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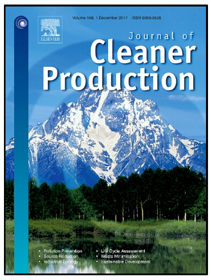

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Determining the Optimal Carbon Tax Rate based on Data Envelopment Analysis

Minyue Jin[1], Xiao Shi[2*], Ali Emrouznejad[3*], Feng Yang[1]

Abstract

Carbon tax policy is widely used to control greenhouse gases and how to determine a suitable carbon tax rate is very important for policy makers considering the trade-off between environmental protection and economic development. In an industry regulated by carbon tax policy, we consider two competing firms who sell ordinary products and green products respectively. In order to promote the firm who sells ordinary product to reduce carbon emissions, the government of China imposes carbon tax on the ordinary products. For the government, three objectives are considered when it makes carbon tax policy. They are increasing the government revenue, reducing the government expenditure and decreasing the carbon emissions. For the firms, it is important to explore their pricing strategies taken into account of the government tax policy. To find an optimal carbon tax rate and to achieve the three objectives simultaneously, we consider this as a multiple criteria decision-making problem. Hence, we propose to use a centralized data envelopment analysis (DEA) approach to solve it. We find that when one firm produces ordinary products and the other produces green products, the government may set a high tax rate. While when both firms sell ordinary products, the optimal tax policy for each firm is different and the government may impose a higher tax rate for one firm and a lower tax rate for the other firm.

***Keywords*:** Carbon tax policy; government revenue; government expenditure; carbon emissions; centralized DEA approach

1. Introduction

The recognition of the climate change effected by greenhouse gases (GHG) has received a large amount of attention over the last several years (Lee 2011, Al-Mulali and Sab 2012, Wang et al. 2013). The first treaty aims at reducing carbon emissions, i.e., United Nations Framework Convention on Climate Change (UNFCCC), entered into force in 1994. Then the Kyoto Protocol extends the 1994 UNFCCC and asks different countries to fulfill their obligations of GHG emissions limitations (Grubb 2004). From the perspective of firms, it is also widely accepted that environmental issues such as carbon emissions will have bad impacts on shareholders' value (McKinsey&Company 2010). Thus, a large number of firms and companies are participating actively in emission reduction activities. For instance, Tesla Motors aims at eventually offering zero emission electric cars at prices affordable to average consumers. As another example consider Hewlett Packard (HP), HP focuses on materials innovation, includes reducing each product carbon emissions during manufacturing stage and usage stage (Raz et al. 2013). However, for most firms, manufacturing low-emissions products may need advanced technology and require substantial up front investments, for example, Tesla invests a large amount of money in battery technology. This, on the other hand, makes firms afraid to move toward environmentally friendly technology. Therefore, it is important and necessary for the governments and organizations to implement regulations and laws to motivate firms to adopt green technology and produce low-carbon products.

The taxation approach is widely used among regulators to achieve environmental benefits (Felder and Schleiniger 2002, Lin and Li, 2011). A significant tax policy can induce the firms to adopt pollution abatement technologies and produce environmentally friendly products (Avi-Yonah and Uhlmann 2009). For example, in 1990, the US government imposes upon tax on chlorofluoro carbons (CFCs). Because the tax is much higher than the cost of CFCs, some new technologies are used to improve the utility ratio of one unit of CFCs and the consumption of CFCs had dropped by over 70% in the next 5 years (Krass et al. 2013). Tax policy is perceived as a useful tool to reduce carbon emissions. However, it may hurt firms' profit because of its enforcement. Therefore, when policy makers make taxation decisions, they have to consider the effect of the tax policy from multiple aspects, like environment impact, firms' profit and government expenditure (Mankiw et al. 2009). Therefore, our first research question is *how the government should make carbon tax policy considering multiple objectives*.

In practice, a large number of consumers are showing interests in green products. According to a survey made by the Gallup Organization in 2009[1], 83% of the Europeans express their willingness to buy an eco-safe product. Bei and Simpson (1995) indicate that in addition to the utility obtained directly from a purchased product, green consumers can receive psychological benefits from buying environmentally friendly products. Bansal (2008) study the design of regulatory instruments under the assumption that the consumers are willing to pay extra for buying green products. Based on these research, our second research question explores *how the firms make pricing decisions if the consumers are sensitive to the carbon emissions*.

In this paper, we discuss the policy decision of the government on how to determine the optimal tax rate considering the firms' pricing strategies. The objectives of the government include three goals, increasing the government revenue, reducing the government expenditure and decreasing the carbon emissions. As it can be shown later in this paper, these three objectives are conflicting because increasing the carbon tax rate may leads to lower carbon emissions but higher government expenditure. Therefore there is trade-off between the three goals. To select the best tax policy, we regard the problem as a multi-criteria decision-making problem and use centralized DEA approach to solve it.

From the numerical example, we find that when there is one firm selling ordinary products and the other selling green products in the market, the government may set a highest tax rate. We find that when one firm produces ordinary products and the other

[1]http://ec.europa.eu/public_opinion/flash/fl_256_en.pdf

produces green products, the government may set a high tax rate. While when both firms sell ordinary products, the optimal tax policy for each firm is different and the government may impose a higher tax rate for one firm and a lower tax rate for the other firm.

The rest of this paper is organized as follows. We review relevant literature in Section 2. In Section 3, we describe our model setup and introduce the centralized DEA approach. We analyze the benchmark model with one firm selling ordinary product and the other selling green product in Section 4. We study the firms' pricing strategies and government carbon tax policies for both firms in Section 5. Section 6 offers conclusions and discussions of extensions for future research.

2. Literature review

Our work contributes to the operations management literature that study environmental policy (Zhang and Xu 2013, Qiu et al. 2017, Sabzevar et al. 2017). For example, Drake et al. (2015) study the impact of emission tax on a company's long-run technology choice and show that in certain conditions an increase in tax rate would decrease investment in clean technology. Krass et al. (2013) investigate how to use environmental taxes to motivate firms to adopt greener technologies and they find that over increase in taxes may have a negative impact on the firms' technology choice strategies. Manikas and Kroes (2015) present a new forward buying method to reduce the impact of emissions allowance acquisitions on firms' financial performance. From the perspective of supply chain cooperation, Ji et al. (2017) compare three different modes of carbon allowance allocation rules and show that cap and trade regulation based on benchmarking mechanism can more effectively push manufacturers to produce low-carbon products. And it would be more beneficial to the retailer to cooperate with the manufacturer with lower emission reduction cost. Zakeri et al. (2015) examine the supply chain performance at the operational planning level under the carbon taxes policy and show that carbon trading mechanisms leads to better supply chain performance in terms of emissions and cost. Park et al. (2015) study how carbon penalty changes the supply chain structure and social welfare.

