The optimal principal-agent model for the CO_2 allowance allocation under asymmetric information

Huibin Du[1,2,*] Bingli Li[1] Jian Zuo[3] Rita Yi Man Li[4]

[1] College of Management & Economics, Tianjin University, Tianjin 300072, China

[2] Center for Energy & Environmental Policy Research, Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100190, China

[3] School of Natural & Built Environments, University of South Australia, Adelaide 5000, SA, Australia

[4] Department of Economics and Finance, Hong Kong Shue Yan University, Hong Kong, China

Abstract

In this paper, the carbon allowance allocation is studied from the perspectives of government and the whole society under the lens of contract theory. It investigates the principle problem under asymmetric information, in which the government (as a principal) is not able to observe the emission rate of the firm (as an agent). A principal-agent model of different scenarios is developed with an aim to maximize the government's expected social welfare. The results show that the allocated allowances and CO_2 emissions are low when asymmetric information is considered. This indicates that offering different contracts to different reported emission rate is beneficial to the environment whereas most allowances will be wasted when private information is omitted. In addition, the proposed principal-agent model provides a useful illustration of how the allowance is allocated to the firm and how to define the contract combining allowance allocation rate with emission reduction in a bid to reduce the environmental damage. Moreover, the sensitivity analysis shows that higher carbon price leads to lower allowance allocation rate and emission reductions under complete information than incomplete information. The variation of allocation rate and the coefficient of emission abatement cost indicate a similar trend

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[*] Corresponding author. E-mail: duhuibin@tju.edu.cn

between allowance allocation rate and emission reductions. It is relevant to decision makers with the goal of social welfare maximization and environmental damage minimization. This study not only suggests an optimal allowance allocation method for policy makers when the private information is taken into consideration, but may also provide a reference for allowance allocation and emission reduction when the relevant markets change.

1 Introduction

It is well recognized that climate change has led to extreme weather and consequently, one of the greatest threats to human survival and political stability[IPCC, 2007]. Furthermore, the climate change due to an the increase in CO_2 concentration is largely irreversible for 10 centuries, even after CO_2 emissions cease [1]. Various mechanisms have been designed in order to mitigate impacts of global warming and reduce CO_2 emissions into the atmosphere. Specifically, on 16th February, 2005, the Kyoto Protocol was officially approved. Three flexible mechanisms were introduced in the Protocol, i.e. emissions trading (ET), joint implementation mechanism (JI) and clean development mechanism (CDM) [2]. The emission trading is a cost-effective instrument to control green-house gas (GHG) emissions as well as providing incentives for participants in the market [3]. It has been recognized as a useful policy which takes both environmental and economic issues into consideration [4].

The concept of emission trading was first proposed by Pigou in 1920 [5], which was further developed by Coase [6]. In a typical carbon trading market, a fixed number of permits or allowances are issued by the government, which gives the right to emit a certain amount of pollutants. Permits or allowances are valuable due to the relative high demand therefore an initial allocation of carbon is one of the most important factors to be considered during the carbon trading system development.

Indeed, the initial allocation of permits or allowances not only affects the fairness and equity between firms, but also determines the cost-effectiveness of the emission trading policy [7]. According to Hahn (1984) [8] the initial distribution of tradable allowances is one of the most influential factors determining the efficiency of the final resource allocation particularly when the market is not mature. As a result, the past decades have witnessed an increasingly level of attention on the carbon emission allowance allocation.

The existing studies on the allocation of carbon emission allowance mainly focus on three aspects: the comparison of different allocation methods, the fairness of allowance allocation mechanisms and the market efficiency of allowance allocation. Concerning the allocation methods, the allowance can be either allocated for free by the government, sold by auction, or a combination of these two methods [9]. Free allowance allocation is mainly based on historical emissions (emission-based method) and output (output-based method). In contrast, auction approach allows allocating allowances to firms which need them most [10]. The researches relating to allowance allocation mainly shed lights on the assessment or comparison of the effectiveness of different allocation approaches and their associated economic efficiency. Bohringer and Lange [11] considered both emission-based and output-based allocation methods in a dynamic context. Their study found that the emission-based allocation is better than the output-based allocation in closed trading systems with a cap on emissions based on a multi-period partial equilibrium model. Burtraw et al. [12] investigated the cost-effectiveness and distributional effects of auction approach, and emission-based and output-based allocations for distributing allowances in the electricity sector. They found that manufacturers prefer emission-based approach whereas the output-based method leads to a low electricity price at the cost of the natural gas price. However, Cramton and Kerr [13] argued that an auction of carbon emission allowances is more effective than the free allocation approach as it provides more flexibility in distribution of cost and greater incentives for innovation.

Subsequently, fairness is the key issue associated with allowance allocation. A number of principles have been proposed to encourage the participation of firms. The allowance allocation is characterized with a single standard among all the participants. Thus, a fair and reasonable allocation should consider a variety of principles such as various forms of allocation and contextual factors. Bohm and Larsen (1994) [14] suggested that the allowance allocation scheme based on the equalization emission charge per capita is beneficial for short-term fairness while the allowance allocation based on population size is more appropriate for the long-term fairness. Baer and Athanasiou (2008) [15] developed the 'Responsibility and Capacity Indicator' (RCI) index according to the weighting of historical emission and the national income so that allowances can be allocated among various countries. According to Kverndokk (1995) [16] the allowance allocation based on population size is more equity and feasible. Vaillancourt et al. (2004) [17] considered five allowance allocation modes based on: GDP, population, land area, emissions and output respectively according to the economic development level (developed or developing countries) or the type of business (clean or polluted firms). Xie et al. (2011) [18] proposed an alternative methodology for the emission allowance allocation with an aim to reach "a global consensus for emission allowance allocation in deregulated power systems".

Futhermore, the initial allowance allocation affects not only fairness but also the market efficiency. Theoretically, carbon emission trading achieves the goal of emission reduction with a minimum cost in a perfectly competitive market without transaction cost. However, when transaction cost and market power exist, the initial allowance allocation will affect the market efficiency as well [7]. As a market-oriented environmental regulation, tradable emission allowance is heavily influenced by market power such as price change and production inefficiency (Eshel (2005) [19] ,Tanaka et al. (2012)[20]).

The rapid development of the economy in China has created a massive demand for energy while the environmental deterioration has attracted a growing public concern. The 12th Five-year plan stipulated that the goal was to reduce the total amount of major pollutants emissions will be reduced by 8% to 10% comparing to 2010 level. As a result, China has proposed a carbon emission trading mechanism in which seven pilot cities were chosen, i.e. Beijing, Tianjin, Shanghai, Guangdong, Shenzhen, Hubei, Chongqing to explore the future "uniformly carbon emission trading market". Nevertheless the initial allocation of allowance remains an issue. Hence, it calls for a timely study on effective allocation method based on national conditions.

However, the vast majority of existing studies on the allowance allocation are from the firm's perspective without taking the government and social welfare into consideration. Furthermore, it is apparent that there is asymmetric information between the firm and government. Therefore, a principal-agent model is developed in this study in order to explore the allowance allocation. In this paper, the government as a principal will offer the agent a menu of contract of emission reductions as well as an allowance allocation rate to maximize social welfare so that the environmental damage can be reduced. The firm as an agent, with the private information about its emission rate, will decide which kind of contract should be sighed, and consequently decide the level of production output to maximize its profits according to the selected contract. In addition, the contract theory is applied to solve the model. The contract theory has been widely applied in various related fields such as finance (Mugge (2011) [21]), supply chain (Chen (2005)[22]), taxation (Lan et al. (2011) [23] and Cui et al. (2007) [24]), government regulation (Viaggi et al. (2009)[25]) and so on.

