal bottom layer. The bottom layer uses the BFGS algorithm. The top layer uses the Particle Swarm Optimization algorithm.

5. Data Collection

[†] BFGS: Broyden, Fletcher, Goldfarb, Shanno; PSO: Particle Swarm Optimization.

5.1. Data source

The department implementing PIEA policy coincides with the administrative jurisdiction range. Thus, the PC and TEC policy implementing areas additionally correspond to the administrative jurisdiction range, dividing China to province and municipality level regions as sample sets. This study involves 31 regions in the mainland of China (provinces, municipalities, and autonomous regions). The data of the empirical simulation is based on the China Environmental Statistics Database in 2013. The data contain 3 categories, 39 industries, and 30,865 enterprises' information on energy and raw material consumption information, production, and pollutant emission information. The study also employs the total pollutant emissions for each region from the Ministry of Environmental Protection Total Emission Reduction Database set in 2013, pollution charge standard for each region (latest standard), emission standard for each industry (latest standard), and gross profit rate for each industry in 2013.

5.2. Data processing

The price model involves many other data, which cannot be obtained directly. Thus, the following parameters and coefficients are calculated based on existing samples:

(1) Calculate the pollution discharge coefficients by establishing a model describing the correlations among polluter emissions and product output and presents the value of abatement investment(Biglaiser et al., 1995), then change it to a regression model with regression samples from the China Environmental Statistics Database in 2013.

(2) The PIEA price model needs the treatment cost for each pollutant separately, but the facility running fee from the environmental statistics data is for all pollutants. We adopted the cost allocation approach to separate treatment costs for each pollutant(Wang, 2005).

(3) Calculate each enterprise's production cost, using the industrial average gross profit rate to calculate the enterprise product cost(Helfert, 2001).

(4) After sample screening and trial calculation, we choose the function form and variables to establish the regression equation according to past studies(Friedler and Pisanty, 2006; Gonzalez-Serrano et al., 2005; Tsagarakis et al., 2003). Then, we obtain the marginal pollution treatment cost through the marginal treatment cost function(Dasgupta et al., 1996).

(5) Calculate the marginal damage for the region.

(6) TEC constrains the pollution quantity to each region every year.

The data and coefficients involved are as follows: production cost, treatment cost, cost allocation, emission coefficients, region pollutant emission target, pollution charge standard, pollution control investment, pollution treatment cost function, marginal treatment cost, and region marginal damage, see in SI.

6. Results and Discussion

6.1. Optimal social benefits

The objective of the PIEA optimal model is to achieve maximum social benefit. Therefore, social benefit is the key point of focus in this study. The empirical simulation result shows the social benefit, as shown in Fig 4. The social benefit after charging the PIEA fee is approximately 50% of social benefit compared with baseline. The present model only considers pollutant emission damage to the environment and does not take into account the profit for pollutant emission reducing, such as ecological service function and effect on human health.

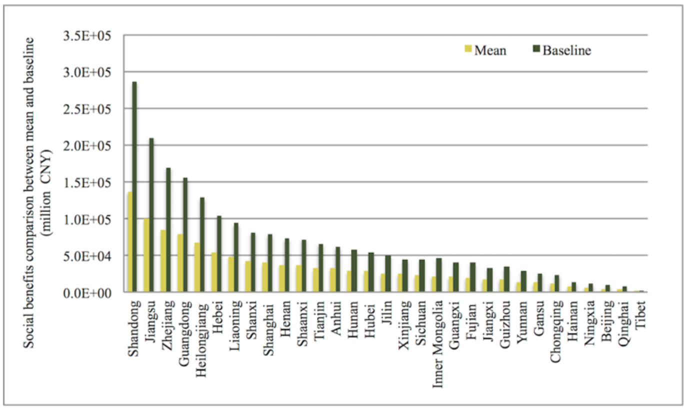

Fig 4 Social benefit comparison between mean and baseline

To clarify the difference in the social benefit in the four policy scenarios, we used the paired t-test to compare the results in Table 1. First, we tested S1–S2 and S3–S4 paired t-tests separately to determine whether the PIEA-only policy scenario and PIEA in combination with PC policy scenario can achieve equal social benefits. Table 1 shows the social benefit paired t-tests for the four scenarios. There is no significant difference observed for the social benefit in S1–S2 and S3–S4. Therefore, only the PIEA implemented and PIEA in combination with PC scenarios can achieve equal social benefit. Second, we performed

S1–S3 and S2–S4 paired t-tests to determine whether the TEC policy will affect the social benefit. When the TEC policy is implemented, there is a significant difference in social benefit with the scenario without the TEC policy. Looking back at the results in Fig 4, the social benefit in the scenario without the TEC policy is higher than the scenario with the TEC policy. This result indicates that the social benefit will decrease with the TEC policy.

Table 1 Social benefit paired t-test

Item	Variable	Obs	MeanDiff	t
Social benefit	S1–S2	31	3.258065	t = 0.3697
	S3–S4	31	20.09677	t = 0.1110
	S1–S3	31	130840.3	t = 2.0656**
	S2–S4	31	130857.2	t = 2.0663**

6.2. Best pollutant emission

Next, the best pollutant emission corresponding to the social benefit is shown. Fig 5 and Fig 6 display the simulated annual emissions of the two pollutants on average for the four scenarios compared to the baseline.