Additional, Liu et al. (2015) focus on the impact of carbon emission regulation on firms' remanufacturing strategies and Wang et al. (2015) study how carbon taxes affect the selection of transportation modes and social welfare. While in these papers, they assume that the government has single goal, i.e. maximize social welfare or minimize the total pollution. In our paper, we consider multidimensional missions of the government, which include increasing the government revenue, decreasing the government expenditure and reducing carbon emissions, and centralized DEA approach to find out the best carbon tax policy.

A number of studies examine environmental efficiency evaluation based on DEA method (Bian and Yang 2010, Wang et al. 2013, Han et al. 2015). Xie et al. (2014) investigate the environmental efficiencies of electric power industries in 26 OECD from 1996 to 2010 and find that fuel structure change and economic situation and energy prices are main driving forces that affect environmental total factor productivity. Song et al. (2014) consider the internal structure of production system and propose a two-stage DEA approach to evaluate the environmental efficiency of China. Furthermore, Wu et al. (2016) combines individual interest preference with efficiency evaluation to reflect the current environmental situation in China. Chen and Jia (2017) introduce big data theory to select input and output data of different region and apply Slack-based measure model to evaluate the environmental efficiencies of China's industry.

Recently, Lozano et al. (2004), Lozano et al. (2011), and Yu et al. (2013) utilize centralized DEA models to deal with centralized resource allocation problems. In these models, the objective of the centralized decision-makers is to maximize the overall output production by all DMUs or optimize the combined resource consumption of all units, rather than considering them separately (Feng 2013, Yu et al. 2013). To evaluate the environmental efficiency from the overall view, centralized DEA approach is also applied to model undesirable variables, e.g., carbon emissions (Zhou et al. 2014, Sun et al. 2015).

Much different from the literature above, in this paper, we focus on how to choose a best carbon tax policy for the government considering the firms' carbon reduction activities and the government multiple goals. In order to solve the problem, we use backward induction combined with centralized DEA approach to select the optimal carbon tax rate. To the best of our knowledge, we are the first to use centralized DEA method to consider multidimensional problems of the government along with pricing decisions of the firms.

3. Model set-up and assumptions

We consider two competing firms in the market ($i = 1, 2$), each of which sells a kind of product. The products can be differentiated by the selling prices, production costs and carbon emissions per unit. Except these, the two products are of no difference. There is a local government in the market. In order to promote the firms to reduce carbon emissions, the government decides to impose a carbon tax on the products which exceeds the green standard. Next, we present the decisions of each players and the sequence of the event. Notations are summarized in Table 1.

Table 1 Summary of Notations

Symbol	Definition
e_i	Carbon emissions of PRO_i per unit
c_i	Production cost of PRO_i per unit
p_i	Selling price of PRO_i per unit
λ	The turnover tax imposed by the government for each unit of product
t_i	The carbon tax rate for PRO_i
δ_i	The government expenditure for each unit of PRO_i

3. 1 Firms

There are two competing firms F_1 and F_2 in the market. The subscript 1 represents F_1 and the subscript 2 represents F_2. The products are denoted by PRO_1 and

PRO_2. We assume that each consumer buys at most one unit of either PRO_1 or PRO_2. The net utility of a consumer can be stated as follows (Bi et al. 2016):

$$U = u_i - \theta e_i - p_i, \quad i=1, 2 \tag{1}$$

Where u_i (i=1, 2) is the consumer's potential utility in possessing a product if e_i=0 and p_i=0 and is large enough to guarantee non-empty market coverage. In other words, one consumer can choose to buy a PRO_1 or a PRO_2, and he cannot choose to buy nothing. Without loss of generality we normalize that $u_1 = u_2 = u$, e_i (i=1,2) is the amount of carbon emissions per unit of product and we assume $e_1 > e_2$. θ is the sensitivity coefficient of a particular consumer to the carbon emissions and is assumed to be uniformly distributed on $[\underline{\theta}, \overline{\theta}]$. Obviously a higher θ implies that the consumer prefers products with lower carbon emissions better. p_i (i=1,2) is the selling prices of product i. By calculating the utility function, we obtain that consumers with $\theta \in [0, \theta^*]$ would buy PRO_1, while consumers with $\theta \in [\theta^*, 1]$ would buy PRO_2, where $\theta^* = (p_2 - p_1)/(e_1 - e_2)$.

Environmental tax is an effective way to help reducing products' carbon emissions (Krass et al. 2013). It is intuitively believed that the reduction of carbon emissions has a positive correlation with government carbon tax. Therefore, we use $e_i - e = \Delta e_i = \frac{t_i^{-\alpha}}{k_i}$ to represent the impact of carbon tax on the firm's emissions reduction of PRO_i per unit. Here, α is the elasticity parameter of carbon tax and $\alpha > 1$. In other words, decreasing the emissions becomes increasingly necessary with the augment of the carbon tax. k_i denotes the correlation coefficient between the carbon emissions and tax rate. Higher k_i means that the government carbon tax has a greater impact on the firm's emissions reduction activities. If $k_i \to \infty$, then $e_i \to e$. That means the carbon emissions of PRO_i is very close to the green standard. We abandon the situation of $k_i \to 0$ because the carbon emissions of a regular product per unit would always be a definite value and could not be ∞. In order to make it easier to calculate, we let $k = 1/k_i$ and then $\Delta e = \frac{t_i^{-\alpha}}{k_i}$ can be written as $\Delta e_i = kt_i^{-\alpha}$.

3. 2 Government

In practice, many indications impact the government decision of tax rate. In this paper, we consider three objectives, i.e., government revenue, government expenditure and carbon emissions. The definitions of the three objectives are given as follows.

