Economic Research-Ekonomska Istraživanja

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rero20

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To cite this article: Po-Sheng Ko, Chien-Shu Tsai & Jen-Yao Lee (2023) Does compensative subsidy alleviate pollutant emission and improve welfare under cross-industry pollution?, Economic Research-Ekonomska Istraživanja, 36:1, 2120515, DOI: 10.1080/1331677X.2022.2120515

To link to this article: https://doi.org/10.1080/1331677X.2022.2120515

Published online: 23 Sep 2022.

ECONOMIC RESEARCH-EKONOMSKA ISTRAŽIVANJA
2023, VOL. 36, NO. 1, 2120515
https://doi.org/10.1080/1331677X.2022.2120515

Does compensative subsidy alleviate pollutant emission and improve welfare under cross-industry pollution?

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ABSTRACT

This paper establishes a cross-industry pollution externality model under centralized labor union. In delineating the motivations of a benevolent government, it might be possible to tax part of the welfare gains and use the revenue to compensate the affected polluting industry for the damage costs, thereby improving welfare. We show that the magnitude of marginal pollution plays a critical role. When the marginal pollution is large, the government should tax the pollution firm to reduce the pollution. However, when the marginal pollution is small, the government should subsidize the polluted firm to increase output and enhance consumer surplus.

ARTICLE HISTORY
Received 17 January 2022
Accepted 25 August 2022

KEYWORDS
Production externality; centralized union; emission tax; compensative subsidy

JEL CLASSIFICATIONS
D51; H23; J51; Q58

1. Introduction

Pigou (1924) pointed out that in some cases, it is incorrect to distinguish entrepreneur costs and benefits from total costs and benefits, because not all economic costs and benefits are considered. For example, pollutants will reduce social welfare through external damage, but this does not require any private cost by the polluting firm. Environmental externality problems are usually resolved by using environmental taxes to get prices right and thereby reduce environmental pressures. Pigou (1924) believed that through emission taxes, external costs can be internalized, and social welfare can be improved. This environmental policy has become the central idea of environmental economics.

In particular, the reform of the environmental tax system may produce double dividends: environmental dividends can be obtained by improving the environment, while economic dividends can be obtained by improving the efficiency of the tax system and increasing non-environmental benefits (Goulder, 1995a). Traditionally, discussions on environmental pollution have focused on the negative impact on consumer utilities;

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however, decline in productivity caused by cross-industry pollution has recently received attention. As a result, policy discussions on taxation of the pollution sector or subsidies to the polluted sector have also received widespread attention.

In China, cross-industry pollution has become the focus of environmental problems. For example, PM2.5 of air pollution, causing about 1.37 million premature deaths every year (Liu et al., 2016; Gu et al., 2018; Gu & Yim, 2016). In China, the Pearl River Delta region is one of the fastest growing regions, but it has caused serious air pollution problems and high levels of air pollution emissions, due to its high-intensity energy consumption. Due to the large number of PM2.5 incidents and the resulting public health impact, outdoor PM2.5 pollution causes 20,160 premature deaths each year (Hou et al., 2019).

Since 2005, China's climate policy development has undergone major changes, and it has become increasingly intertwined with domestic policy issues (especially energy security, environment/air pollution and domestic stability) (Torney, 2015). Reducing the intensity of carbon on GDP by 18% has become an updated target in China's 13th Five-Year Plan (FYP) during the plan period (2016–2020), and this is equivalent to reducing the intensity of carbon on GDP by 50% relative to the 2005 benchmark, although the Cancun/Copenhagen Agreements promised a more ambitious 2020 carbon intensity target for China. The 13th FYP also puts forward the goal of maintaining energy consumption at 5 billion tons of standard coal equivalent by 2020, which is more aspiring than the target contained in the 12th FYP (King, 2016; Chen & Stanway, 2016).

In response, China's new central leadership formulated a new economic growth strategy, often referred to as the 'new normal.' This is based on the concept of lower but better quality growth. The new strategy involves the transfer of growth structure to domestic consumption, especially services, and the transfer of investment to more innovative and higher value-added manufacturing and service industries; and focus on environmental sustainability and reducing social inequality (Green & Stern, 2015, 2017). Wen et al. (2022) pointed out the substantial industry heterogeneity in China, CO2 emissions and the major forces driving these emissions may vary in different sub-sectors. Therefore, in addition to environmental policies, how to compensate the environmental damaged sectors and promote economic growth will become important policy objectives (Hall, 2014).

In the literature, environmental tax reform (ETR) can be understood as a package of instruments that combines an increase in natural resource (for example, energy) taxes with a component of income redistribution. The latter may include reducing the burden of the tax in other fields and/or targeted government expenditures to countervail the revenue impact of environmental taxes. It refers to environmental taxes that can reduce pollution (the first dividend), and reduce the overall economic costs associated with the tax system by using the income generated to replace other distorting taxes that also reduce economic growth (the second dividend) (Goulder, 1995a; Bovenberg, 1999). In general, the impacts of ETR will have at least four types, each of which may not be distributed equally throughout society: the price increase for the taxed goods; the impact of revenue recycling; the broader economic impacts of ETR; and its environmental effects (Blobel et al., 2011).