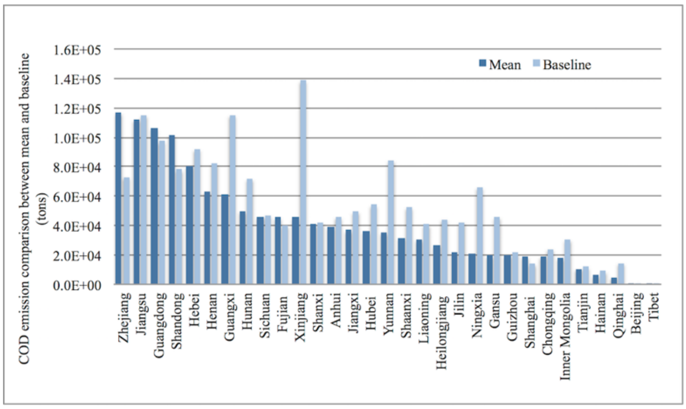

Fig 5 COD emission comparison between mean and baseline

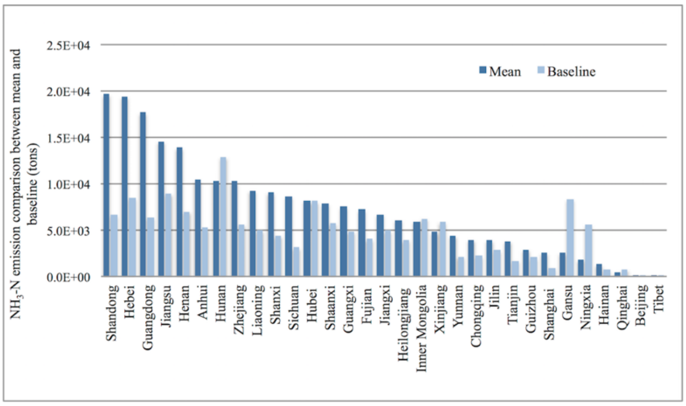

Fig 6 NH_3-N emission comparison between mean and baseline

From Fig 5, we know that most of the regions' emissions are decreased from the baseline, especially Yunnan, Gansu, Qinghai, Ningxia and Xinjiang, which are the top five regions in the emission depression percentage ranking. This result means that after being charged the payment for the initial emission allowance, the enterprises' discharge costs increased, so the pollution from the enterprises in most regions decreased. Unexpectedly, Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, and Guangdong, had emission quantities greater than the baseline. We inferred that for most of the enterprises in the regions whose emission are greater than the baseline, if their marginal profit caused by pollutant emissions per ton are higher than the PIEA expenditure, then the enterprises choose to increase pollutant emissions. Another interesting finding in Fig 6 is that excluding Inner Mongolia, Hubei, Hunan, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang, the NH_3-N emissions after paying the PIEA fee show an increasing trend for the remaining regions. This result is probably due to the major pollution of enterprises in each region and the treatment facilities for major pollution. Some enterprises mainly emit COD, whereas the NH_3-N generation quantity is lower than that of COD. Thus, the pollution treatment facility is primarily for COD and the NH_3-N reduction is a synergistic effect (we can infer that the treatment facility is mainly aimed at allocating pollution treatment efficiency).

In Table 2, we also list the S1–S2, S3–S4, S1–S3, and S2–S4 paired t-tests for the best COD and NH_3-N emissions to discuss the differences between several scenarios. S1–S2 and S3–S4 paired t-tests are for testing if the PC policy will affect best emission quantity. S1–S3 and S2–S4 paired t-tests are for testing if the TEC policy will affect the best emission quantity. S1–S2 and S3–S4 paired t-tests show that the best emission quantities have no differences whether PC is implemented or not. In other words, the best emission quantities are equal regardless of the PC policy implementation. This result means both PIEA policy strategy and PIEA plus PC policy strategy will achieve similar best emission quantities. S1-S3 and S2–S4 paired t-tests show that the TEC policy has a significant effect on the best emission quantity. The COD emission quantity with TEC is lower than that without the TEC policy. However, the effect of NH_3-N emissions is not significant whether TEC is implemented.

Table 2 Best pollutant emission paired t-test

Item	Variable	Obs	MeanDiff	t
Best COD emission	S1–S2	31	10.15589	t = 0.9137
	S3–S4	31	49.16717	t = 1.3466
	S1–S3	31	3423.794	t = 2.0729**
	S2–S4	31	3462.806	t = 2.0980**
Best NH_3-N emission	S1–S2	31	4361.168	t = 1.0016
	S3–S4	31	-7.652266	t = -1.6471
	S1–S3	31	4480.461	t = 1.0222
	S2–S4	31	111.641	t = 0.9029

6.3. Initial emission allowance price

The price is the key point of the PIEA policy. Fig 7 displays the price of the initial emission allowance in the four scenarios for each region. Comparing the price of the four scenarios, S1 is higher than S2 and S3 is higher than S4. The result is related to the scenario setting. S1 and S3 only included the PIEA policy, while S2 and S4 included the PC policy in addition to PIEA. Reviewing previous discussion shows that the charge for the best emission quantity is constituted by damage compensation and scarcity rent. If the charge is deducted by the existing PC price, then the remaining part is the PIEA price. Next, the portion of the S1 price that is higher than S2 is the pollution charge. S3 is higher than S4 for the same reason.