The rest of the paper is organized as follows. In Section 2, the problem on allowance allocation is described and the principal-agent hybrid policy model is developed under different conditions. In section 3, formulation of the model is presented; the optimal allocation rate and emission reduction are obtained by means of applying the contract theory. In section 4, an empirical example is provided to analyze the proposed model and the results obtained in the previous sections. Concluding remarks are provided in Section 5.

2 The model

The carbon emission allowance is the effective amount of CO_2 emissions that the firms can emit within a certain period of time, as approved by the government [4]. The main principles of allowance allocation are: fairness, cost-effectiveness and environmental benefits. The major challenge is how the government allocates the allowances under output-based allocation method where the quantity of allowance a firm receives is based on output under two scenarios, i.e. incomplete information (government cannot observe the firm's private information) and complete information (government can fully access the firm's private information).

2.1 Problem description and assumptions

In this model, a principal-agent problem is considered that covers three types of participants, i.e. governments, firms and consumers. The emission rate of each firm is its private information which is not available to the government. The distribution of the firm's emission rate ex ante is the only information made available to the government rather than the specific emission rate variable information [26]. Therefore, it is imperative for the government to design an appropriate allowance allocation policy which is most beneficial to the social welfare. The revelation principle proposed by Lan et al. [26] is adopted in this study, i.e. only the direct allowance allocation under which each firm will reveal its emission rate x will be considered. Therefore, the allowance allocation rate ϕ can be described as a function of the emission rate x.

Furthermore, a game between the government and the firm is considered in order to balance the interests between these two participants of the proposed model. The government as a principal will offer a menu of hybrid contracts of a certain allowance allocation rate $\phi(x)$, and for the recognition of emission reduction efforts $e(x)$ from a firm with an aim to control CO_2 emissions.The firm as an agent, holding the private information about its emission rate, will decide which kind of contract should be sighed, and consequently determine the level of production output q in order to maximize its profits.

To be more specific, the following assumptions are made throughout the paper.

I: The corresponding markets are perfectly competitive including the product market and the allowance trading market. Therefore, the participants(i.e. the government, firms and consumers) are price takers in the markets. The product is sold at the price p and allowance price τ is decided by the carbon trading market. The products are homogeneous.

II: Since the firm's carbon emission rate is uncertain to the government due to incomplete information, it is reasonable to use a random variable ξ to denote the government's assessment of firm's emission rate. Without the loss of generality, it is assumed that ξ is a continuous random variable with a support $\Omega = [a \quad b]$, where a and b are acquired from the historical information of firm's emission rate and denote the firm's lowest and highest reported emission rates respectively. The probability density function and the probability distribution function of ξ are $f(x)$ and $F(x)$ respectively. Both of them denote the structure of the government's assessment of each firm.

III: The firm's production cost function is denoted by $C_1(q) = \frac{1}{2}c_1q^2$, where q is the quantity of the goods produced by the firm and c_1 is the coefficient of production cost. The emission abatement cost function $C_2(e) = c_2e$ is defined as the level of the firm's efforts to reduce the CO_2 emissions. It varies according to the contract which the firm selected, where e represents the emission reductions the firm should achieve and c_2 is the coefficient of emission abatement cost.

IV: Of the participants in market, consumers are passive and the other two (the government and the firm) act strategically. By consuming the production of the amount q, the consumer surplus can be expressed as follows:

$$S(q) = (mq - nq^2) - pq,$$

where m and n are coefficients [27].

V: The consumption of products leads to accumulated CO_2 emissions in the atmosphere and the stock externality of CO_2 emissions lead to environmental damage. The amount of CO_2 emissions is denoted by $E(q, e, x) = xq - \gamma e$ and the environment damage by $D(q, e, x) = hE(q, e, x)$, where γ is the adjustment coefficient and h is the CO_2 environmental value measured by means of the marginal social welfare loss of CO_2 emissions [28].

VI: The firm's profit

$$\begin{aligned}\pi_{q(\cdot)} &= pq(x) - C_1(q) - C_2(e(x)) - \tau[E(q, e, x) - \phi(x)q] \\ &= pq - \frac{1}{2}c_1q^2 - c_2e - \tau[xq - \gamma e - \phi(x)q].\end{aligned}$$

where $\phi(x)$ is the allowance allocation rate according to the output-based method.

2.2 Modeling process

In this section, the game between firm and government is studied with a focus on the decision problem by one after another. The government decides the allowance allocation rate $\phi(x)$ and the firm's emission reduction $e(x)$ with an aim to maximize social welfare and provides different contract portfolios $(\phi(x), e(x))$ to the firm. Then, the firm chooses an appropriate form of contract according to its actual emission rate and business situation. Specifically, the firm decides its production output based on the allowance allocation rate and emission reduction in order to maximize its profits.

Firstly, the firm's profit maximization is considered. The optimal output q is decided according to the selected allowance allocation rate ϕ and emission reduction e, thus the first-order condition is taken into consideration as follows:

$$\frac{\partial \pi}{\partial q} = p - \tau x + \tau\phi(x) - c_1q = 0.$$

Then,

$$q = \frac{p - \tau x + \tau\phi(x)}{c_1}.$$

Take q into π, we can obtained the equation:

$$\pi = \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2 + (\tau\gamma - c_2)e(x).$$

Then we turn to the government whose objective is to design the contract on allowance allocation rate and emission reduction as well as to maximize the social welfare. In this paper, two scenarios are considered, i.e. complete information that the government can fully observe the firm's emission rate, and incomplete information that the private information emission rate are only available to the firm.

2.2.1 Under complete information

A simplified theoretical model is developed under complete information that the government can fully observe the firm's emission rate x. In this scenario, the government maximizes its welfare and the firm reaches an optimal profit at the same time.

The government aims to maximize a weighted sum of consumer surplus, the expected welfare of the firms and the reduction of environmental damage. Therefore, the government's objective is to maximize:

$$\begin{aligned} \max_{e(\cdot),\phi(\cdot)} W = S(q) + \pi(e(x), \phi(x), x) - D(e(x), x) = \frac{m - p - hx}{c_1}[p - \tau x + \tau\phi(x)] \\ +(\frac{1}{2c_1} - \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 + (\tau\gamma - c_2 + h\gamma)e(x) \end{aligned} \tag{1}$$

Under complete information, the government aims to maximize its welfare based on the allowance allocation rate and emission reduction. Meanwhile, it also guarantees the firm's participation in carbon trading market. As a result, the optimal model can be formulated as follows:

$$\begin{cases} \max\limits_{q(x),\phi(x)} W = \frac{m - p - hx}{c_1}[p - \tau x + \tau\phi(x)] + (\frac{1}{2c_1} - \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 + (\tau\gamma - c_2 + h\gamma)e(x) \\ \text{subject to:} \\ \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2 + (\tau\gamma - c_2)e(x) \geq 0 \\ \phi(x) \geq 0 \end{cases} \tag{2}$$

2.2.2 Under incomplete information

The incentive compatible and participation constraints are described under the situation that the government cannot fully observe the firm's emission rate.