Government revenue

Government revenue refers to the revenue of the government finance from its imposition of a tax, a fee or any other charge. Taxation is the main source of government revenue and can help to stabilize the economy and promote desirable behavior. Therefore it is necessary for policy makers to consider the government revenue when they implement a carbon tax policy. The government revenue is calculated by the following equation

$$R = (p_1 - c_1)(\theta^* - \underline{\theta})\lambda + (p_2 - c_2)(\overline{\theta} - \theta^*)\lambda + t_1(e_1 - e)(\theta^* - \underline{\theta}) + t_2(e_2 - e)(\overline{\theta} - \theta^*) \quad (2)$$

In Equation (2), the first two terms are turnover tax from PRO_i, the second two terms are carbon tax of PRO_i.

Government expenditure

The government expenditure includes the cost that the government pays for supervising the production process of each unit of product, like personnel, information technology and telecommunications (Chen 2001). For different types of the products, the spending may be different. We assume that government spending of PRO_1 per unit is Δ_1 and that of PRO_2 per unit is Δ_2. Based upon this, we identify government expenditure as follows

$$E = (\theta^* - \underline{\theta})\Delta_1 + (\overline{\theta} - \theta^*)\Delta_2 \quad (3)$$

The total government expenditure consists of two parts, i.e., the spending generated from PRO_1 and the spending generated from PRO_2.

Carbon emissions

Carbon emission, particular CO_2, is the major factor that causes potentially irreversible changes in global climate. Therefore, we use carbon emissions as the third indicator for the government to implement the tax policy. The total carbon emission is expressed as

$$Q = (\theta^* - \underline{\theta})e_1 + (\overline{\theta} - \theta^*)e_2 \quad (4)$$

Where the first term is the total carbon emissions of PRO_1 and the second term is the total carbon emissions of PRO_2.

The sequence of the events can be described as follows: First, the local government determines the tax policy for each firm. Upon seeing the tax policy, the two firms, simultaneously, choose their product selling prices p_i. We use backward induction to characterize the problem. In the first step we present the firms pricing decisions given the government tax rates, while in the second step, we offer a bundle of feasible carbon tax rates, and use centralized DEA approach to select the government optimal tax rates proposed to each firm.

3. 3 Method

Suppose there are a bundle of n feasible choices, denoted by t_1, t_2, …, t_n. The corresponding government revenue, government expenditure and carbon emission for t_i are R_i, E_i and Q_i respectively. In the decision making process, the government aims to increase the revenue and decrease the government expenditure and carbon emissions. Then to determine the optimal tax rate becomes a multiple criteria decision-making problem, which is to rank or select from a set of alternative courses of action in the presence of conflicting criteria. Correspondingly in our problem, the government revenue R is positive criteria while the government expenditure E and carbon emissions Q are negative ones. Next, we give the method for the government on selection of best carbon tax policy based on centralized DEA approach.

3. 3. 1 Environmental DEA Technology

The joint production of desirable and undesirable outputs can be described as "environmental production technology". It depicts the process of converting input vectors (E) to desirable output vectors (R) and undesirable output vectors (Q) (Fare et al. 1989). The production technology set (T) is assumed to satisfy the following assumptions:

(1) If $(E,R,Q)\in T$ and $0\le\theta\le 1$, then $(x,\theta E,\theta Q)\in T$ (weak disposability for desirable and undesirable outputs).

(2) If $(E,R,Q)\in T$ and $Q=0$, then $R=0$ (null-jointness of desirable and undesirable outputs).

The conceptual definition of environmental production technology can be approximated by piecewise linear combinations of the observed data, which is similar theoretically to DEA form; as such, it can also be called "environmental DEA technology". Under CRS assumption, environmental production technology T can be approximately formulated as follows:

$$T_W=\left\{\begin{array}{l}(E,R,Q):\sum_{j=1}^{n}\lambda_j E_{ij}\le E_i, i=1,\dots,m\\ \qquad\qquad \sum_{j=1}^{n}\lambda_j R_{rj}\ge R_r, r=1,\dots,s\\ \qquad\qquad \sum_{j=1}^{n}\lambda_j Q_{dj}=Q_d, d=1,\dots,D\\ \qquad\qquad \lambda_j\ge 0, j=1,\dots,n\end{array}\right\} \tag{5}$$

The formulation of Shephard environment DEA technology is as follows:

$$T_S = \left\{ \begin{array}{l} (E,R,Q): \sum_{j=1}^{n} \lambda_j E_{ij} \le E_i, i = 1,\dots,m \\ \qquad \theta \sum_{j=1}^{n} \lambda_j R_{rj} \ge R_r, r = 1,\dots,s \\ \qquad \theta \sum_{j=1}^{n} \lambda_j Q_{dj} = Q_d, d = 1,\dots,D \\ \qquad 0 \le \theta \le 1, \sum_{j=1}^{n} \lambda_j = 1 \\ \qquad \lambda_j \ge 0, j = 1,\dots,n \end{array} \right\} \tag{6}$$

Where θ is the abatement factor, which ensures that T_s satisfies the above two assumptions. The second and third constraints in Model (6) are non-linear, which they can be transformed to linear form by defining a new variable $\hat{\lambda}_j = \theta \lambda_j$ to replace the old variables. The converted model can be expressed as follow:

$$T_S = \left\{ \begin{array}{l} (E,R,Q): \sum_{j=1}^{n} \hat{\lambda}_j E_{ij} \le \theta E_i, i = 1,\dots,m \\ \qquad \sum_{j=1}^{n} \hat{\lambda}_j R_{rj} \ge R_r, r = 1,\dots,s \\ \qquad \sum_{j=1}^{n} \hat{\lambda}_j Q_{dj} = Q_d, d = 1,\dots,D \\ \qquad 0 \le \theta \le 1, \sum_{j=1}^{n} \hat{\lambda}_j = \theta \\ \qquad \hat{\lambda}_j \ge 0, j = 1,\dots,n \\ \qquad E_i \ge min\{E_{ij}\} \end{array} \right\} \tag{7}$$

It is worth noting that the reason to add constrain $E_i \ge \min\{E_{ij}\}$ is to prevent the condition $\theta = 0$ (which cause $\hat{\lambda}_j = 0$), than any activity $(E,0,0)$ will be feasible (This is because according to the first constraint in Model (3), input vectors E cannot be smaller than the observed practical value).