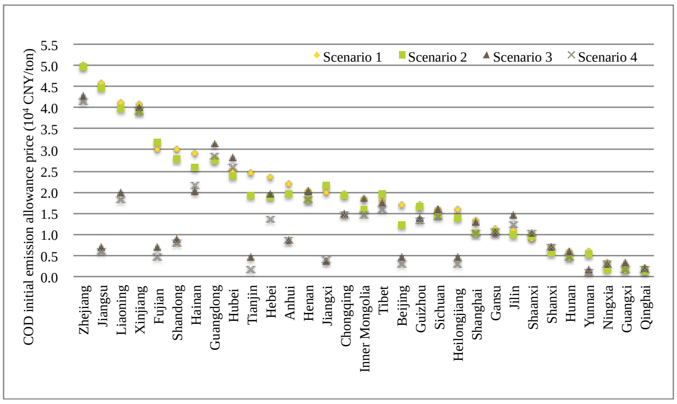

Fig 7 COD initial emission allowance price of each region in S1–S4

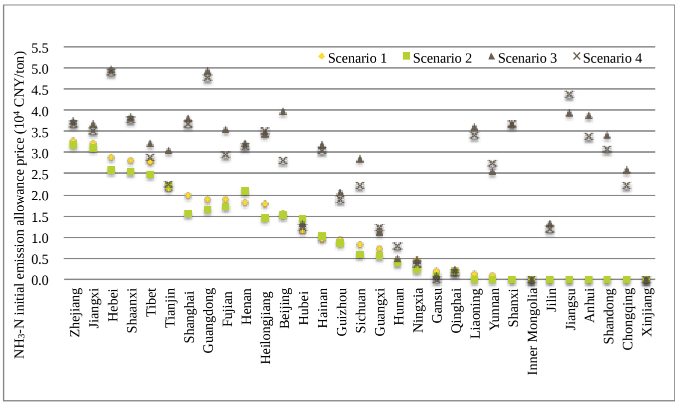

Fig 8 NH_3-N initial emission allowance price for each region in S1–S4

Interestingly, the initial allowance price of NH_3-N in some regions was found to be zero, as shown in Fig 8. In the modeling process, we set the price of the COD and NH_3-N initial allowance as two independent variables, to avoid duplicating charges to different pollutants discharged by the same enterprise under the existing synergistic control effect. When the enterprises adjust the output of product, the amount of pollutants will also be changed. Depending on the enterprise and the production process, some products discharge both COD and NH_3-N contaminants, but the production process of others discharges a single contaminant, such as only COD or NH_3-N. For products that discharge two contaminants simultaneously, if the enterprise adjusts the product output, the amount of both pollutants will change in a collinear trend. In this way, if adjust the emission of one pollutant, then the other associated pollutant emission will also be changed. For enterprises discharging two pollutants simultaneously, if charge is for one pollutant for emission control, the other associated pollutant emission will be under control also. Therefore, the model provides the simulation results: if most of the enterprises discharge COD and NH_3-N simultaneously in one region, then only charging for the COD emission allowance, or charging for NH_3-N according to the ratio of NH_3-N discharged by the only NH_3-N emission enterprises to total NH_3-N emission in the region, can achieve the region's optimal social benefit. This explains why the NH_3-N price in some regions is lower than the COD price, or even zero.

Next, the TEC policy effect on price is discussed. As shown in Fig 7 and Fig 8, the price trend of S3 and S4 considering the TEC policy are obviously different from S1 and S2. The COD price in S1 is higher than S3. Moreover, the COD price in S2 is higher than in S4. The NH_3-N price shows an opposite trend, that S1 is lower than S3, and the NH_3-N prices in some regions are zero. According to the principle of optimal social benefits, a model should charge treatment facilities producing major pollutants. When considering the TEC policy that is restricted by a target emission, the model calculation should determine the best emission quantities in close proximity to the emission target as principle. According to the best emission quantities in Fig 6, when pollutants emissions are beyond the restricted target, the beyond part will be “punished”. Thus, the NH_3-N price considering the TEC policy is higher than that without the TEC policy. When the region’s total NH_3-N emission is beyond the restricted target, the enterprises in the region must pay for NH_3-N at a high price. Remember that the treatment facilities have a synergistic effect on COD and NH_3-N, which means if the NH_3-N emission is controlled, then COD will be controlled. So, if the enterprises pay for the NH_3-N emission at a high price, then they could pay for COD at a low price.

6.4 Difference of price for pollutants compared to the pollution charge

If the difference of price for S1 and S2 is equal to the pollution charge fee, then we demonstrate the previous hypothesis: to achieve the best emission under the optimal social benefit, the cost paid by the enterprise should include the compensation for environmental damages and scarcity rents gained by the enterprises that are using the environmental capacity. However, in reality, only compensation for the environmental damage was charged, the scarcity rents were missed. The model setting in this research calculates the scarcity rents deducting the pollution charge, the PIEA policy compensates for the missing scarcity rents.

To demonstrate that the differences between S1 and S2, S3 and S4 are caused by the pollution charge, we did paired t-tests for the difference of S1 minus S2 to the pollution charge, and S3 minus S4 to the pollution charge, as shown in Table 3. According to the paired t-test results, S1 minus S2 and S3 minus S4 exhibit no significant difference with the pollution charge. This condition suggests that the PIEA price for scenarios regardless of the PC policy always achieves the optimal social benefits. The empirical results support the PIEA theory that the price difference of S1–S2 and S3–S4 should be the PC price.

Table 3 Difference in two scenarios' emissions PIEA prices compared to the pollution charge price paired t-test

Item	Variable	Obs	MeanDiff	t
Difference of two scenarios' COD PUER price with EC price	S1–S2 with EC price	31	-0.0593548	t = -1.9816
	S3–S4 with EC price	31	-0.0487097	t = -1.2884
Difference of two scenarios' NH_3-N PUER price with EC price	S1–S2 with EC price	31	-0.1774194	t = -2.9543
	S3–S4 with EC price	31	-0.06	t = -1.5030

From the result, we know that whether PIEA is implemented or PIEA in combination with PC, the two types of scenarios can achieve equal social benefits. We can infer that no matter what kind of policy, they achieve equivalent optimal social benefits. Therefore, in the PIEA and PC mixed policy, the combination policy can achieve the optimal social benefit in the current condition. Therefore, in this policy design, PIEA is complimenting a missing part of the optimal pollution charge rather than duplicating it with PC.

In the model assumption, the investment will be placed in existing facilities if the enterprise decides to invest more to improve the treatment efficiency, which means improving the existing facilities, rather than adding new facilities. A disparity exists between the assumption and reality. Adding new facilities or processes is not easy. Many factors need to be considered when adding new facilities, such as the enterprise pollution generation quantity. The treatment process is constrained by the concentration if a new process is implemented in an existing structure or new structure. All of the problems should be discussed according to a concrete case, rather than a general summary. Thus, in the model assumption, the effects caused by investment improved the existing treatment facility efficiency. By employing this process, an enterprise for which the primary pollutant is COD (NH_3-N is synergistic pollutant) chooses to improve the production output. Next, NH_3-N generation will increase. However, the facilities aimed at NH_3-N have not been improved. This factor will result in an NH_3-N emission increase. Thus, the result is a warning because of insufficient treatment capabilities. NH_3-N emissions will increase after PIEA is implemented if new treatment facilities are not added.

7 Conclusions and Policy Implications

7.1. Conclusions

We establish an optimal control-based model with COD and NH_3-N, two independent pollutants variables, to calculate the initial emission allowance price in PIEA policy and simulate the results after the policy is applied. At the same time, we illustrate the impact of pre-existing policies on the performance of the PIEA policy. Using data containing 3 categories, 39 industries, and 30,865 enterprises samples, we obtain the optimal social benefit, the best pollutant emissions, and the initial emission allowance price.