In an ETR transitional economy, intervention by government in the market is usually regarded as a way to promote efficiency. When implementing regulations to improve social welfare, a benevolent government may be inclined to tax a portion of welfare gains and use its income to compensate for the loss of the industry. Cheng et al. (2019) pointed out that the social welfare using emission tax with production subsidy is higher than the one using emission tax only. However, in this paper, we show that the equilibrium of the policy combination of emission tax with production subsidy may not exist, and the social welfare ranking among emission tax, compensative subsidy and emission tax with production subsidy will depend on the magnitude of negative externality under centralized union. Wen et al. (2021) pointed out that emissions trading scheme (ETS) is widely regarded as a cost-effective instrument for curbing global climate change. Nie et al. (2022) showed the identical effects of carbon tax and emission tax under complete information. Wang et al. (2021) analyzed the impact of order financing on green finance and green transition. They showed the efficiency of order financing increases as the government charges carbon taxes. Metcalf (2021) also pointed out the growing empirical literature on the economic impact of carbon taxes.

In this paper, we show that when a combination of emission tax with compensative subsidy is adopted by the government, the compensative subsidy can effectively increase the marginal revenue of the polluted firm and expand the output of the polluted sector, thereby offsetting the productivity losses caused by the pollutant emission. The emission tax coupled with a compensative subsidy will regulate the externalities and raise the social welfare accordingly. Further, we show that if the negative externality of pollution is very large, then the government should charge an emission tax to reduce the output of polluting firm, and via price adjustment to reduce environmental pressures.

The rest of this article is prepared as follows: The literature review is provided in Section 2; Section 3 provides model settings; Section 4 discusses the production decision and wage bargaining; Section 5 discusses the combinations of emission tax and compensative subsidy; Section 6 discusses the welfare ranking among the policy regimes; and finally, a conclusion is provided.

2. Literature review

The main idea of Pigou (1924) is solving environmental externalities by internalizing external costs. The literature revealed that in a competitive market, the optimal emission tax rate should be equal to the marginal damage of pollution. A large number of studies has also focused on the impact of environmental policies under imperfect market competition (see, for example, Simpson, 1995; Katsoulacos & Xepapadeas,1995; Damania, 1996; Yin, 2003; Lahiri & Ono, 2007; Cato, 2010; Fujiwara, 2009; Kato, 2011; Pal, 2012; Ouchida & Goto, 2014; Ikefuji et al., 2016; Hsu et al., 2017; Xu et al., 2016; Ino & Matsumura, 2019; Wang et al., 2021; Nie et al., 2022). However, the above literature lacks environmental policy discussion under cross-industry pollution.

As mentioned above, the issue of an ETR causing double dividends has been analyzed under a static framework in the literature (see, e.g., Ulph, 1992; Bovenberg & van der Ploeg, 1994a, 1994b; Bovenberg & de Mooij, 1994a, 1994b; Oates, 1995; Parry, 1995; Schöb, 1994; Fernández et al., 2011; Schlegelmilch et al., 2016; Böhringer et al., 2019; Aubert & Chiroleu-Assouline, 2019). An intertemporal framework with numerical analysis is used in exogenous growth and endogenous growth (see, e.g., Goulder, 1995b; Proost & van Regemorter, 1995; Bovenberg & de Mooij, 1994a; Jacobs & van der Ploeg, 2010; Radulescu et al., 2017; Costantini & Sforna, 2020). Empirical evidence has shown that pollution can cause severe productivity losses in developing and industrialized countries (see, e.g., Alfsen et al., 1992; Brendemoen & Vennemo, 1994; Ewijk & Wijnbergen, 1995; Williams, 2002; Addo et al., 2013; Neidell, 2017). By modeling the environment as a public consumption product, former analysis of the issues of double dividends has been abstracted from the externalities affecting production. Yang et al. (2021) examined the differences of environment pollution by comparing feed-in tariff (FIT) with renewable portfolio standard (RPS) under uncertainty. Wen et al. (2021) in their empirical study show that the emissions trading scheme (ETS) pilots had significant emission mitigation effects, but their economic benefits have not matched expectations.