3. 3. 2 Centralized Model for Environmental DEA Technology

Based on environmental DEA technology, the centralized models (6) and (7) are employed in order to make sure that all firms act in a way which optimize the performance for the government as a whole. After centralized optimization, all DMU activities are as efficient as possible under the potential desirable outputs and allocated undesirable outputs set by the model. Then, the centralized DEA model (Lozano and Villa, 2005; Yu et al. 2013) can be formulated as follows:

$$\begin{aligned} & Min \quad \theta \\ & s.t. \quad \sum_{r=1}^{n}\sum_{j=1}^{n}\lambda_{jr}E_{ij} \le \theta\sum_{r=1}^{n}E_{ir}, i=1,\dots,m \\ & \qquad \sum_{r=1}^{n}\sum_{j=1}^{n}\lambda_{jr}R_{tj} \ge \sum_{r=1}^{n}R_{tr} \backslash, r=1,\dots,s \\ & \qquad \sum_{r=1}^{n}\ \sum_{j=1}^{n}\lambda_{jr}Q_{dj} = \sum_{r=1}^{n}Q_{dr}, d=1,\dots,D \\ & \qquad 0 \le \theta \le 1, \sum_{j=1}^{n}\lambda_{jr} = 1 \\ & \qquad \lambda_{jr} \ge 0, j=1,\dots,n, r=1,\dots n \\ & \qquad E_i \ge \min\left\{E_{ij}\right\} \end{aligned} \tag{8}$$

This is a linear optimization model with n^2+n+1 variables. By solving this model above, the efficiency of each DMU can be obtained.

In section 4, we first explain a benchmark model considering the situation where there is only one firm that produce ordinary products with carbon emissions exceed the green standard. We then extended this, in section 5, to the case where the government imposes carbon taxes on both firms.

4. Benchmark model: tax policy on one firm

In this section, we assume that there is only one firm in the market whose carbon emissions of its product exceed the green standard. In other words, the other firm that produce green product do not need to pay for carbon tax. Next, we derive the pricing strategies of the two competing firms and give government optimal carbon tax policy considering the government three goals.

4.1 The pricing decisions of the two firms

As can be seen above, the demand of the ordinary product PRO_1 is $\theta^* - \underline{\theta}$ and demand of the green product PRO_2 is $\overline{\theta} - \theta^*$. Then, F_1's optimization problem is given by

$$\max_{p_1, p_2} \pi_1 = (p_1 - c_1)(\theta^* - \underline{\theta})(1-\lambda) - t(e_1 - e_2)(\theta^* - \underline{\theta}) \tag{10}$$

Where c_1 is F_1's variable cost per unit of product and p_1 is the selling price. λ is the turnover tax rate for each product that sells out. The first term represents the net sale profit and the second term represents the government carbon tax.

The profit of F_2 can be written as follows:

$$\max_{p_1, p_2} \pi_2 = (p_2 - c_2)(\overline{\theta} - \theta^*)(1-\lambda) \tag{11}$$

Where c_2 is F_2's variable cost per unit of product and p_2 is the selling price. The products that F_2 manufactures can meet the green standard. Therefore it does not need to pay carbon taxes.

To find the optimal p_1 and p_2 to maximize $\pi_1(p_1, p_2)$ and $\pi_2(p_1, p_2)$, we differentiate $\pi_1(p_1)$ with respect to p_1 and $\pi_2(p_2)$ with respect to p_2, which yield the first-order conditions:

$$\frac{\partial \pi_1}{\partial p_1} = (k^{-1} t^{\alpha}(p_2 - p_1) - \underline{\theta})(1-\lambda) - k^{-1} t^{\alpha}(p_1 - c_1)(1-\lambda) + t \tag{12}$$

$$\frac{\partial \pi_2}{\partial p_2} = (\overline{\theta} + k^{-1} t^{\alpha}(p_1 - p_2))(1-\lambda) - k^{-1} t^{\alpha}(p_2 - c_2)(1-\lambda) \tag{13}$$

Since it can be verified that the two functions are convex in p_1 and p_2 respectively, the optimal p_1 and p_2 can be obtained by forcing $\partial \pi_1 / \partial p_1 = 0$ and $\partial \pi_2 / \partial p_2 = 0$. Then we have

$$p_1(t) = \frac{1}{3}(k\overline{\theta} t^{-\alpha} - 2k\underline{\theta} t^{-\alpha} + 2c_1 + c_2 + \frac{2kt^{-\alpha+1}}{1-\lambda}) \tag{14}$$

$$p_2(t) = \frac{1}{3}(2k\overline{\theta} t^{-\alpha} - k\underline{\theta} t^{-\alpha} + c_1 + 2c_2 + \frac{kt^{-\alpha+1}}{1-\lambda}) \tag{15}$$

4.2 Determining the optimal tax policy based on centralized DEA

In this section we use a numerical example to illustrate our method. Some parameters are given in Table 2.

Table 2. Parameters setting in the numerical example

c_1=1	c_2=3	e_2=10	λ=0.1
$\underline{\theta}=0$	$\overline{\theta}=1$	k=1.5	α=1.5
Δ_1=4	Δ_2=3		

We let tax rate t to be 0.4, 0.55, …,6.25 with common difference of 0.15, and thus 40 feasible choices on the tax rate are obtained, as shown in the first column of Table 3.

According to Equations (2)-(4), all values of the government revenue, government expenditure and carbon emissions are obtained, as can be seen in Table 3.

Table 3. Government revenue, government expenditure and carbon emissions

No.	***t***	R_i	E_i	Q_i	**No.**	***t***	R_i	E_i	Q_i
1	0.4	1.13	3.30	11.765	**21**	3.4	1.78	4.86	10.445
2	0.55	0.91	3.31	11.143	**22**	3.55	1.87	4.99	10.447
3	0.7	0.81	3.33	10.856	**23**	3.7	1.96	5.13	10.448
4	0.85	0.77	3.37	10.702	**24**	3.85	2.06	5.26	10.450
5	1	0.76	3.41	10.611	**25**	4	2.15	5.41	10.451
6	1.15	0.77	3.46	10.554	**26**	4.15	2.25	5.55	10.453
7	1.3	0.80	3.51	10.517	**27**	4.3	2.34	5.70	10.455
8	1.45	0.84	3.57	10.492	**28**	4.45	2.44	5.86	10.457
9	1.6	0.88	3.64	10.475	**29**	4.6	2.54	6.01	10.458
10	1.75	0.94	3.71	10.463	**30**	4.75	2.64	6.18	10.460
11	1.9	1.00	3.79	10.455	**31**	4.9	2.74	6.34	10.462
12	2.05	1.06	3.88	10.449	**32**	5.05	2.85	6.51	10.464
13	2.2	1.13	3.97	10.445	**33**	5.2	2.95	6.68	10.465
14	2.35	1.20	4.06	10.443	**34**	5.35	3.05	6.85	10.467
15	2.5	1.28	4.16	10.442	**35**	5.5	3.16	7.03	10.469
16	2.65	1.36	4.27	10.441	**36**	5.65	3.26	7.21	10.470
17	2.8	1.44	4.38	10.441	**37**	5.8	3.37	7.39	10.472
18	2.95	1.52	4.49	10.442	**38**	5.95	3.48	7.58	10.473
19	3.1	1.61	4.61	10.443	**39**	6.1	3.59	7.77	10.475
20	3.25	1.69	4.73	10.444	**40**	6.25	3.70	7.96	10.476