First, because PIEA policy increases the enterprises' discharging cost, most regions' COD emissions are less than the baseline. However, there are exceptions, Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, and Guangdong, in which emission quantities are greater than the baseline. We inferred that in the case when the marginal profit caused by pollutant emissions per ton are higher than the PIEA expenditure, the enterprises choose to increase pollutant emissions. For the other case of water pollutants, the NH_3-N emission shows an opposite trend. The simulation result is that excluding Inner Mongolia, Hubei, Hunan, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang, the NH_3-N emissions in the rest of regions are increased. We inferred the reason is that the pollution treatment facility is mainly for COD and the NH_3-N reduction is a synergistic effect.

Second, whether only the PIEA policy or PIEA combined with the PC policy, both types of policy can achieve equal optimal social benefits and best pollutant emissions. However, the initial emission allowance price in S1 that only implements the PIEA policy is higher than the price in S2, where PIEA is combined with the PC policy. By paired t-test, we inferred that there is no significant difference between the price difference between S1 and S2 and the pollution charge price. At the same time, the price of the NH_3-N initial allowance in some regions was zero. We set the COD and NH_3-N initial allowance prices as two independent variables to avoid the duplicated charges to different pollutants discharged by the same enterprise under the existing synergistic control effect.

Third, the COD emission quantity with TEC is lower than that without the TEC policy, Therefore, the TEC policy will be effective for pollutant emission control. At the same time, the TEC policy will also affect price. The TEC policy means that regions have their own target emissions, and when the emission is beyond the restricted target, the beyond part will be “punished”. Then, the pollutant beyond the restricted target will be charged a payment for IEA at a higher price than without the TEC policy.

7.2 Policy implications

In this study, the pricing method for initial allowance in the PIEA policy considers the existing pollution charge policy. When the PIEA policy has not been implemented, only a pollution charge is not sufficient to achieve the best pollutant emissions. In the pricing method designed, the initial allowance fee and the pollution charges are combined to achieve the best pollutant emissions. This study proves that under the pricing method designed, the PIEA policy is not a duplicate policy of the pollution charge, but rather a supplement to the existing pollution charge for achieving the best emission discharge.

According the result that the social benefit after being charged the PIEA fee with TEC is lower than without it, we can infer that the social benefit will lose economic efficiency with the TEC policy. Although economic efficiency is lost under the TEC policy, it necessary for the areas whose pollutant emission increase after being charged the PIEA fee because the increment of pollutants will be higher than without the TEC policy.

In reality, certain enterprises’ pollution treatment facilities are primarily for COD, and the NH_3-N reduction is a synergistic effect. The simulation results indicate that under the assumption that enterprises invest in the existing facilities instead of adding new facilities, the NH_3-N emission will increase because of insufficient treatment capability. Thus, the NH_3-N emission will increase after PIEA is implemented if new treatment facilities are not added. The government should increase treatment facilities for NH_3-N.

The effect of economic policy is inclined to screen higher marginal benefit income enterprises which use emission allowances rather than reducing pollutant emissions. Some regions’ pollutant emissions will increase even if charged PIEA fees, meanwhile other regions’ pollutant emissions will decrease after being charged. Therefore, the policy maker should take into consideration the appropriate time for launching a new policy in the whole nation because a new policy may induce an economic recession.

7.3. Research limitation

There are some inadequacies in this research. In the social benefit model, only the recovery cost method is used to calculate the damage caused by the pollutants discharged into the environment, and the damage to the ecological environment and human health is not considered. The heterogeneous pollutants effects on human health and ecological service is related to the place where the point source is located. The point source location belonging to which environmental function zone should be determined following the discharge standards and considering the effects of the pollution source on the humans living in the area and the surrounding ecological environment. Not enough information on the human living nearby and the ecological environment surrounding the pollution source were available to support calculations in this research. Therefore, we use the cost for removing pollutants discharged to the environment the pollutant damage effect instead of the costs to the ecological environment and to human health. Similarly, the income caused by the environmental quality improvement is not included.

In the model assumptions, there are some simplified situations, such as when the firm determines its product output, they do not consider the market equilibrium of the product supply and demand, and keep the price stable. In the simulation of enterprises decision-making behavior, some details cannot be shown. There are three ways to reduce pollutant emissions for enterprises: promoting the production process technology, updating the end of pipe technology, and improving the efficiency of the existing facilities; but in the model, the emission reduction method is only the improvement of efficiency of the existing facilities, technological progress has not yet been considered.

Due to lacking fixed investment data for pollutant treatment facilities, all the parameters involved in the pollution reduction cost in this study are based on the operating costs of the enterprises' pollution abatement facilities. The state variables in the model are the only present emissions reduction facility operating costs in this part.

The empirical simulation result has finite precision because of model simplification and lack of data. The model has been simplified for curving the complicated realistic situation under certain hypotheses. Thus, in the future, we will take the pollutant emission effect on human health and the ecological service function into consideration as components of the social benefit.

Supporting Information

Additional information includes details on data, modeling process, parameters and implementation algorithms. This material is available free of charge via the Internet at XXXX.