In an industry that produces pollutant emissions, harmful externalities will be generated and negatively affect the production processes of other industries. Some studies have mentioned that the marginal product of labor in one industry will be damaged by pollutant emissions from another industry (see, e.g., Copeland & Taylor, 1999; Benarroch & Thille, 2001; Williams, 2002). In a monopolistic model with cross-industry pollution, Bárcena-Ruiz (2011) examined that labor productivity in one industry was damaged by industrial pollution in another industry. However, the above-mentioned studies lack discussion on policy combinations between polluting and polluted sectors. Aubert and Chiroleu-Assouline (2019) studied the distribution and efficiency consequences of environmental tax reforms, which distribute income from green taxes according to different labor tax rates. They found that if the reform seems to be gradual, then the double benefits from dividends can be re-distributed to achieve a Pareto improvement through the non-linear income tax, provided that the initial benefits of the redistribution are not large. Cheng et al. (2019) pointed out that a benevolent government might be able to levy an emission tax on the polluting firm and use the income to compensate the polluted industry, thereby improving welfare; however, they did not consider the impact of the union structure and policy pairs of emission tax and compensative subsidy.

Unionization structures on wage bargaining are mainly classified as follows. Firstly, an individual union sets wage for respective firm, namely decentralization bargaining; secondly, a cross-industry-wide union does wage negotiation with other firms, namely centralization bargaining. Under the wage bargaining games, centralization bargaining usually obtains higher wages owing to better bargaining power; hence, firms prefer decentralization bargaining, while workers like centralization bargaining (see Horn & Wolinsky, 1988; Davidson, 1988).

Bárcena-Ruiz and Garzón (2009) indicated that the government will impose an environmental tax with decentralization bargaining, which achieves higher social welfare than that in the centralization bargaining, but the former makes more massive damage to the environment than the latter. Hoel (1998) analyzed the influence of labor market and environmental policies on employment, and he pointed out that under exogenous wages the environmental tax will lead to higher employment than with non-revenue-raising environmental policies (for example, emission quotas and direct regulation). Hoel (1997) utilized a perfect competition model with cross-border pollution to explore the coordination of environmental policy. He pointed out that policy coordination may not be necessary, which is depended on the wage bargaining between unions and firms.

In this paper, following Bárcena-Ruiz (2011) and Cheng et al. (2019), we consider the centralized wage bargaining model with negative cross-industry externality to explore policy combinations between emission tax and compensation subsidy. In differing from the above literature, this study analyzes policy combinations of the government with four scenarios: no policy, taxation on the polluting firm, subsidization on the damaged firm, and simultaneous use of both of the two policies. In the meanwhile, we discuss the welfare effects among the four scenarios.

3. The model

In the domestic market, there are two monopolistic industries without trade. In the pollution industry, the firm produces with pollutant emission which reduces the marginal productivity of labor in the polluted industry. Assuming the inverse demand functions are respectively as follow:

$$P_k = A - q_k, k = x, y, \tag{1}$$

where A denotes the market scale, P_k and q_k denote the price and the output of industry k.

There is one input; namely, the labor force. Both firms have the same cost function $C = w_k L_k$, where L_k and w_k are the number of employees and the wage of the labor union k respectively. According to Ulph (1996), the polluting firm of industry x (firm x) is producing with efforts in pollution abatement a_x, and the abatement cost is quadratic ${a_x}^2$. A quadratic cost function of abatement effort is used because a decreasing return technology is assumed. In other words, we use a stylized marginal abatement cost curve to reflect the additional costs of reducing the last unit of pollution and is upward-sloping, that is, marginal costs rise with an increase of the abatement effort. Furthermore, the government levies an emission tax with tax rate t on the remaining pollution e_x ($e_x = q_x - a_x$). The government gives an output subsidy s to the firm in the polluted industry y (firm y) in compensation for the pollution damage. The total tax revenue and subsidy payment are te_x and sq_y respectively.

Assume that the profit functions of the polluting firm x and the polluted firm y are respectively, expressed as:

$$\pi_x = P_x q_x - w_x L_x - te_x - {a_x}^2, \tag{2}$$

$$\pi_y = P_y q_y - w_y L_y + sq_y. \tag{3}$$

The emission is assumed additively separable as indicated in David and Sinclair-Desgagné (2005). For example, an investment in end-of-pipe abatement does not modify the production process and so does not affect the amount of pollution attributable to each unit produced. To highlight the cross-industry pollution, we assume that production inefficiency in industry y will be caused by the remaining pollution of industry x. In the presence of cross-industry pollution, the output functions are given $q_x = L_x,\ \ q_y = L_y/(1+\beta e_x)$. Assume $\beta > 0,$ which indicates how the cross-industry pollution affects the labor productivity of industry y. We have $\beta = 0,$ if there are no cross-industry effects (Bárcena-Ruiz, 2011).

Individual industries have their own labor union, however, different from Cheng et al. (2019), we consider that wages are negotiated by a cross-industry-wide labor union and individual firms.