In order to get a more intuitive result, we use Figs. 1-3 to show the relationship between the tax rate and the three objectives. As shown in Fig. 1, when the tax rate increases, the government revenue decreases rapidly at first, then increases. While in Fig. 2, the government expenditure increases quickly. In Fig. 3, the total carbon emissions decrease quickly and then increases slowly and smoothly with increasing t. Next we use DEA analysis to evaluate each tax rate's efficiency to select the optimal carbon tax rate.

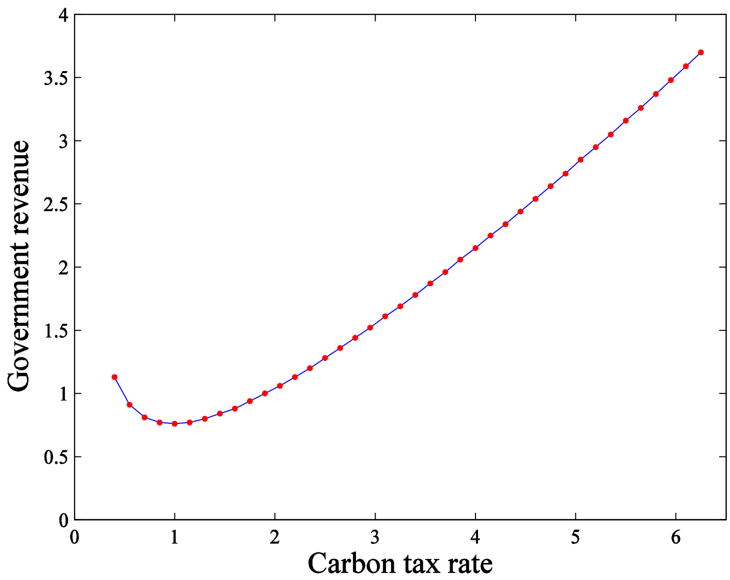

Fig. 1. Government revenue under the carbon tax policy

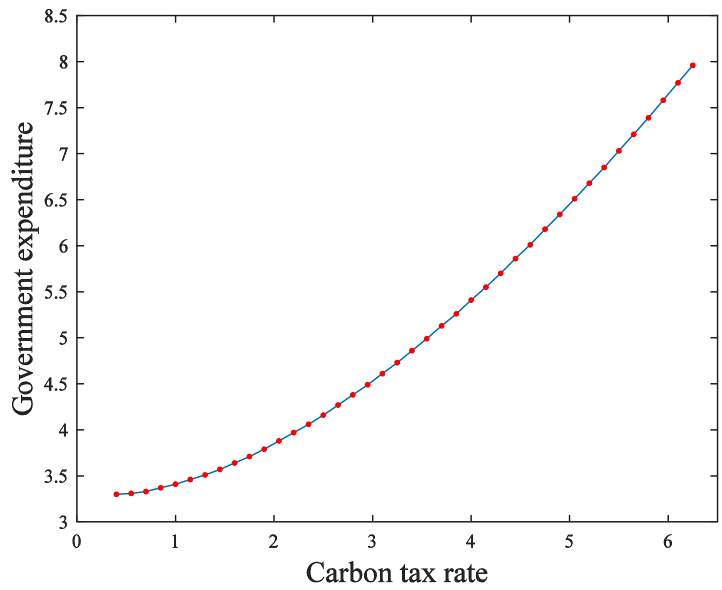

Fig. 2. Government expenditure under the carbon tax policy

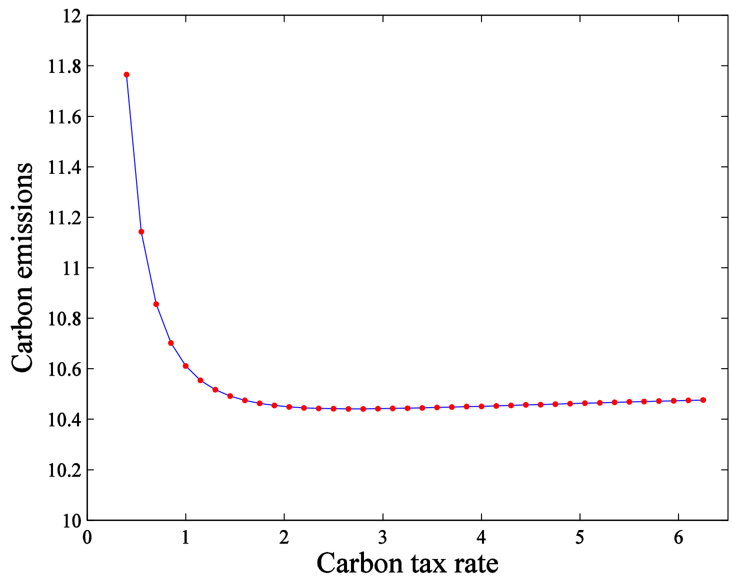

Fig. 3. Total carbon emissions under the carbon tax policy

Using model (7), we obtain the DEA efficiency scores of all feasible candidates. Results show that, policy 40 is the best choice, which leads to highest government revenue and government expenditure, while it maintain lower carbon emissions.