Similarly, the government aims to maximize a weighted sum of consumer surplus, the expected welfare of the firms and the reduction of environmental damage. Therefore, the government's objective under incomplete information is

$$\max_{e(\cdot),\phi(\cdot)} W = \int_a^b [S(q) + \pi(e(x),\phi(x),x) - D]f(x)dx$$
$$= \int_a^b \left(\frac{m-p-hx}{c_1}[p-\tau x+\tau\phi(x)] + (\frac{1}{2c_1} - \frac{n}{c_1^2})[p-\tau x+\tau\phi(x)]^2 + (\tau\gamma - c_2 + h\gamma)e(x) \right) f(x)dx \tag{3}$$

However, if private information is taken into consideration, the firm may not report its emission rate accurately to pursuit of maximum profits. As a result, the government's optimal welfare is not only necessarily achieved. Incentive constraint seems to be necessary to encourage the firm to report its accurate emission rate for the determination of an appropriate allowance allocation rate. The most appropriate policy should ensure that the optimal social welfare does not rely on the firm's emission rate.

For each regulation policy $(\phi(\cdot), e(\cdot))$, if the firm reports its emission rate x accurately, its profit is

$$\pi(e(x),\phi(x),x) = \frac{1}{2c_1}[p-\tau x+\tau\phi(x)]^2 + (\tau\gamma - c_2)e(x). \tag{4}$$

If the firm's real emission rate is x but its reported emission rate is y, the firm's profit is

$$\pi(e(y),\phi(y),x) = \frac{1}{2c_1}[p-\tau x+\tau\phi(y)]^2 + (\tau\gamma - c_2)e(y). \tag{5}$$

To encourage the firm to report its real emission rate, the incentive compatibility constraints is introduced as follows:

$$\pi(e(x),\phi(x),x) \geq \pi(e(y),\phi(y),x), \quad \forall x,y \in \Omega. \tag{6}$$

In addition, it is not fair to force the firm to run business under the circumstance of negative welfare. Therefore, the participation constraint should be satisfied, i.e.,

$$\pi(e(x),\phi(x),x) \geq 0, \quad \forall x \in \Omega. \tag{7}$$

To maximize the government's welfare, the principal-agent model can be formulated as follows:

$$\left\{\begin{array}{l} \max\limits_{e(x),\phi(x)} W = \displaystyle\int_a^b \{\frac{m-p-hx}{c_1}[p-\tau x+\tau\phi(x)] + (\frac{1}{2c_1}-\frac{n}{c_1^2})[p-\tau x+\tau\phi(x)]^2 \\ \qquad\qquad +(\tau\gamma - c_2 + h\gamma)e(x)\}f(x)dx \\ \text{subject to:} \\ \dfrac{1}{2c_1}[p-\tau x+\tau\phi(x)]^2 + (\tau\gamma - c_2)e(x) \geq \dfrac{1}{2c_1}[p-\tau x+\tau\phi(y)]^2 + (\tau\gamma - c_2)e(y) \\ \dfrac{1}{2c_1}[p-\tau x+\tau\phi(x)]^2 + (\tau\gamma - c_2)e(x) \geq 0 \end{array}\right. \tag{8}$$

3 The model analysis

3.1 The optimal decision mechanism under complete information

In this section, Kuhn-Tucker condition is employed to solve model (2) and the optimal solution is as follows:

Proposition 1. *The optimal solution* $(\phi^*(x), e^*(x))$ *of model (2) is*

$$\phi(x) = \left(1 + \frac{hc_1(c_2-\tau\gamma)}{\tau[hc_1\gamma - 2n(c_2-\tau\gamma)]}\right)x - \frac{p}{\tau} + \frac{c_1(\tau\gamma - c_2)(m-p)}{\tau[hc_1\gamma - 2n(c_2-\tau\gamma)]}. \tag{9}$$

and

$$e(x) = -\frac{[p-\tau x+\tau\phi(x)]^2}{2c_1(\tau\gamma - c_2)}. \tag{10}$$

Remark 1. *In order to ensure the emission reduction is positive,* $\tau\gamma - c_2 < 0$ *must be satisfied according to Eq. (10).*

3.2 The optimal solution under incomplete information

In order to solve the proposed model, the equivalent form of model (8) in section 2.2.2 is considered.

3.2.1 Equivalent form of the principal-agent model

Firstly, the incentive constraint is analyzed and the following proposition can be deduced:

Proposition 2. *The incentive compatibility constraint (6) is equivalent to:*

$$\frac{\tau(p-\tau x+\tau\phi(x))}{c_1}\frac{d\phi}{dx}+(\tau\gamma-c_2)\frac{de}{dx}=0, \forall x\in\Omega. \tag{11}$$

and

$$\frac{d\phi}{dx}\leq 0, \forall x\in\Omega. \tag{12}$$

Proof. Refer to Appendix A for the specific progress. □

Remark 2. *Eq. (12) indicates that the optimal allowance allocation rate depends on the actual emission rate of the firm. In other words, the lower the firm's actual emission rate is, the higher allowance allocation rate it can obtain. This illustrates the government's measures to reduce the* CO_2 *emissions.*

This is followed by the analysis of the participation constraint to ensure the involvement of the firm in the emission trading market. With the assumption VI, we can obtain that

$$\frac{d\pi}{dx}=\frac{p-\tau x+\tau\phi(x)}{c_1}(\tau\frac{d\phi}{dx}-\tau)+(\tau\gamma-c_2)\frac{de}{dx}.$$

It follows from (11) that

$$\frac{d\pi}{dx}=-\frac{\tau}{c_1}[p-\tau x+\tau\phi(x)].$$

It is worth noting that $q=\dfrac{p-\tau x+\tau\phi(x)}{c_1}\geq 0$, it means $p-\tau x+\tau\phi(x)\geq 0$, thus $\dfrac{d\pi}{dx}\leq 0$, indicating $\pi(\phi(x),e(x),x)$ is strictly decreasing with respect to x. Consequently, the participation constraint (7) is equivalent to

$$\pi(\phi(q(b)),e(b),b)=\frac{1}{2c_1}[p-\tau b+\tau\phi(b)]^2+(\tau\gamma-c_2)e(b)\geq 0.$$

Indeed, the participation constraint is binding if the optimal mechanism is considered [28]. As for any feasible mechanism $(\phi(\cdot),e(\cdot))$ of Model (7), a new mechanism $(\phi(\cdot),e^*(\cdot))$ can be established, where

$$e^*(b)=\frac{[p-\tau b+\tau\phi(b)]^2}{2c_1(c_2-\tau\gamma)}$$

and

$$\frac{de^*(x)}{dx}=\frac{de(x)}{dx}.$$

Similarly, $(\phi(\cdot),e^*(\cdot))$ is also feasible for model(7) and $e^*(x)\leq e(x)$ for all $x\in\Omega$. The derivation of government's welfare about e equals to $\tau\gamma-c_2\leq 0$. In other words, the government's welfare decreases with respect to e. As a result, the government will choose the smallest e in order to satisfy the participation constraint. Therefore, the optimal mechanism should satisfy the following condition

$$\frac{[p - \tau b + \tau\phi(b)]^2}{2c_1} = (c_2 - \tau\gamma)e(b).$$

Proposition 3. *The participation constraint (7) can be written as*

$$\frac{[p - \tau b + \tau\phi(b)]^2}{2c_1} = (c_2 - \tau\gamma)e(b). \tag{13}$$

As a result, the principal-agent model under incomplete information can be derived into the equivalent form summarized in the following proposition:

Proposition 4. *Model (8) is equivalent to:*

$$\begin{cases} \max\limits_{\phi(x),e(x)} W = \displaystyle\int_a^b \{\frac{m-p-hx}{c_1}[p - \tau x + \tau\phi(x)] + (\frac{1}{2c_1} - \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 \\ \qquad\qquad +(\tau\gamma - c_2 + h\gamma)e(x)\}f(x)dx \\ \text{subject to:} \\ \dfrac{\tau(p - \tau x + \tau\phi(x))}{c_1}\dfrac{d\phi}{dx} + (\tau\gamma - c_2)\dfrac{de}{dx} = 0 \\ \dfrac{d\phi}{dx} \le 0 \\ \dfrac{[p - \tau b + \tau\phi(b)]^2}{2c_1} = (c_2 - \tau\gamma)e(b) \end{cases} \tag{14}$$

Proof. This proposition can be verified according to Propositions 2-3. □

The equivalent form can be obtained from model (14) and consequently the optimal decisions are determined by using the optimal control method. How much is the value of the allowance allocation rate? How much emission should be reduced and how does the allowance rate change according to the variation of firm's emission rate? The optimal allowance allocation rate and emission reduction under incomplete information should satisfy the following proposition:

Proposition 5. *If optimal mechanism $(\phi^*(\cdot), e^*(\cdot))$ exists under incomplete information,* *then the following equations must be satisfied as*

$$\frac{d\phi^*(x)}{dx}\{\int_x^a \left(\frac{\tau}{c_1}(m-p-hx)-2\tau[\frac{h}{2c_1(\tau\gamma-c_2)}+\frac{n}{c_1^2}][p-\tau x+\tau\phi^*(x)]^2\right)f(x) \\ +\frac{\tau^2(\tau\gamma-c_2+h)}{c_1(\tau\gamma-c_2)}F(x)\}dx=0. \tag{15}$$

and

$$e^*(x)=\frac{\tau}{c_1(\tau\gamma-c_2)}\int_x^b[p-\tau s+\tau\phi(s)]ds-\frac{[p-\tau x+\tau\phi(x)]^2}{2c_1(\tau\gamma-c_2)}. \tag{16}$$

3.2.2 A special case: ϕ with finite first-order derivative

To obtain the solution of the optimal decision under incomplete information, the following special case is considered.

1: $B \le \frac{d\phi}{dx} \le 0, \forall x \in \Omega$, where B is a negative constant. In other words, the first-order derivative of the allowance allocation rate is bounded. This means the decrease of each firm's allocation rate with its emission rate should be within a certain level.

2: $\phi(b)=e(b)=0$, both the allowance allocation rate and allowances are zero when the firm's emission rate reaches its highest level.

With the additional assumptions and the above analysis, the principal-agent problem is reformulated as a control problem below:

$$\begin{cases} \max\limits_{e(x),\phi(x)} W=\int_a^b\{\frac{m-p-hx}{c_1}[p-\tau x+\tau\phi(x)]+(\frac{1}{2c_1}-\frac{n}{c_1^2})[p-\tau x+\tau\phi(x)]^2 \\ \qquad +(\tau\gamma-c_2+h\gamma)e(x)\}f(x)dx \\ \text{subject to:} \\ \mu(x)=\frac{d\phi(x)}{dx}, \forall x\in\Omega \\ B\le\mu\le 0, \forall x\in\Omega \\ \phi(b)=e(b)=0. \end{cases} \tag{17}$$

According to Eqs(15) and (16), the optimal decision mechanism is obtained.

$$\phi(x)=B(x-b), \forall x\in\Omega. \tag{18}$$

and

$$e(x) = -\frac{\tau^2(B-1)}{2(\tau\gamma - c_2)}(1+\frac{B-1}{c_1})x^2 - \frac{\tau(p-\tau Bb)}{\tau\gamma - c_2}(1+\frac{B-1}{c_1})x \\ +\frac{\tau^2(B-1)b^2}{2(\tau\gamma - c_2)} + \frac{\tau b(p-\tau Bb)}{\tau\gamma - c_2} - \frac{(p-\tau Bb)^2}{2c_1(\tau\gamma - c_2)}. \tag{19}$$

4 Empirical simulation

An empirical simulation is provided in this section on electric industry. The government as the principal sets the contracts of allowance allocation rate and emission reduction while the electricity firm makes decision accordingly. Similarly, sensitivity analysis is undertaken, including the effects on allowance allocation and emissions caused by the change of carbon price τ and the rate of change on allocation rate B.

4.1 Consumer surplus

The demand for electricity is represented by the price-responsive linear inverse demand function [20]. In general, it is assumed that the relationship between the consumer's electricity demand within a certain period of time and the electricity price is as follows:

$$Q = f(p). \tag{20}$$

It is assumed the initial demand of electricity is q_0 if the the initial price of electricity is p_0. Therefore, the Eq. (20) can be expressed as follows:

$$q_0 = f(p_0). \tag{21}$$

Consequently, the Taylor series expansions at p_0 can be obtained as follows:

$$Q = q_0 + \frac{dq}{dp} |_{p_0} (p - p_0). \tag{22}$$

On the other hand, based on microeconomics principles, the elasticity of demand for electricity can be expressed as follows:

$$E = -\frac{dq}{dp} \cdot \frac{p}{q}. \tag{23}$$

Substitute Eq.(22) into Eq.(23), the demand function for electricity can be obtained:

$$Q = q_0 - E \cdot \frac{q_0}{p_0} \cdot (p - p_0). \tag{24}$$

Based on the assumption IV, the consumer surplus can be described as:

$$S = mQ - nQ^2 - pq. \tag{25}$$

in which Q is the consumer demand of electricity and q is the electricity production. It is assumed that $Q = q$.

4.2 Parameters setting

Due to the existence of asymmetric information, the government should design regulatory policies $(\phi(\cdot), e(\cdot))$ for a representative electricity firm, where $\phi(\cdot)$ denotes the allowances allocation rate it gains and $e(\cdot)$ denotes the emission reduction of the electric firm. The values of emission rate, output, abatement and production cost of the representative firm come from the average value of six firms, i.e. China Huaneng Corporation, China Datang Corporation, China Huadian Corporation, China Guodian Corporation, China Power Investment Corporation, China Shenhua Energy Company Limited. The selected average variation range of the emission rate a and b are $[0.00004 \quad 0.00006]$. From the assumption 2, $\phi(b) = 0$ and $e(b) = 0$ illustrates the possibility of production halts derived from the high emission rate, which means that the electricity industry will not obtain any allowance or achieve any emission reduction when the emission rate is too high. The value of environmental loss caused by the emission of CO_2 into the atmosphere $h = 23$ [28]. What's more, the unit price of the firm's product $p = 0.473$ CNY/Kwh and the carbon price in carbon trading market is $\tau = 30$ CNY as the product market and permit market are all perfectly competitive. The sources of primary data are "China Electricity Industry Development Annual Report 2012", "China Electric power Yearbook 2012" and "Beijing Statistical Yearbook 2012".

Furthermore, from the analysis of section 4.1, the primary form of consumer surplus coefficients m and n are $m = p(1 + \frac{1}{E})$ and $n = \frac{p}{2q_0E}$, where E represents the elasticity of demand for electricity. The coefficients value of production and abatement cost c_1 and c_2 are obtained by linear regression.