There are two kinds of bargaining between unions and firms: one is right-to-manage bargains (RTM), which is bargaining over wages alone; the other is Efficient Bargaining (EB), which is negotiations also over employment directly (e.g., David & Sinclair-Desgagné, 2005; Nickell & Andrews, 1983; McDonald & Solow, 1981). The bargaining regime is relevant for the labor economics as well as for the industrial organization literature. To simplify the analysis, we assume that the firm and union bargain over wages alone. By following Bárcena-Ruiz (2011), the maximization problems of labor unions are:

$$\max_{\{w_x, w_y\}} U_x + U_y = (w_x - r)L_x + (w_y - r)L_y, \tag{4}$$

where r denotes the reserved wage of the labor.

Moreover, the consumer surplus, the producer profit, the labor union utilities, the tax revenue and subsidy expense are taking into account to the social welfare function as follows:

$$W = CS_x + CS_y + \pi_x + \pi_y + U_x + U_y - sq_y + te_x, \tag{5}$$

where $CS_k = q_k^2/2,\ \ k = x, y,$ is consumer surplus.

Besides, we assume that the decision problem of the government is social welfare maximizing. The environmental policy may have a negotiating stage with other countries (see Carraro & Siniscalco, 1993; Barrett, 1994; Hoel, 1997). The bottom-up approach of the Paris Agreement, using voluntary pledges by countries rather than top-down country or regional commitments, was quite different from the approach used earlier in the climate negotiating process at the (unsuccessful) Conference of the Parties in Copenhagen in 2009 (Falkner, 2016). For simplicity, we focus on the policy combination between emission tax and compensative subsidy in a domestic market without other countries. Ultimately, a three-stage dynamic policy-production game is used to explore the equilibrium. In the first stage, policy combinations on emission tax and/or compensative subsidy by the government are considered. In the second stage, the firms bargain the wage with the centralized union. In the final stage, the outputs are determined by the monopolistic firms. Backward induction is used under the premise of Subgame Perfect Nash equilibrium (SPNE).

4. Production and wage bargaining

4.1. Production decision

In the production stage, the output decisions of the firms are firstly determined. Firm x also performs the abatement of pollution. By the profit-maximum problems, the first-order conditions for the profit-maximum problems are:

$$\frac{\partial \pi_x}{\partial q_x} = A - t - 2q_x - w_x = 0, \tag{6}$$

$$\frac{\partial \pi_x}{\partial a_x} = t - 2a_x = 0, \tag{7}$$

$$\frac{\partial \pi_y}{\partial q_y} = A + s - 2q_y - \left[1 + \beta(q_x - a_x)\right] w_y = 0. \tag{8}$$

From Eqs. (6) to (8), we obtain the response functions of the output and the pollution abatement as follows:

$$q_x = \frac{1}{2}(A - t - w_x), \tag{9}$$

$$q_y = \frac{1}{4}\left[2(A + s - w_y) - \beta(A - w_x - 2t)w_y\right], \tag{10}$$

$$a_x = \frac{t}{2}. \tag{11}$$

Taking differentiation of q_x and q_y with respect to β, t and s yields:

$$\frac{\partial q_x}{\partial \beta} = 0, \tag{12}$$

$$\frac{\partial q_y}{\partial \beta} = -\frac{1}{4}(A - w_x - 2t)w_y < 0, \tag{13}$$

$$\frac{\partial q_x}{\partial t} = -\frac{1}{2} < 0, \tag{14}$$

$$\frac{\partial q_y}{\partial t} = \frac{1}{2}\beta w_y > 0, \tag{15}$$

$$\frac{\partial q_x}{\partial s} = 0, \tag{16}$$

$$\frac{\partial q_y}{\partial s} = \frac{1}{2} > 0. \tag{17}$$

Accordingly, an increase in the negative externalities (β) leads to a decrease in the labor productivity of the polluted industry, and reduces the output of the polluted firm. An increase in emission tax (t) will directly decrease the output of firm x due to the rising marginal cost and will also raise the output of firm y due to the diminishing negative externality. Moreover, an increase in compensative subsidy (s) will directly raise the output of firm y due to the rising marginal revenue.

4.2. Wage bargaining

In the second stage, the response functions of the firms are considered. Substituting the response functions of Eqs. (9)–(11) into Eq. (4), we rewrite the utility of the unions as:

$$U_x = \frac{1}{2}(A - t - r)(w_x - r), \tag{18}$$

$$U_y = \frac{1}{8}[2 + \beta(A - 2t - w_x)]\left[2(A + s - w_y) - \beta(A - w_x - 2t)w_y\right](w_y - r). \tag{19}$$

In the second stage, when the unions negotiate the optimal wage with the firms to maximize their joint utility, the unions operate as a centralized union. Assuming the union has full bargaining power, the wages are set by the union and the firms choose a take-it-or-leave-it market. (see Mukherjee & Pennings, 2011; Bárcena-Ruiz, 2011)