Table 4. DEA efficiency scores of all feasible policies

No.	η_i	**No.**	η_i	**No.**	η_i	**No.**	η_i
1	0.737	**11**	0.568	**21**	0.788	**31**	0.930

2	0.591	**12**	0.588	**22**	0.806	**32**	0.942
3	0.523	**13**	0.612	**23**	0.822	**33**	0.950
4	0.492	**14**	0.636	**24**	0.843	**34**	0.958
5	0.479	**15**	0.662	**25**	0.855	**35**	0.967
6	0.479	**16**	0.685	**26**	0.872	**36**	0.973
7	0.490	**17**	0.707	**27**	0.883	**37**	0.981
8	0.506	**18**	0.728	**28**	0.896	**38**	0.988
9	0.520	**19**	0.751	**29**	0.909	**39**	0.994
10	0.545	**20**	0.769	**30**	0.919	**40**	1.000

In the next section, we analyze the situation where both of the firms produce ordinary products and should pay for carbon tax. Similar to Section 4, we first obtain the firms pricing strategies given the government carbon tax rate. Then we analyze how the government makes different carbon tax policies for the two firms.

5. Tax policy on two firms

In this section, we assume that there are two firms in the market and the carbon emissions of both of their products exceed the green standard. In other words, both of the firms produce ordinary products and need to pay for carbon tax. Next, we derive the pricing strategies of the two competing firms and give government optimal carbon tax policy considering the government three goals.

5.1 The pricing decisions of the two firms

Similar to Section 4.1, we obtain the demand of product PRO_1 as $\theta^* - \underline{\theta}$ and demand of product PRO_2 as $\overline{\theta} - \theta^*$. Then, F_1's optimization problem is given by

$$\max_{p_1, p_2} \pi_1 = (p_1 - c_1)(\theta^* - \underline{\theta})(1-\lambda) - t_1(e_1 - e)(\theta^* - \underline{\theta}) \quad (16)$$

Where e is the green standard for both of the products, c_1 is F_1's variable cost per unit of product and p_1 is the selling price. λ is the turnover tax rate for each unit of product that sells out. The first term represents the net sale profit and the second term represents the government carbon tax.

The profit of F_2 can be written as follows:

$$\max_{p_1, p_2} \pi_2 \;=(p_2 - c_2)(\overline{\theta} - \theta^*)(1-\lambda) - t_2(e_2 - e)(\overline{\theta} - \theta^*) \tag{17}$$

Where c_2 is F_2's variable cost per unit of product and p_2 is the selling price.

We obtain the firms optimal selling prices as followers:

$$p_1(t_1, t_2) = \frac{t_1^{-\alpha} t_2^{-\alpha} \left(k t_1^{\alpha} \left(-1 + t_2 + \lambda \right) + t_2^{\alpha} \left(\left(2c_1 + c_2 \right) t_1^{\alpha} \left(1 - \lambda \right) + k \left(1 + 2t_1 - \lambda \right) \right) \right)}{3\left(1 - \lambda\right)} \tag{18}$$

$$p_2(t_1, t_2) = \frac{t_1^{-\alpha} t_2^{-\alpha} \left(t_2^{\alpha} \left(k \left(2\lambda - 2 - t_1 \right) + \left(c_1 + 2c_2 \right) t_1^{\alpha} \left(1 - \lambda \right) \right) - 2k t_1^{\alpha} \left(1 - t_2 - \lambda \right) \right)}{3\left(1 - \lambda\right)} \tag{19}$$

Next, we use a numerical example to analyze the government optimal tax policy for each of the firm.

5.2 Determining the optimal tax policies based on centralized DEA

In this section we use a numerical example to illustrate our results. We give some of the parameters in Table 5.

Table 5. Parameters setting in the numerical example

c_1=0.5	c_2=0.8	e=50	λ=0.3
$\underline{\theta}$ = 0	$\overline{\theta} = 1$	k=3.5	α=1.5
Δ_1=4	Δ_2=2		

The government may use different tax policies for the two firms respectively. Here we let tax rate t_1 be 0.1, 0.2 … 1.0 with common difference of 0.1, and let t_2 be 0.2, 0.4 … 2.0 with common difference of 0.2. There are 100 tax portfolios of t_1 and t_2. Eliminating the results that cannot meet the condition, we get 95 feasible choices on each firm's tax rates, as can be shown in the first column of Table 6. Table 6 also shows the corresponding government revenue, government expenditure and carbon emissions to each t_1 and t_2.