From the assumption 1, the decrease of the electricity industry's allowance allocation rate according to its emission rate are bounded below. Therefore, it is reasonable to assume that $-10 = B \leq \frac{dq}{dx} \leq 0$. Assume the adjust coefficient $\gamma = 1.0E-7$, parameters and units used in this paper are summarized in Table 1.

Table 1: Parameters and values in the model

Parameters	Values	Units
p	0.4735	CNY/Kwh
τ	30	CNY/tCO$_2$
a	0.00004	t/Kwh
b	0.00006	t/Kwh
h	23	CNY/tCO$_2$
m	1.866	CNY/Kwh
n	2.699E-11	CNY/(Kwh)^2
c_1	1.99E-12	CNY/(Kwh)^2
c_2	0.001	CNY/t
γ	1.0E-7	–
B	-10	Kwh/t

4.3 Results and discussions

4.3.1 A comparison between complete information and incomplete information

Different assumptions lead to different consequences. In order to have a more comprehensive understanding, a comparison between the two scenarios appears to be of vital important. Both the agent (firm) and the principle (government) face the optimal decision problem. The comparison of optimal decisions under the two scenarios not only reflect the impact of asymmetric information but also affect the decision making of regulator. According to Eq.(9), (10), (18), (19) and the illustrations described in the previous sections, the optimal allowance allocation rate $\phi(x)$ and emission reduction $e(x)$ can be obtained under complete or incomplete information.

It can be observed from Fig.1 that the optimal allowance allocation rate decrease with the increase of emission rate as stated in Proposition 2. This indicates that the firm has to reduce their emission rate so as to achieve a high allowance allocation rate. In addition, the emission rate is higher under complete information than incomplete information according to the value of y. It illustrates that firm only considers maximizing its own

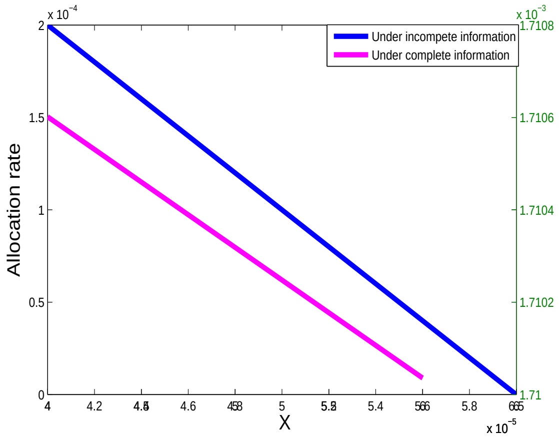

Figure 1: The optimal allowance allocation rate under two scenarios

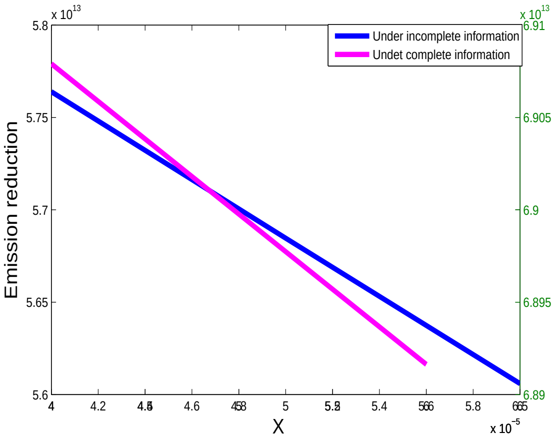

Figure 2: The optimal emission reduction under two scenarios

interests and ignores the environmental damage caused by CO_2 emissions under complete information. When private information is considered, an emission abatement incentive could be considered. A combination of emission reduction and allowance allocation rate can further promote emission abatement and consequently reduce the environmental damage. Therefore, it is necessary to take the private information into account. It is beneficial to the environment by offering different contracts to different reported emission rates. Indeed, the allocation allowance mechanism will not be effective if the private information is omitted.

Fig.2 shows that the emission reduction decreases since the emission rate increases as the emission abatement becomes more different when the firm's emission rate is high. It should be noted that the emission reduction is higher under complete information than incomplete information. This may be due to, on the one hand, the high output under complete information as illustrated by Fig.4. On the other hand, the contract combination of allowance allocation rate and emission reductions will lessen emission reductions.

In this paper, the allowances that the firm obtained is equal to allowance allocation rate multiplying the output. As shown in Fig.3, the variation trend of allowances is very similar to that of the allowance allocation rate. The conclusions are also similar therefore will not be further explained. Fig. 4 shows the output under different scenarios. When the emission rate increases, the output decreases because of the emission rate growth and allocation rate reduction. The quantity of output under complete information is larger

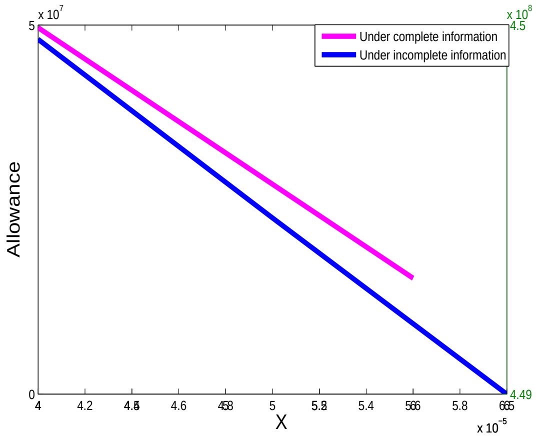

Figure 3: The optimal allowances under two scenarios

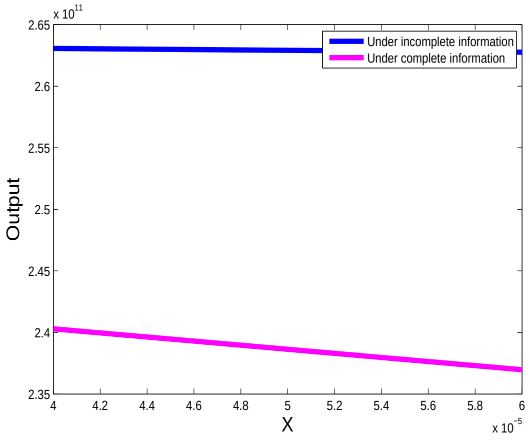

Figure 4: The optimal output under two scenarios

than that under incomplete information due to motivation on the emission reduction when the private information is considered. When private information is taken into consideration, the firm may not produce the product as before since the emission expenditure is large.

An important indicator to evaluate the arousal effect is CO_2 emissions E which is in connection with the optimal decision e, output q and emission rate x (see Fig. 5). The variation on actual CO_2 emissions shows a growth pattern as the emission rate increases. Moreover, when the emission rate is relatively small the firm's CO_2 emissions are large under incomplete information than that under complete information. By contrary, when the emission rate exceeds a certain level, the emissions under incomplete information become much lower than the emissions under complete information. This indicates an encouraging sign when the private information is considered. CO_2 emissions show a dramatic decline under incomplete information thereby reducing the environmental loss as well as slowing down the climate change. This demonstrates the necessity of offering different contract to different firms.