To decide the bargaining wages of centralized union in the second stage game, we obtain:

$$\begin{aligned}\frac{\partial(U_x + U_y)}{\partial w_x} = \frac{1}{4}\Big(&2(A + r - t) + r(A + s)\beta - \beta\big(A + 2r + s + r(A - 2t)\beta\big)w_y \\ &+ \beta(2 + A\beta - 2t\beta)w_y^2 + w_x\Big(-4 + \beta^2(r - w_y)w_y\Big)\Big) = 0,\end{aligned} \tag{20}$$

$$\begin{aligned}\frac{\partial(U_x + U_y)}{\partial w_y} = \frac{1}{8}&(2 + A\beta - 2t\beta - \beta w_x)(2(A + r + s) \\ &+ r(A - 2t)\beta - \beta w_x(r - 2w_y) - 2(2 + A\beta - 2t\beta)w_y\big) = 0.\end{aligned} \tag{21}$$

Thus, the optimal bargaining wages can be derivable as:

$$w_x = A - 2t + \frac{s + 3t}{4 - r\beta} - \frac{2A - 2r + s - 3t}{4 + r\beta}, \tag{22}$$

$$w_y = \frac{8(A + r + s) + 2r(A - r - 3t)\beta - r^2(A + s)\beta^2}{16 + 4(A - r - 3t)\beta - r(A + s)\beta^2}. \tag{23}$$

By taking partial differentiation of the wages with respect to β and evaluating it at the point without policy, that is, $t = s = 0,$ we obtain:

$$\frac{\partial w_x}{\partial \beta}|_{t=s=0} = \frac{2(A-r)r}{(4+r\beta)^2} > 0, \tag{24}$$

$$\frac{\partial w_y}{\partial \beta}|_{t=s=0} = \frac{-2A(A-r)}{(4+A\beta)^2} < 0, \tag{25}$$

Accordingly, from Eqs. (24) and (25), the wage of the polluted sector will decrease due to the externalities of the polluting sector damaging the productivity of the polluted sector. In the meanwhile, the wage of the polluting sector will increase due to the relatively high productivity of the polluting sector. Furthermore, considering the impact of emission tax and compensative subsidy, we take partial differentiation of the wages (w_x and w_y) with respect to t and $s,$ we have:

$$\frac{\partial w_x}{\partial t} = -\frac{2(4-r^2\beta^2)}{(4-r\beta)(4+r\beta)} < 0, \tag{26}$$

$$\frac{\partial w_y}{\partial t} = \frac{6(A+s)\beta(16-r^2\beta^2)}{(16+4(A-r-3t)\beta-r(A+s)\beta^2)^2} > 0, \tag{27}$$

$$\frac{\partial w_x}{\partial s} = \frac{2r\beta}{16-r^2\beta^2} > 0, \tag{28}$$

$$\frac{\partial w_y}{\partial s} = \frac{2(4-(A-r-3t)\beta)(16-r^2\beta^2)}{(16+4(A-r-3t)\beta-r(A+s)\beta^2)^2} > 0. \tag{29}$$

As mentioned above, due to the negative externalities of the polluting sector damaging the productivity of the polluted sector, the wage of the polluted sector will decline. An emission tax will reduce the output of the polluting sector and raise the productivity of the polluted sector. The labor demand of the polluting sector falls and the labor demand of the polluted sector rises. Hence, the wage of the polluting sector will decrease with the size of emission tax, however, the wage of the polluted sector will increase with the size of emission tax. In addition, as emission tax increases, total output and consumer surplus will decline since the emission tax leads to raising the marginal costs of the polluted firm.

In particular, different from Cheng et al. (2019), a compensative subsidy will increase the output and thus the derived demand of the polluted firm due to the decentralized union structure. A compensative subsidy will raise the output of the polluted firm, and the labor demand of the polluted sector and lead to the higher total labor demand in a centralization union. Hence, the compensative subsidy increases both the wages of the polluting sector and the polluted sector in a centralized union. In addition, as compensative subsidy increases, total output and consumer surplus will increase since the compensative subsidy leads to raising the marginal revenue of the polluted firm.

According to the above mentioned, we have Lemma 1.

Lemma 1. *The wages of the polluting sector and the polluted sector in a centralized union increase with the size of compensative subsidy.*