Table 6. Government revenue, government expenditure and carbon emissions

No.	t_1	t_2	R_i	E_i	Q_i	No.	t_1	t_2	R_i	E_i	Q_i
1	0.1	0.2	24.86	2.63	111.54	**49**	0.6	0.2	4.20	2.56	80.27
2	0.1	0.4	27.02	2.61	93.58	**50**	0.6	0.4	6.36	2.48	62.32
3	0.1	0.6	27.15	2.61	88.90	**51**	0.6	0.8	6.30	2.52	55.58
4	0.1	0.8	27.03	2.60	86.85	**52**	0.6	1	6.12	2.48	54.46
5	0.1	1	26.88	2.60	85.72	**53**	0.6	1.2	5.94	2.45	53.76
6	0.1	1.2	26.74	2.60	85.02	**54**	0.6	1.4	5.78	2.43	53.28
7	0.1	1.4	26.61	2.60	84.54	**55**	0.6	1.6	5.64	2.41	52.93
8	0.1	1.6	26.50	2.60	84.19	**56**	0.6	1.8	5.51	2.40	52.67
9	0.1	1.8	26.40	2.59	83.93	**57**	0.6	2	5.40	2.39	52.46
10	0.1	2	26.31	2.59	83.73	**58**	0.7	0.2	3.78	2.56	79.91
11	0.2	0.4	13.31	2.59	71.28	**59**	0.7	0.4	5.94	2.48	61.96
12	0.2	0.6	13.41	2.57	66.59	**60**	0.7	0.6	6.04	2.33	57.27
13	0.2	0.8	13.28	2.56	64.54	**61**	0.7	0.8	5.90	2.61	55.22
14	0.2	1	13.12	2.56	63.42	**62**	0.7	1	5.71	2.48	54.10
15	0.2	1.2	12.96	2.55	62.71	**63**	0.7	1.2	5.53	2.44	53.40
16	0.2	1.4	12.82	2.55	62.23	**64**	0.7	1.4	5.37	2.42	52.92
17	0.2	1.6	12.70	2.54	61.89	**65**	0.7	1.6	5.22	2.40	52.57
18	0.2	1.8	12.59	2.54	61.63	**66**	0.7	1.8	5.09	2.38	52.31
19	0.2	2	12.49	2.54	61.42	**67**	0.7	2	4.98	2.37	52.10
20	0.3	0.2	7.44	2.58	83.97	**68**	0.8	0.2	3.47	2.55	79.68
21	0.3	0.4	9.58	2.58	66.02	**69**	0.8	0.4	5.64	2.47	61.73
22	0.3	0.6	9.67	2.55	61.33	**70**	0.8	0.6	5.74	2.37	57.04
23	0.3	0.8	9.53	2.54	59.28	**71**	0.8	1	5.41	2.53	53.87
24	0.3	1	9.36	2.52	58.16	**72**	0.8	1.2	5.23	2.45	53.16
25	0.3	1.2	9.19	2.51	57.45	**73**	0.8	1.4	5.07	2.41	52.68
26	0.3	1.4	9.05	2.51	56.97	**74**	0.8	1.6	4.92	2.38	52.34
27	0.3	1.6	8.92	2.50	56.63	**75**	0.8	1.8	4.79	2.36	52.08
28	0.3	1.8	8.80	2.50	56.37	**76**	0.8	2	4.67	2.35	51.87
29	0.3	2	8.70	2.49	56.16	**77**	0.9	0.2	3.23	2.55	79.52
30	0.4	0.2	5.76	2.57	81.89	**78**	0.9	0.4	5.41	2.47	61.57
31	0.4	0.6	7.99	2.54	59.25	**79**	0.9	0.6	5.52	2.38	56.88
32	0.4	0.8	7.84	2.52	57.20	**80**	0.9	0.8	5.36	2.15	54.83
33	0.4	1	7.66	2.50	56.08	**81**	0.9	1	5.19	2.70	53.71
34	0.4	1.2	7.49	2.49	55.37	**82**	0.9	1.2	5.01	2.48	53.01
35	0.4	1.4	7.34	2.47	54.89	**83**	0.9	1.4	4.84	2.42	52.53
36	0.4	1.6	7.21	2.47	54.55	**84**	0.9	1.6	4.70	2.38	52.18
37	0.4	1.8	7.09	2.46	54.28	**85**	0.9	1.8	4.56	2.35	51.92
38	0.4	2	6.98	2.45	54.08	**86**	0.9	2	4.44	2.33	51.71
39	0.5	0.2	4.81	2.57	80.86	**87**	1	0.2	3.05	2.55	79.41
40	0.5	0.4	6.95	2.47	62.90	**88**	1	0.4	5.24	2.46	61.46
41	0.5	0.6	7.05	2.58	58.22	**89**	1	0.6	5.34	2.38	56.77
42	0.5	0.8	6.90	2.51	56.17	**90**	1	0.8	5.19	2.24	54.72

43	0.5	1	6.72	2.48	55.04	**91**	1	1.2	4.84	2.56	52.90
44	0.5	1.2	6.54	2.46	54.34	**92**	1	1.4	4.67	2.44	52.42
45	0.5	1.4	6.39	2.45	53.86	**93**	1	1.6	4.52	2.39	52.07
46	0.5	1.6	6.25	2.44	53.51	**94**	1	1.8	4.39	2.35	51.81
47	0.5	1.8	6.12	2.43	53.25	**95**	1	2	4.27	2.32	51.60
48	0.5	2	6.01	2.42	53.05						

Figs 4-6 present the impact of government different carbon tax policies on each of the three goals. Different form the figures in Section 4, we use three-dimensional graphs to show how the tax portfolios of t_1 and t_2 impact the government multiple objectives. In Fig. 4, we find that in most cases, the government revenue may increase with increasing t_2 while decrease with increasing t_1. However, in case 11-13, or 63-66, the government revenue would decrease in t_2. It is difficult to find a best carbon tax policy from the three figures. Therefore, in what followers, we use DEA to evaluate the efficiency of each tax portfolio of t_1 and t_2 and select the optimal carbon tax portfolio for the government.