Acknowledgments

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Figure 1

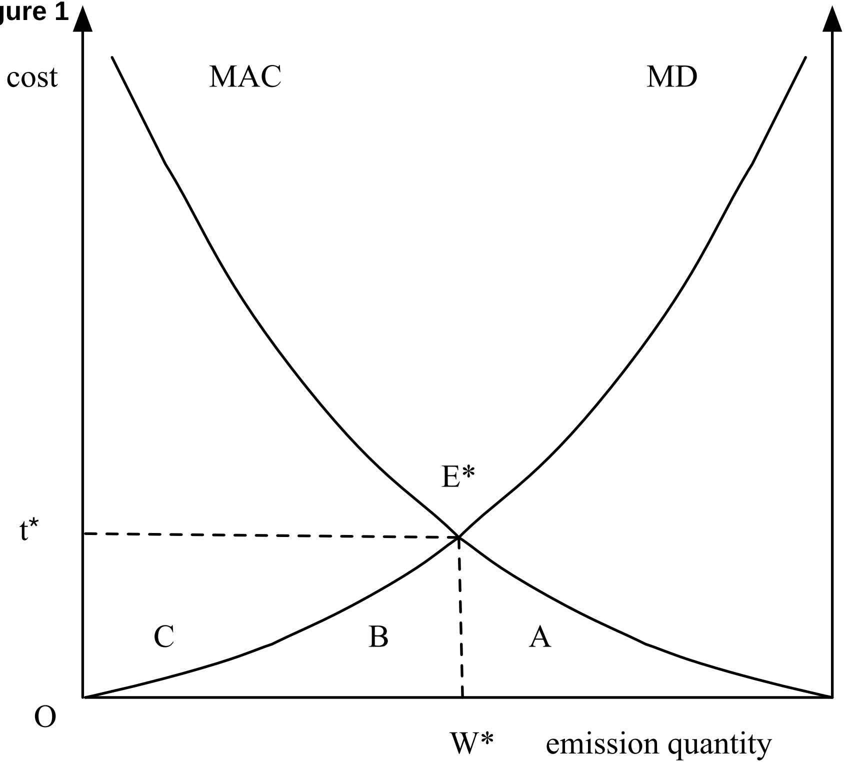
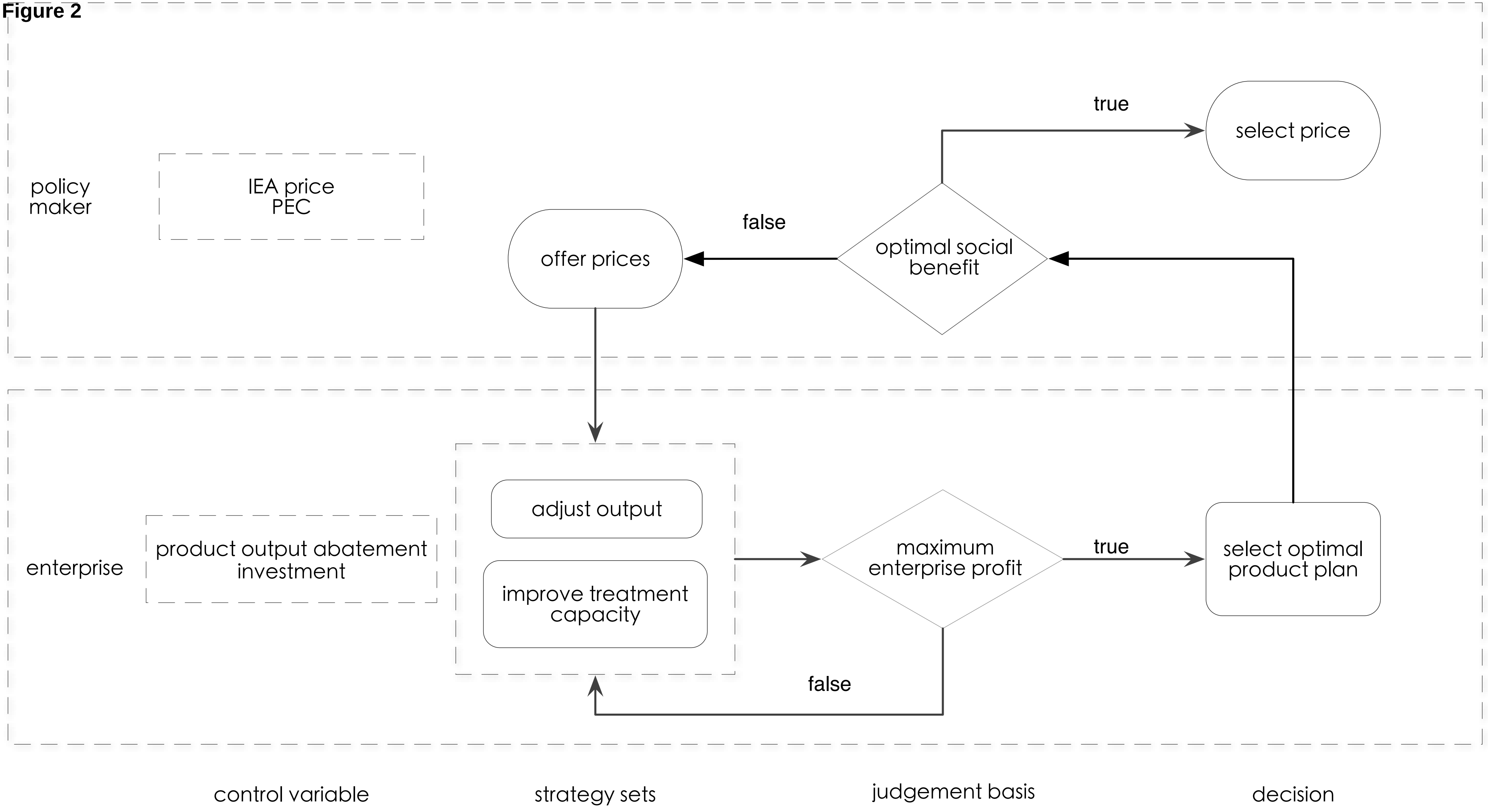


Figure 2



true
select price
policy
maker
IEA price
PEC
false
offer prices
optimal social
benefit
adjust output
enterprise
product output abatement
investment
improve treatment
capacity
maximum
enterprise profit
true
select optimal
product plan
false
control variable
strategy sets
judgement basis
decision