Substituting Eqs. (22) and (23) into Eqs. (2)–(4), we have:

$$\pi_x = \frac{\begin{array}{c}32\left(A^2+r^2+2rt+5t^2-2A(r+t)\right)-16r(A-r+s)(A-r-t)\beta \\ +2r^2((A-r+s)^2-4(A-r)t-4t^2)\beta^2+2r^3(A-r+s)t\beta^3+r^4t^2\beta^4\end{array}}{2(16-r^2\beta^2)^2}, \tag{30}$$

$$\pi_y = \frac{(4(A-r+s)-r(A-r-3t)\beta)^2}{(16-r^2\beta^2)^2}, \tag{31}$$

$$U_x = \frac{(8(A-r-t)+2r(A-r+s)\beta-r^2(A-r-2t)\beta^2)(8(A-r-t)-2r(A-r+s)\beta-r^2t\beta^2)}{2(16-r^2\beta^2)^2}, \tag{32}$$

$$U_y = \frac{2(4(A-r+s)-r(A-r-3t)\beta)^2}{(16-r^2\beta^2)^2}. \tag{33}$$

Taking differentiation of π_x, π_y, U_x and U_y with respect to t and s, we obtain:

$$\frac{\partial U_x}{\partial t} = \frac{(-128+16r^2\beta^2)(A-r-t)-6r^3(A-r+s)\beta^3+r^4(A-r-4t)\beta^4}{2(16-r^2\beta^2)^2} < 0, \tag{34}$$

$$\frac{\partial U_y}{\partial t} = \frac{12r\beta(4(A-r+s)-r(A-r-3t)\beta)}{(16-r^2\beta^2)^2} > 0, \tag{35}$$

$$\frac{\partial U_x}{\partial s} = -\frac{r^2\beta^2(4(A-r+s)-r(A-r-3t)\beta)}{(16-r^2\beta^2)^2} < 0, \tag{36}$$

$$\frac{\partial U_y}{\partial s} = \frac{16(4(A-r+s)-r(A-r-3t)\beta)}{(16-r^2\beta^2)^2} > 0, \tag{37}$$

$$\frac{\partial \pi_x}{\partial t} = \frac{32(r+5t)-A(4-r\beta)(8+r^2\beta^2)+r\beta(8s+r(-8+\beta(-8t+r(4+s\beta+r\beta(-1+t\beta)))))}{(16-r^2\beta^2)^2} < 0, \tag{38}$$

$$\frac{\partial \pi_y}{\partial t} = \frac{6r\beta(4(A-r+s)-r(A-r-3t)\beta)}{(16-r^2\beta^2)^2} > 0, \tag{39}$$

$$\frac{\partial \pi_x}{\partial s} = \frac{-r\beta(8(A-r-t) - 2r(A-r+s)\beta - r^2 t\beta^2)}{(16-r^2\beta^2)^2} < 0, \tag{40}$$

$$\frac{\partial \pi_y}{\partial s} = \frac{8(4(A-r+s) - r(A-r-3t)\beta)}{(16-r^2\beta^2)^2} > 0. \tag{41}$$

Suppose there exist a positive emission tax and a compensative subsidy, then an increase in emission tax and compensative subsidy will decrease both the profit of the firm and the utility of the union in the polluting industry. The main reason is that an emission tax will increase the emission cost of the polluting firm and a compensative subsidy will raise the wage paid to the labor of the polluting firm, which may lead to a low output of the firm and a low labor demand in the industry. Therefore, the profit of the polluting firm and the utility of the union in the polluting industry will decline with the emission tax and compensative subsidy.

However, a greater emission tax and compensative subsidy may increase the profit of the polluted firm and the utility of the polluted union, since an emission tax decreases the output of the polluting firm and raises the productivity of the labor in the polluted firm, and a compensative subsidy, on the other hand, increases the marginal revenue of the polluted firm.

5. Emission tax and compensative subsidy

In differing from the previous literature, this study analyzes policy combinations of the government with four scenarios: no policy, taxation on the polluting firm, subsidization on the damaged firm, and simultaneous adopting both the two policies as follows. In the meanwhile, we discuss the welfare effects among the four scenarios.

5.1. No policy

Firstly, we consider the equilibrium without emission tax and compensative subsidy under centralized union, that is, $t = 0$ and $s = 0$, then we have the following lemma immediately.

Lemma 2. *The equilibrium outcomes without policy*

$$q_x^{NN} = \frac{A-r}{4+r\beta}, \tag{42}$$

$$q_y^{NN} = \frac{A-r}{4+r\beta}, \tag{43}$$

$$a_x^{NN} = 0, \tag{44}$$

$$e_x^{NN} = \frac{A-r}{4+r\beta}, \tag{45}$$

$$\pi_x^{NN} = \frac{(A-r)^2}{(4+r\beta)^2}, \tag{46}$$

$$\pi_y^{NN} = \frac{(A-r)^2}{(4+r\beta)^2}, \tag{47}$$

$$w_x^{NN} = \frac{A(2+r\beta)+2r}{4+r\beta}, \tag{48}$$

$$w_y^{NN} = r + \frac{2(A-r)}{4+A\beta}, \tag{49}$$

$$U_x^{NN} = \frac{(A-r)^2(2+r\beta)}{(4+r\beta)^2}, \tag{50}$$

$$U_y^{NN} = \frac{2(A-r)^2}{(4+r\beta)^2}, \tag{51}$$

$$CS^{NN} = \frac{(A-r)^2}{(4+r\beta)^2}, \tag{52}$$

$$W^{NN} = \frac{(A-r)^2(7+r\beta)}{(4+r\beta)^2}. \tag{53}$$

The superscript '*NN*' indicates the equilibrium without environmental policy and compensative subsidy. According to Lemma 2, we know that if $A > r$, there is a unique equilibrium without environmental policy and compensative subsidy.