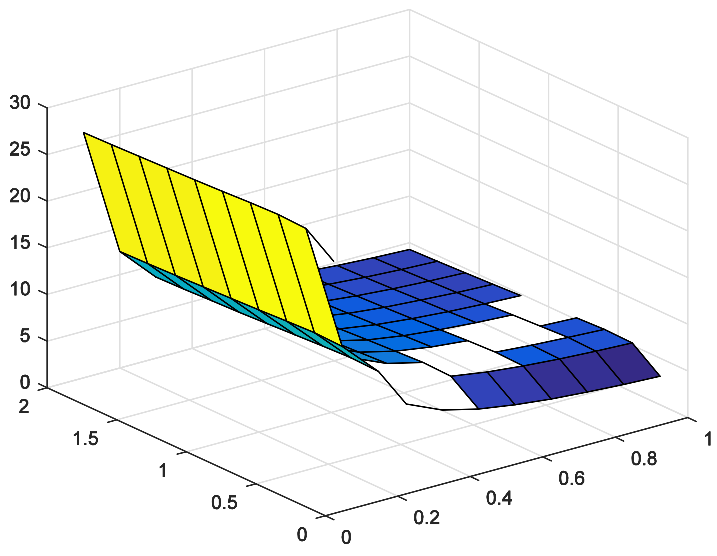

Fig. 4. Government revenue under different carbon tax policies

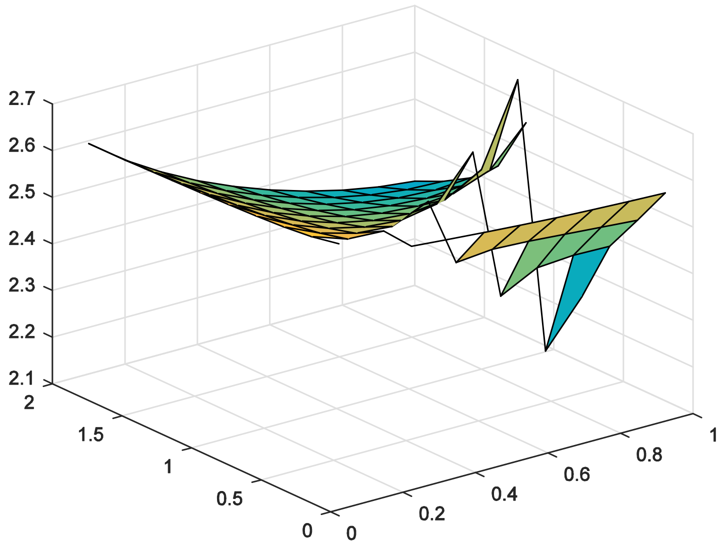

Fig. 5. Government expenditure under different carbon tax policies

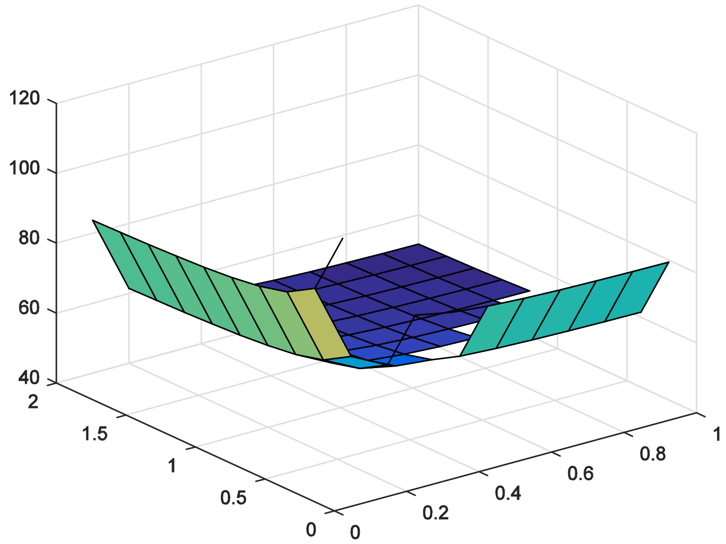

Fig. 6. Total carbon emissions under different carbon tax policies

Using model (5)-(7), we obtain the DEA efficiency scores of all feasible policies respectively in Table 7.

Table 7. DEA efficiency scores of all feasible policies

No.	η_i	No.	η_i	No.	η_i	No.	η_i
1	0.909	**25**	0.508	**49**	0.166	**73**	0.306
2	0.995	**26**	0.505	**50**	0.324	**74**	0.299
3	1.000	**27**	0.500	**51**	0.360	**75**	0.292
4	1.000	**28**	0.496	**52**	0.357	**76**	0.286
5	1.000	**29**	0.492	**53**	0.351	**77**	0.129
6	1.000	**30**	0.223	**54**	0.345	**78**	0.279
7	1.000	**31**	0.428	**55**	0.339	**79**	0.308
8	1.000	**32**	0.435	**56**	0.332	**80**	0.311
9	0.999	**33**	0.434	**57**	0.327	**81**	0.307
10	0.998	**34**	0.430	**58**	0.150	**82**	0.300
11	0.593	**35**	0.425	**59**	0.305	**83**	0.293
12	0.640	**36**	0.420	**60**	0.335	**84**	0.286
13	0.654	**37**	0.415	**61**	0.339	**85**	0.279
14	0.657	**38**	0.410	**62**	0.335	**86**	0.273
15	0.657	**39**	0.189	**63**	0.329	**87**	0.122
16	0.654	**40**	0.351	**64**	0.322	**88**	0.271
17	0.652	**41**	0.385	**65**	0.315	**89**	0.299
18	0.649	**42**	0.390	**66**	0.309	**90**	0.301
19	0.646	**43**	0.388	**67**	0.304	**91**	0.291
20	0.282	**44**	0.382	**68**	0.138	**92**	0.283
21	0.461	**45**	0.377	**69**	0.290	**93**	0.276
22	0.501	**46**	0.371	**70**	0.320	**94**	0.269
23	0.511	**47**	0.365	**71**	0.319	**95**	0.263
24	0.511	**48**	0.360	**72**	0.313		

Table 7 shows the DEA efficiency scores of all 95 feasible policies. It can be found that policy 3, 4, 5, 6, 7 and 8 may all be good choices for the government. Furthermore, much different from the tax policy for one firm that highest tax rate would be chosen, the government would use the strategy to set relatively lower tax rate for one firm and higher tax rate for the other to achieve a comprehensive effect.

6. Conclusions

Policy makers always operate with multiple goals, and a given tax policy may benefit some goals while hinder the others. In this paper, we examine the role the carbon tax policy plays in reducing carbon emissions, increasing government revenue and decreasing government expenditure. In order to select the optimal carbon tax rate that can achieve a comprehensive effect, we regard the problem as multiple criteria decision making problem and use an evaluating method based on centralized DEA approach to solve the problem.

The contribution of this paper can be summarized as follows: we consider multiple goals of a government when making environmental policy decision. In most literature that discuss the government environmental policy, like pollution tax (Krass et al. 2013), green subsidy (Huang et al. 2013, Cohen et al. 2015) and cap-and-trade regulation (Xu et al. 2016), they assume that the government makes policy strategies only considering one goal, i.e., maximize the social warfare or minimize the carbon emissions. While in this paper, we consider government revenue, government expenditure and carbon emissions, and use centralized DEA method to find a most suitable tax rate to achieve comprehensive benefit of the three goals.

Then, we present a three-step decision framework to determine the optimal carbon tax rate for the government. In the first step, we analyze the firms' pricing strategies assuming that the tax rate is given. In the second step, we identify the government three goals and deduce the qualitative estimations to help us understand the conflicts among the three goals. In the last step, we regard the problem as multiple criteria decision making problem and use centralized DEA approach to obtain the optimal carbon tax rate. We use a game-based method to probe into the competition between the ordinary products and the green products, and an equilibrium point is obtained to determine the optimal decisions of the two firms on how to price the products for the maximal profit.

Furthermore, we consider two different cases in this paper. In the first case, we focus on the government carbon tax policy for one firm. We find that the government may set a high tax rate. While in the second case, we expend the current model to focus on the government different policies for two firms. We find that the government would use the strategy to set relatively lower tax rate for one firm and higher tax rate for the other to achieve a comprehensive effect.

We suggest that three possible extensions to our current work are worth investigation. First, some other assumptions e.g. stochastic market demand, multiple companies and multiple types of customers can be considered. Second, the qualitative technique on estimating the values of the three goals can be improved. Third, some other emissions policies e.g. cap-and-trade, mandatory carbon emissions capacity and carbon offsets are meaningful topics for further consideration.

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