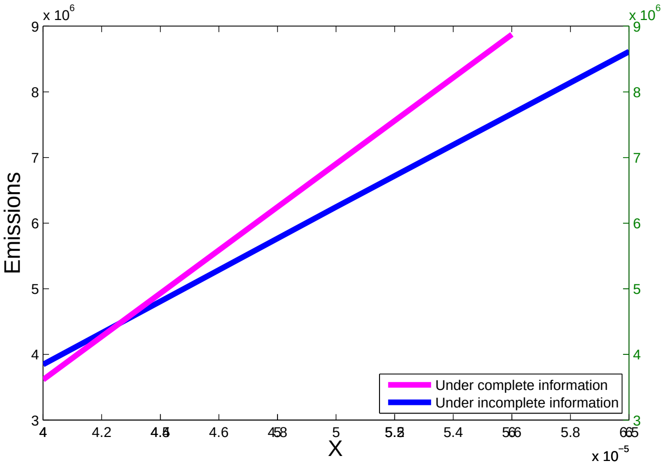

Figure 5: The actual emissions under different conditions

Fig.6 presents the relationship between allocated allowances, CO_2 emission reduction and environmental damage under different scenarios. As shown in Fig.6, the environmental damage presents a downward trend with the increase of the allowance due to the growth of emission reduction as well as reduction of actual emissions. Also, the environmental damage is smaller under incomplete information than complete information. This indicates a necessity to take the private information into consideration and to provide different contracts for the firms according to their reported emission rate in order to stimulate the emission reduction.

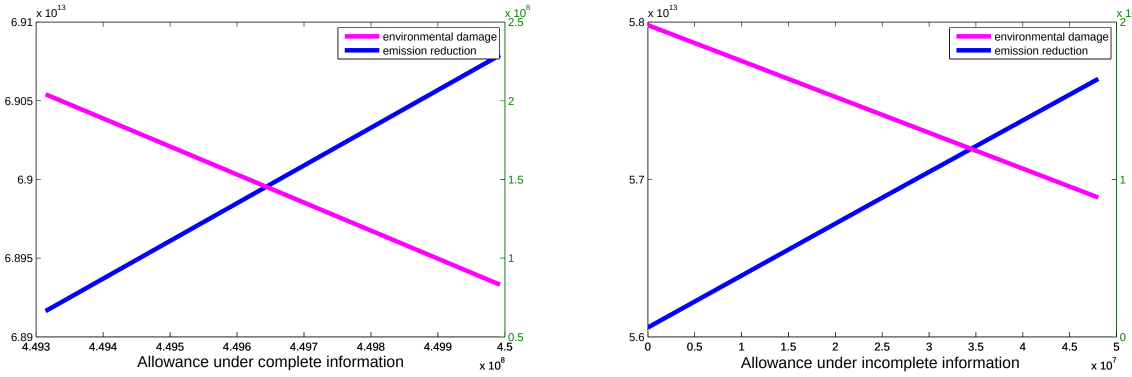

Figure 6: Allowances, CO_2 emission abatement and environmental damage under different scenarios

4.3.2 Sensitivity analysis

There are a large number of factors that affect the allowance allocation and emission reduction in different scenarios. These factors include: the changes of carbon price τ, the coefficient of emission abatement c_2, the adjustment coefficient γ and the rate of change on allowance allocation rate B. It is imperative to identify the most important factors to derive the results.

The impacts of carbon price on allowance allocation rate and emission reduction under different scenarios are illustrated in Fig.7 and Fig.8. It can be observed that there is no correlation between the allowance allocation rate and carbon price under incomplete information, thus the influence of carbon price on allowance allocation rate is only considered under complete information(see Fig.7). Three cases are considered: $\tau_1 = 25$ CNY/t, $\tau_2 = 30$ CNY/t, $\tau_3 = 35$ CNY/t. The allowances allocation rate becomes less with the increase in carbon price under the complete information as higher carbon price leads to lower emissions, so as the allowances that the firm obtains.

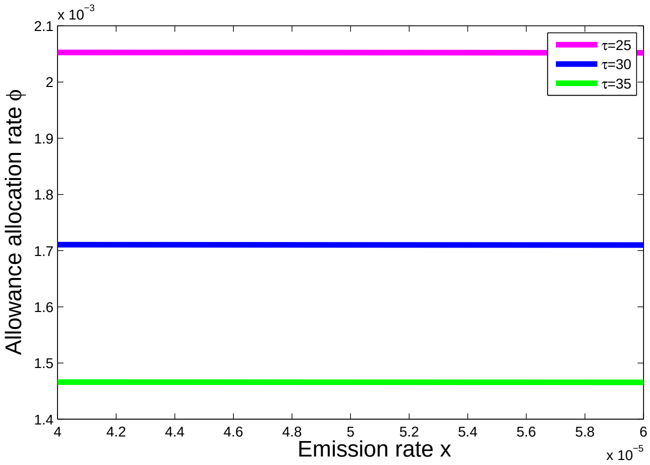

Figure 7: Effect of carbon price change on ϕ under complete information

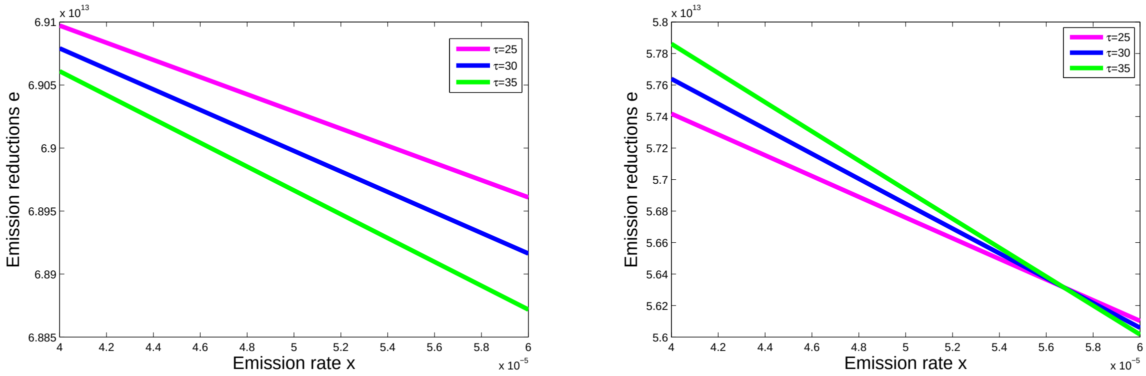

Figure 8: Influence of carbon price on emission reductions under different conditions

The effect of carbon price τ varying in 3 cases on emission reductions e is shown in Fig.8. Under complete information, emission reduction becomes less with an increase in carbon price. By contrast, the higher the carbon price, the smaller emission reduction is achieved when the emission rate is below a certain level under incomplete information. Because the high carbon price leads to the high cost of emissions, the firm has to reduce emissions to maximize its profits. Thus, a high emission reduction is achieved under incomplete information. Under complete information, the maximizing goal is not taking the emission damage and allowance allocation into consideration.

As the variation of allowance allocation rate B is not the same all the time, the effects of changes in B on allocation rate ϕ and emission reductions e are considered in Fig. 9. Results show that the effects on ϕ and e is identical, i.e. the higher B, the less allocation rate ϕ and emission reduction e is. A high B means a tight bound constraint for the variation of allowance allocation rate. Thus, the high N becomes, a more stable amount allowances the firm can get and the less emission reductions the firm reached.