5.2. Emission tax without compensative subsidy

Secondly, following Bárcena-Ruiz (2011), we consider the scenario of emission tax without compensative subsidy in the policy stage game, that is, $s = 0$. By substituting Eqs. (22) and (23) into Eq. (5), and solving the welfare maximization problem of the government, we obtain:

$$t^{TN} = \frac{2(A-r)(4-r\beta)^2(-6+r\beta(7+r\beta))}{576-300r^2\beta^2+3r^4\beta^4} \tag{54}$$

The superscript '*TN*' indicates the equilibrium of emission tax without compensative subsidy. We have a positive pollution of the polluting firm, if $r\beta < 1.1122$. There is a positive output tax, if $r\beta > 0.7720$. We assume that there is a non-negative constraint on the emission tax. If $r\beta < 0.7720$, we have $t^{TN} = 0$.

Due to the externalities of the firm x, the productivity of the firm y will decline. Therefore, the larger the externality, the lower the wage of the polluted sector. For a given emission tax, the centralized union has the incentive to set a higher wage in the polluting sector to reduce the negative externalities on the polluted sector.

Taking differentiation of t^{TN} with respect to β, we obtain:

$$\frac{\partial t^{TN}}{\partial \beta} = \frac{2(A-r)r(4-r\beta)(7680-r\beta(7296-r\beta(2032-r\beta(796-r\beta(104-r\beta)))))}{3(192-100r^2\beta^2+r^4\beta^4)^2} > 0. \tag{55}$$

Eq. (55) shows that a higher externality of production will lead to a higher emission tax levied by the government. The reason is that the greater the negative externality, the larger the damage on the productivity of the polluted industry, hence, the government has to impose a relatively high emission tax rate to regulate the output of the polluting firm and reduce the damage.

Accordingly, from Eq. (55), we have Lemma 3 immediately.

Lemma 3. *The equilibrium outcomes of emission tax policy without compensative subsidy*

$$q_x^{TN} = \frac{(A-r)(6-r\beta)(32-r\beta(14+r\beta(8+r\beta)))}{576-300r^2\beta^2+3r^4\beta^4}, \tag{56}$$

$$q_y^{TN} = \frac{(A-r)(48-r\beta(24+r\beta(2+r\beta)))}{192-100r^2\beta^2+r^4\beta^4}, \tag{57}$$

$$a_x^{TN} = \frac{(A-r)(4-r\beta)^2(-6+r\beta(7+r\beta))}{576-300r^2\beta^2+3r^4\beta^4}, \tag{58}$$

$$e_x^{TN} = \frac{(A-r)(96+r\beta(-92+r\beta(4+r\beta)))}{192-100r^2\beta^2+r^4\beta^4}, \tag{59}$$

$$\pi_x^{TN} = \frac{(A-r)^2(46080+r\beta(-75264+r\beta(34832+r\beta(-5872+r\beta(2680+r\beta(44+r\beta(-155+2r\beta(1+r\beta))))))))}{9(192-100r^2\beta^2+r^4\beta^4)^2}, \tag{60}$$

$$\pi_y^{TN} = \frac{(A-r)^2(-48+r\beta(24+r\beta(2+r\beta)))^2}{(192-100r^2\beta^2+r^4\beta^4)^2}, \tag{61}$$

$$w_x^{TN} = \frac{A(2+r\beta)(192-140r\beta-r^3\beta^3)+2r(96+r\beta(44+r\beta(-80+r\beta(1+2r\beta))))}{576-300r^2\beta^2+3r^4\beta^4}, \tag{62}$$

$$w_y^{TN} = \frac{2r(48 - r\beta(24 + r\beta(2 + r\beta))) + A(96 + r\beta(48 + r\beta(-96 + r\beta(2 + r\beta))))}{192 + \beta(-4r(24 + r\beta(2 + r\beta)) + A(96 + r\beta(-92 + r\beta(4 + r\beta))))}, \tag{63}$$

$$U_x^{TN} = \frac{(A - r)^2(6 - r\beta)(2 + r\beta)(-192 + 140r\beta + r^3\beta^3)(-32 + r\beta(14 + r\beta(8 + r\beta)))}{9(192 - 100r^2\beta^2 + r^4\beta^4)^2}, \tag{64}$$

$$U_y^{TN} = \frac{2(A - r)^2(-48 + r\beta(24 + r\beta(2 + r\beta)))^2}{(192 - 100r^2\beta^2 + r^4\beta^4)^2}, \tag{65}$$

$$CS^{TN} = \frac{(A - r)^2(57600 + r\beta(-65280 + r\beta(3856 + r\beta(8656 + r\beta(1544 + r\beta(-332 + r\beta(-55 + r\beta(4 + r\beta))))))))}{18(192 - 100r^2\beta^2 + r^4\beta^4)^2}, \tag{66}$$

$$W^{TN} = \frac{(A - r)^2(540 + r\beta(5 + r\beta)(-60 + r\beta(-1 + r\beta)))}{6(192 - 100r^2\beta^2 + r^4\beta^4)}. \tag{67}$$

According to Eqs. (60)–(61) (64)–(67), and (54), we have Proposition 1.