Figure 3

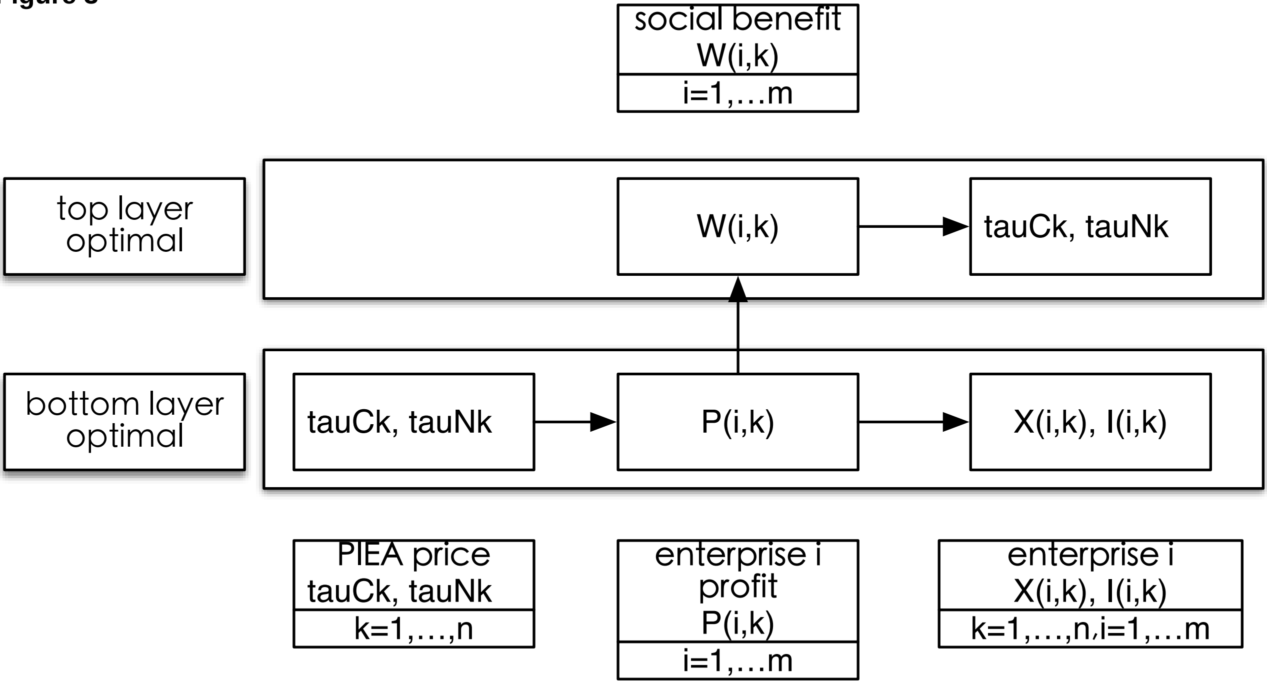
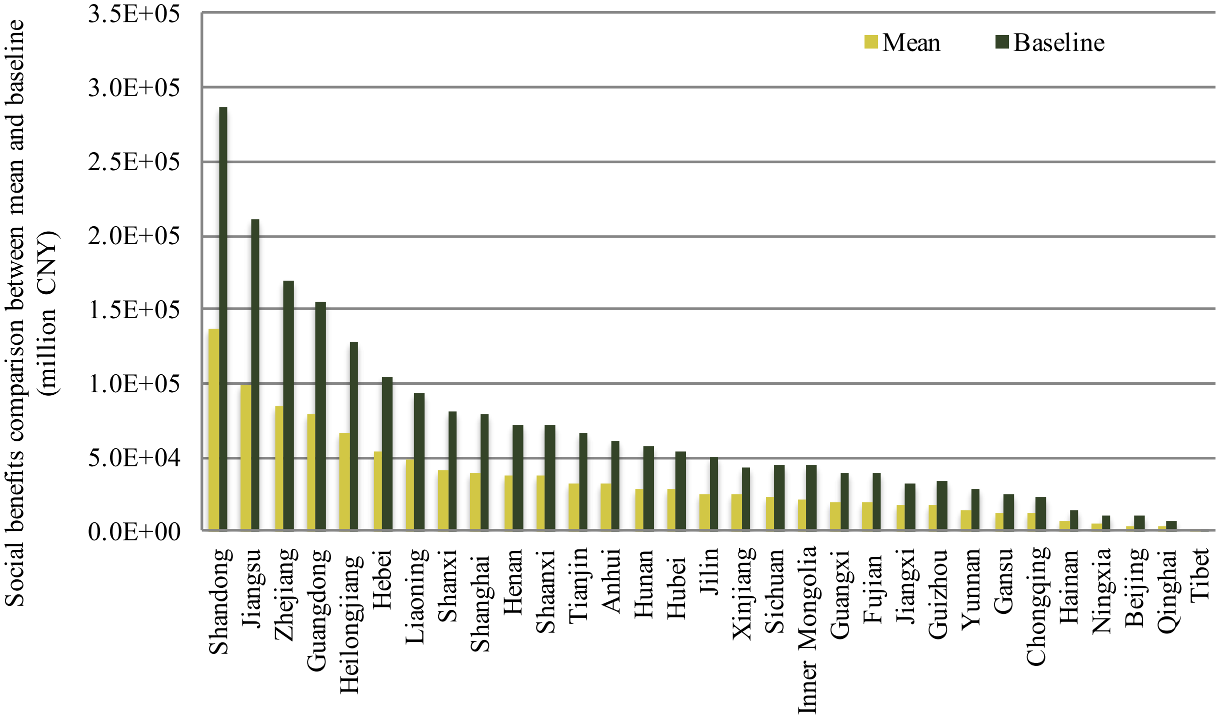
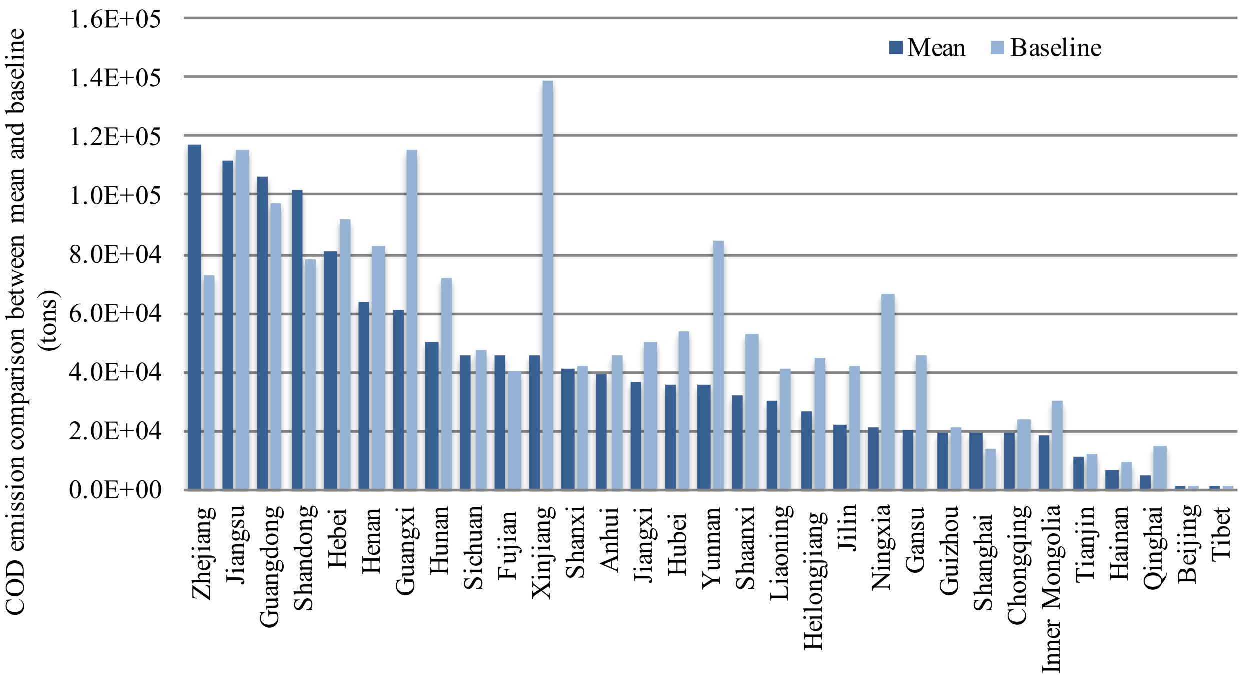