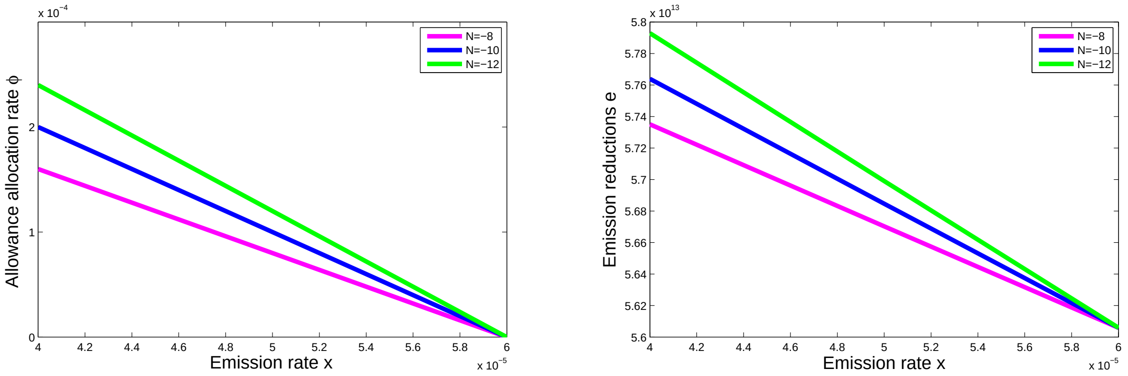

Figure 9: Influence of changes in B on the ϕ and e

In addition, the effects of variation in the coefficient of emission abatement cost c_2 are shown in Fig. 10. As the change of c_2 has nothing to do with the allowance allocation rate ϕ under incomplete information, only the effects under complete information are showed. Similarly, three values of c_2 is considered: $c_2 = 0.0001$CNY/t, $c_2 = 0.001$CNY/t and $c_2 = 0.01$CNY/t. As shown in Fig.10, the allowance allocation rate ϕ gradually decreased with the increase of the coefficient of emission abatement cost c_2 as the high abatement cost resulting a smaller amount of carbon emissions. And furthermore, the low allowance allocation rate is achieved. Similar results are obtained when examining the influence of variations in c_2 on emission reductions under different scenarios (see Fig. 11).

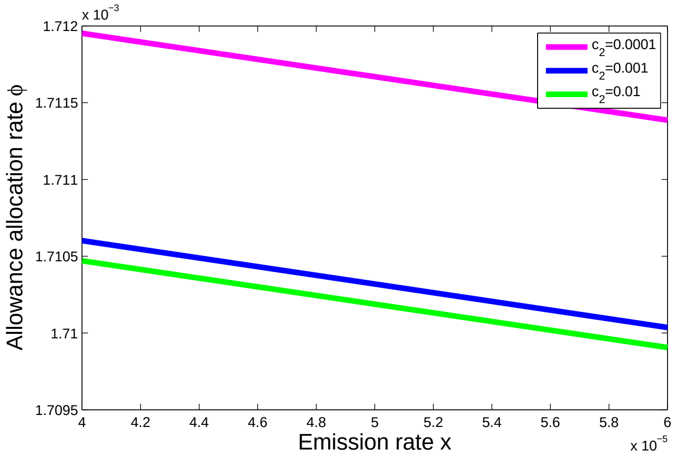

Figure 10: Effects of changes in c_2 on allowance allocation rate

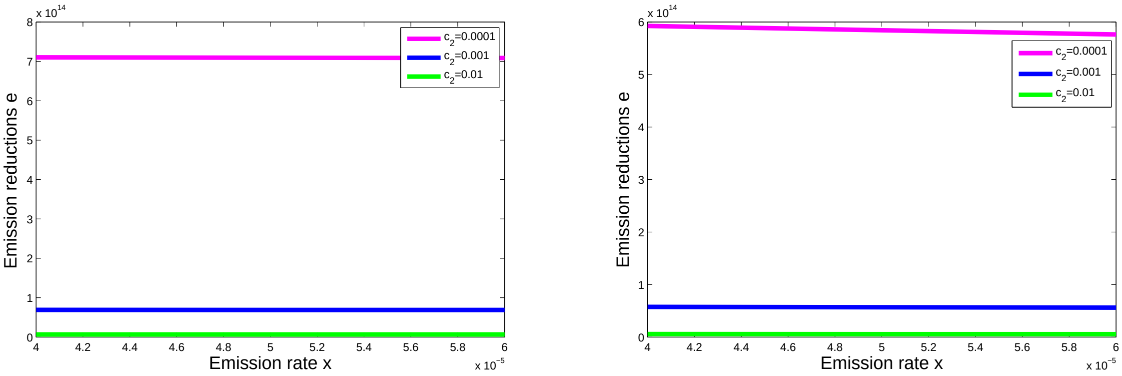

Figure 11: Influence of variations in c_2 on emission reductions

5 Conclusions

It is recognized that emission trading is a cost-effective instrument to deal with environmental issues. Allowance allocation presents one of most critical issues during the policy design in emission trading. In the real world, the private information (e.g. emission rate) is not necessarily communicated between the government and the firms. These two parties have different objectives, i.e. the government allocates the carbon allowances to maximize social welfare and reduce environmental damage whereas the firm aims to maximize its profits without considering the emission damage. Such asymmetric information presents a significant challenge to the policy making on emission trading. In this research, a CO_2 allowance allocation method was developed by applying the contract theory. The government makes decisions on allowance allocation rate and offers the contract on allowance allocation and emission reductions. Then the firm chooses the appropriate contract and decides its output. A comparison of the two scenarios, i.e. under complete information and incomplete information was also undertaken.

The results show that offering different contract with different reported emission rate is beneficial to the environment whereas most allowances will be wasted if the private information is omitted. In addition, this research developed a principal-agent model to illustrate an effective approach to allocate the allowance to the firm and to develop the contract which combines allowance allocation rate with emission reductions so that environmental damage can be reduced. As research only considered the perfectly competitive market, it is worthwhile to examine the impacts of other factors on the behaviors of individual firms in the proposed principal-agent model.

A Appendix

Proof Proposition 2

Let $L(x,y) = \frac{1}{2c_1}[p - \tau x + \tau\phi(y)]^2 + (\tau\gamma - c_2)e(y)$ denoted the profit of firm with the true emission rate x but the reported emission rate y, where $x, y \in \Omega$. Thus, inequality (6) can be written as

$$L(x,x) \geq L(x,y), \forall x, y \in \Omega,$$

which means that (x,x) is one of the maximal value points of $L(x,y)$. Therefore, for any fixed x, $L(x,y)$ satisfied the first-order condition $\frac{\partial L(x,y)}{\partial y} \mid_{y=x} = 0$ and the second-order condition $\frac{\partial^2 L(x,y)}{\partial y^2} \mid_{y=x} \leq 0$. It follows from the first-order condition that

$$\frac{\tau(p - \tau x + \tau\phi(x))}{c_1}\frac{d\phi}{dx} + (\tau\gamma - c_2)\frac{de}{dx} = 0, \forall x \in \Omega. \tag{26}$$

By the second-order condition, we can obtain

$$\frac{\tau(p - \tau x + \tau\phi(x))}{c_1}\frac{d^2\phi}{dx^2} + \frac{\tau^2}{c_1}(\frac{d\phi}{dx})^2 + (\tau\gamma - c_2)\frac{d^2e}{dx^2} \leq 0, \forall x \in \Omega. \tag{27}$$

By the differentiating (26) with respect to x,

$$\frac{\tau(p - \tau x + \tau\phi(x))}{c_1}\frac{d^2\phi}{dx^2} - \frac{\tau^2}{c_1}\frac{d\phi}{dx} + \frac{\tau^2}{c_1}(\frac{d\phi}{dx})^2 + (\tau\gamma - c_2)\frac{d^2e}{dx^2} = 0, \forall x \in \Omega. \tag{28}$$

Combining (27) and (28) yields

$$\frac{\tau^2}{c_1}\frac{d\phi}{dx} \leq 0, \forall x \in \Omega. \tag{29}$$

Thus, $\frac{d\phi(x)}{dx} \leq 0, \forall x \in \Omega$. That is, (6)$\Rightarrow$ (11) and (12).