social benefit
W(i,k)
i=1,…m
top layer optimal
W(i,k)
tauCk, tauNk
bottom layer optimal
tauCk, tauNk
P(i,k)
X(i,k), I(i,k)
PIEA price
tauCk, tauNk
k=1,…,n
enterprise i profit
P(i,k)
i=1,…m
enterprise i
X(i,k), I(i,k)
k=1,…,n,i=1,…m

Figure 4



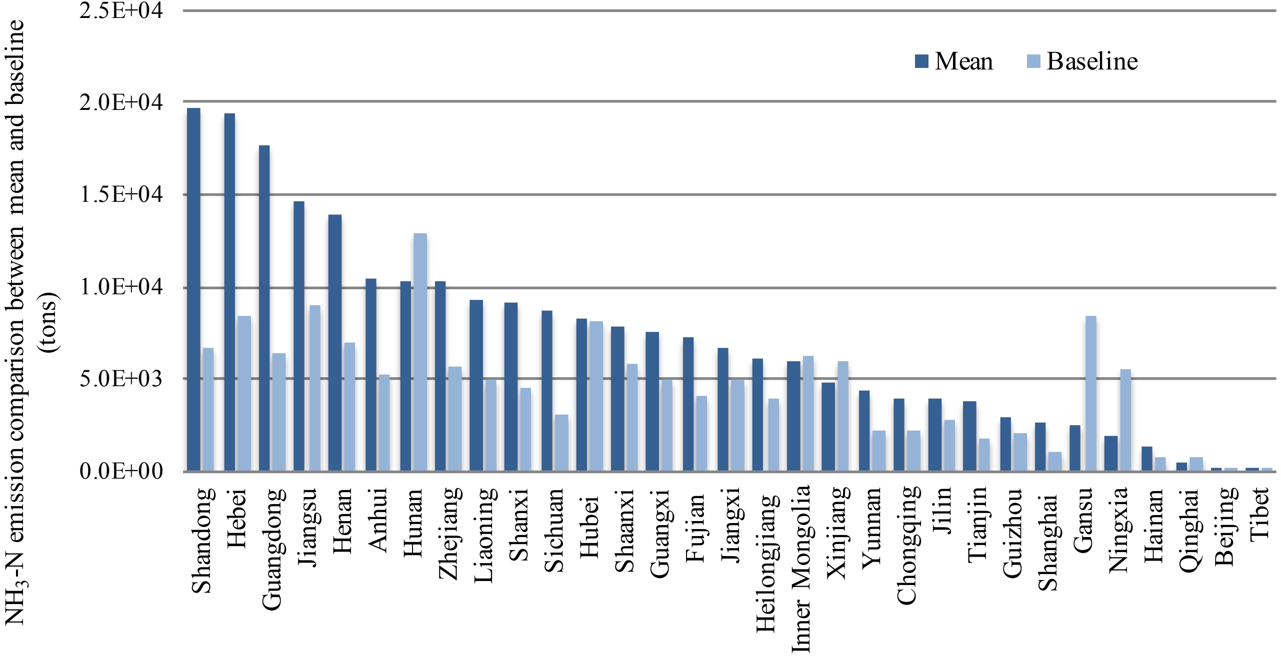
Social benefits comparison between mean and baseline (million CNY)
3.5E+05
3.0E+05
2.5E+05
2.0E+05
1.5E+05
1.0E+05
5.0E+04
0.0E+00
Mean
Baseline
Shandong
Jiangsu
Zhejiang
Guangdong
Heilongjiang
Hebei
Liaoning
Shanxi
Shanghai
Henan
Shaanxi
Tianjin
Anhui
Hunan
Hubei
Jilin
Xinjiang
Sichuan
Inner Mongolia
Guangxi
Fujian
Jiangxi
Guizhou
Yunnan
Gansu
Chongqing
Hainan
Ningxia
Beijing
Qinghai
Tibet