On the other hand, note that $\frac{d\phi(x)}{dx} \leq 0$. Integrating (11) yields

$$\begin{aligned}(\tau\gamma - c_2)(e(x) - e(y)) &= \frac{\tau}{c_1}\int_x^y (p - \tau s + \tau\phi(s))\frac{d\phi}{ds}ds \\ &\geq \frac{\tau}{c_1}\int_x^y (p - \tau x + \tau\phi(s))\frac{d\phi}{ds}ds \\ &= \frac{1}{2c_1}[p - \tau x + \tau\phi(y)]^2 - \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2\end{aligned}$$

when $y > x$; and

$$\begin{aligned}(\tau\gamma - c_2)(e(x) - e(y)) &= \frac{\tau}{c_1}\int_y^x (p - \tau s + \tau\phi(s))\frac{d\phi}{ds}ds \\ &\geq \frac{\tau}{c_1}\int_y^x (p - \tau x + \tau\phi(s))\frac{d\phi}{ds}ds \\ &= \frac{1}{2c_1}[p - \tau x + \tau\phi(y)]^2 - \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2\end{aligned}$$

when $y < x$. Therefore, the incentive constraint (6) are satisfied. That is, (11) and (12) ⇒ (6). Therefore, the proof of the proposition is complete.

B Appendix

Proof Proposition 5

As we have proofed before that

$$\frac{d\pi}{dx} = -\frac{\tau}{c_1}[p - \tau x + \tau\phi(x)]$$

and $\dfrac{d\pi}{dx} \leq 0$. Integrating $\frac{d\pi}{dx}$ from x to b yields

$$\pi(b) - \pi(x) = -\frac{\tau}{c_1}\int_x^b [p - \tau s + \tau\phi(s)]ds$$

Then

$$\pi(x) = \frac{\tau}{c_1}\int_x^b [p - \tau s + \tau\phi(s)]ds$$

It follows from (4) that

$$e(x) = \frac{\tau}{c_1(\tau\gamma - c_2)}\int_x^b [p - \tau s + \tau\phi(s)]ds - \frac{[p - \tau x + \tau\phi(x)]^2}{2c_1(\tau\gamma - c_2)} \tag{30}$$

Substituting $e(x)$ and $\pi(x)$ into the government's welfare function yields

$$\int_a^b \left(mq - nq^2 - pq + \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2 + (\tau\gamma - c_2)e(x) - h(xq - e(x)) \right) f(x)dx$$

$$= \int_a^b \{ \frac{1}{c_1}(m - p - hx)[p - \tau x + \tau\phi(x)] - \frac{n}{c_1^2}[p - \tau x + \tau\phi(x)]^2 + \frac{1}{2c_1}[p - \tau x + \tau\phi(x)]^2$$

$$+(\tau\gamma - c_2 + h)e(x)\} f(x)dx$$

$$= \int_a^b \left(\frac{1}{c_1}(m - p - hx)[p - \tau x + \tau\phi(x)] - (\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 \right) f(x)dx$$

$$+\frac{\tau(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)} \int_a^b \int_x^b ([p - \tau s + \tau\phi(s)]ds)\, ds f(x)dx$$

$$= \int_a^b \{ \left(\frac{1}{c_1}(m - p - hx)[p - \tau x + \tau\phi(x)] - (\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 \right) f(x)$$

$$+\frac{\tau(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)}[p - \tau x + \tau\phi(x)]F(x)\} dx \tag{31}$$

The Hamiltonian

$$H(\phi, e, \lambda, \mu) = \left(\frac{1}{c_1}(m - p - hx)[p - \tau x + \tau\phi(x)] - (\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2})[p - \tau x + \tau\phi(x)]^2 \right) f(x)$$

$$+\frac{\tau(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)}[p - \tau x + \tau\phi(x)]F(x) + \lambda(x)\mu(x) \tag{32}$$

where $\phi(x)$ are the corresponding state variables, $\mu(x)$ are control variables and $\lambda(x)$ are adjoint variables.

According to Pontryagin maximum principle,if $\mu^*(x)$ and $\phi^*(x)$ are the optimal solutions to the problem(17),then there exist optimal adjoint variables $\lambda(x)$ such that $\mu^*(x), \phi^*(x)$ and $\lambda^*(x)$ satisfy the following conditions.

(1)The canonical differential equations of the system are

$$\frac{d\lambda}{dx} = -\frac{\partial H}{\partial \phi} \tag{33}$$

(2)Since the variation of the state at point $x = a$ is free,we have the boundary conditions

$$\lambda(a) = 0 \tag{34}$$

(3)$\mu^*(x)$ maximize the Hamiltonian(32) over $\mu(x) \leq 0$ for all x, i.e.,

$$H(\phi^*(x), \mu^*(x), \lambda(x), x) = \max_{\mu(x) \leq 0} H(\phi^*(x), \mu(x), \lambda(x), x) \tag{35}$$

It follows from the canonical differential equations (33) that

$$\frac{d\lambda}{dx} = -\left\{ \left(\frac{\tau}{c_1}(m - p - hx) - 2\tau[\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2}][p - \tau x + \tau\phi(x)]^2 \right) f(x) + \frac{\tau^2(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)} F(x) \right\} \tag{36}$$

Since $\lambda(a) = 0$, we can obtain

$$\begin{aligned} &\lambda(x) = \lambda(a) - \int_x^a \frac{d\lambda}{dx} dx \\ &\int_x^a \left\{ \left(\frac{\tau}{c_1}(m - p - hy) - 2\tau[\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2}][p - \tau y + \tau\phi(y)]^2 \right) f(y) + \frac{\tau^2(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)} F(y) \right\} dy \end{aligned} \tag{37}$$

It follows from (32)and (35)that $\lambda(x) \geq 0$,when $\lambda(x) > 0, \mu(x) = 0$, therefore,the optimal allowance allocation policies can be described as

$$\begin{aligned} \frac{d\phi^*(x)}{dx}\{\int_x^a &\left(\frac{\tau}{c_1}(m - p - hx) - 2\tau[\frac{h}{2c_1(\tau\gamma - c_2)} + \frac{n}{c_1^2}][p - \tau x + \tau\phi^*(x)]^2 \right) f(x) \\ &+ \frac{\tau^2(\tau\gamma - c_2 + h)}{c_1(\tau\gamma - c_2)} F(x)\} dx = 0 \end{aligned} \tag{38}$$

and according to (31) we can obtain

$$e^*(x) = \frac{\tau}{c_1(\tau\gamma - c_2)} \int_x^b [p - \tau s + \tau\phi^*(s)] ds - \frac{[p - \tau x + \tau\phi^*(x)]^2}{2c_1(\tau\gamma - c_2)}.$$

Thus, the results (15) and (16) hold.

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