Figure 5



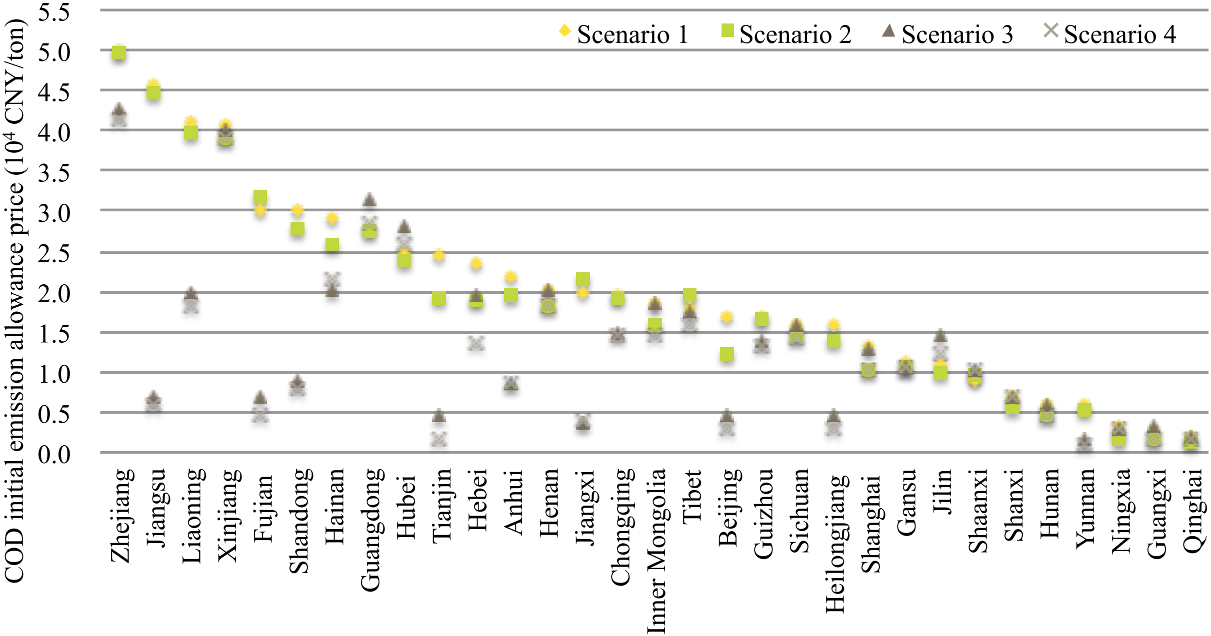
COD emission comparison between mean and baseline (tons)
Mean
Baseline
1.6E+05
1.4E+05
1.2E+05
1.0E+05
8.0E+04
6.0E+04
4.0E+04
2.0E+04
0.0E+00
Zhejiang
Jiangsu
Guangdong
Shandong
Hebei
Henan
Guangxi
Hunan
Sichuan
Fujian
Xinjiang
Shanxi
Anhui
Jiangxi
Hubei
Yunnan
Shaanxi
Liaoning
Heilongjiang
Jilin
Ningxia
Gansu
Guizhou
Shanghai
Chongqing
Inner Mongolia
Tianjin
Hainan
Qinghai
Beijing
Tibet

Figure 6



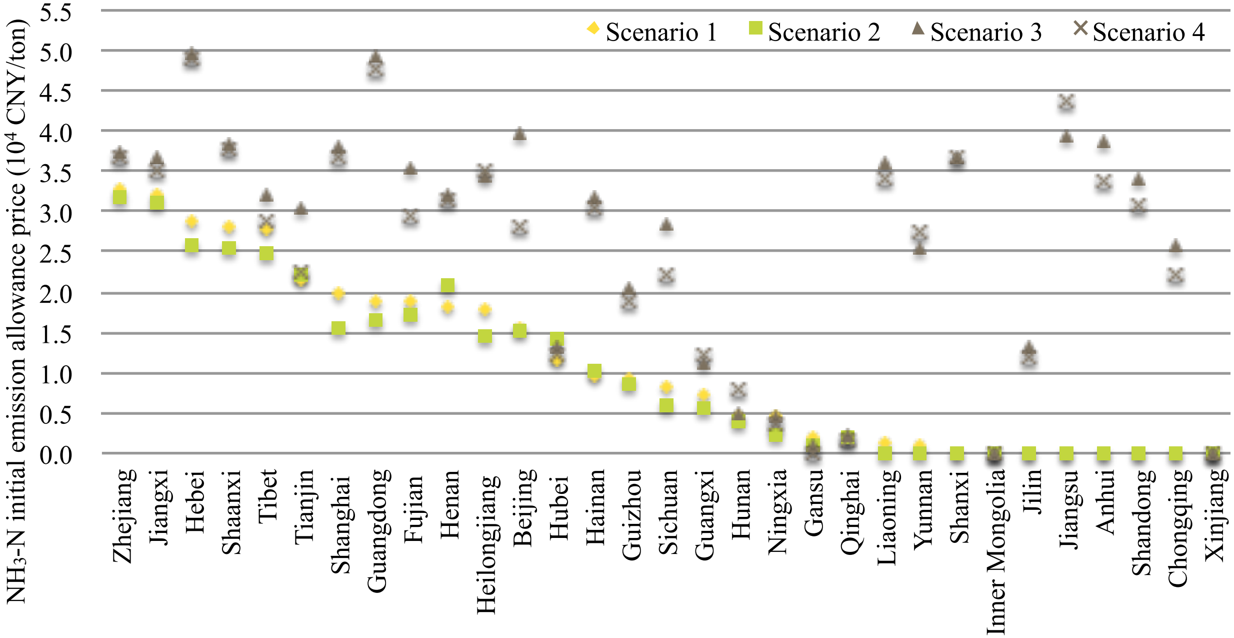
2.5E+04
2.0E+04
1.5E+04
1.0E+04
5.0E+03
0.0E+00
Mean
Baseline
NH_3-N emission comparison between mean and baseline (tons)
Shandong
Hebei
Guangdong
Jiangsu
Henan
Anhui
Hunan
Zhejiang
Liaoning
Shanxi
Sichuan
Hubei
Shaanxi
Guangxi
Fujian
Jiangxi
Heilongjiang
Inner Mongolia
Xinjiang
Yunnan
Chongqing
Jilin
Tianjin
Guizhou
Shanghai
Gansu
Ningxia
Hainan
Qinghai
Beijing
Tibet

Figure 7



COD initial emission allowance price (10⁴ CNY/ton)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Zhejiang
Jiangsu
Liaoning
Xinjiang
Fujian
Shandong
Hainan
Guangdong
Hubei
Tianjin
Hebei
Anhui
Henan
Jiangxi
Chongqing
Inner Mongolia
Tibet
Beijing
Guizhou
Sichuan
Heilongjiang
Shanghai
Gansu
Jilin
Shaanxi
Shanxi
Hunan
Yunnan
Ningxia
Guangxi
Qinghai

Figure 8


Scenario 1
Scenario 2
Scenario 3
Scenario 4
NH3-N initial emission allowance price (10[4] CNY/ton)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Zhejiang
Jiangxi
Hebei
Shaanxi
Tibet
Tianjin
Shanghai
Guangdong
Fujian
Henan
Heilongjiang
Beijing
Hubei
Hainan
Guizhou
Sichuan
Guangxi
Hunan
Ningxia
Gansu
Qinghai
Liaoning
Yunnan
Shanxi
Inner Mongolia
Jilin
Jiangsu
Anhui
Shandong
Chongqing
Xinjiang