Proposition 1. If $0.7720 < r\beta < 1.1122$, there is a positive emission tax that raises the firm's profit and union utility in the polluted sector and the social welfare, whereas it causes harm to the consumer surplus, the firm's profit and union utility in the polluting sector.

As mentioned above, due to the externalities of the polluting sector damaging the productivity of the polluted sector, the wage(s) in the polluted sector will decline. In particular, there exist two types of distortions: pollutant emissions from firm x which damage the productively of the polluted sector and the underproduction associated with the exercise of market power of the monopolistic firm. The emission tax reduces the damage caused by firm x, leads to a reduction of the firm's production, and thereby hurts the consumer surplus; hence, the government will set an emission tax, t^{TN}, which is lower than marginal damage to avoid an excessive reduction of the output of firm x and enhance the consumer surplus. Therefore, when $r\beta < 1.1122$, the degree to which the marginal product of labor in firm y harmed by emissions from firm x is low enough.

As a result, the second distortion has a greater effect than the first one and the government does not set an emission tax. By contrast, when $r\beta > 0.7720$, the government sets a positive emission tax since the marginal damage caused by firm x is high enough.

5.3. Compensative subsidy without emission tax

Thirdly, we solve the optimal compensative subsidy without emission tax in the policy stage game, that is, $t = 0$. By substituting Eqs. (22) and (23) into Eq. (5), and solving the social welfare maximization problem, we obtain the optimal subsidy as:

$$s^{NS} = \frac{3(A-r)(4-r\beta)^2}{16 - 7r^2\beta^2} \tag{68}$$

The superscript '*NS*' indicates the equilibrium of compensative subsidy without emission tax under centralized union. The pollution of the polluting firm is non-negative, if $r\beta \le 1$.

Due to the externalities of the polluting sector, the labor productivity of the polluted firm y is lower. Therefore, when the externality is larger, the wage of the polluted sector is lower. Moreover, for a given compensative subsidy, the centralized union would have the incentive to set higher wages in the polluting sector to reduce the negative externalities of the polluted sector. Therefore, the compensative subsidy should be positive in order to increase the output of the polluted firm due to the increase of the marginal revenue.

Then, we take differentiation of s^{NS} with respect to β, and obtain:

$$\frac{\partial s^{NS}}{\partial \beta} = -\frac{24(A-r)r(4-r\beta)(4-7r\beta)}{(16-7r^2\beta^2)^2} > 0, \text{ if } r\beta > 0.5714 \tag{69}$$

Eq. (69) points out that an increase in the negative externalities causes an increase in the compensative subsidy which is subsidized to the polluted firm. The reason is a greater externality of production leads to a higher damage on the labor productivity of the polluted firm y. Hence, the government has to impose a high compensative subsidy to raise the output of the polluted firm.

Thus, from Eq. (68), we have Lemma 4.

Lemma 4. *The equilibrium outcomes of compensative subsidy policy without emission tax*

$$q_x^{NS} = \frac{4(A-r)(1-r\beta)}{16 - 7r^2\beta^2}, \tag{70}$$

$$q_y^{NS} = \frac{(A-r)(16-7r\beta)}{16 - 7r^2\beta^2}, \tag{71}$$

$$a_x^{NS} = 0, \tag{72}$$

$$e_x^{NS} = \frac{4(A-r)(1-r\beta)}{16 - 7r^2\beta^2}, \tag{73}$$

$$\pi_x^{NS} = \frac{16(A-r)^2(1-r\beta)^2}{(16-7r^2\beta^2)^2}, \tag{74}$$

$$\pi_y^{NS} = \frac{(A-r)^2(16-7r\beta)^2}{(16-7r^2\beta^2)^2}, \tag{75}$$

$$w_x^{NS} = A - \frac{8(A-r)(1-r\beta)}{16-7r^2\beta^2}, \tag{76}$$

$$w_y^{NS} = r + \frac{2(A-r)(16-7r\beta)}{16+4A\beta(1-r\beta)-r\beta(4+3r\beta)}, \tag{77}$$

$$U_x^{NS} = \frac{4(A-r)^2(8+r^2\beta^2(15-7r\beta))}{(16-7r^2\beta^2)^2}, \tag{78}$$

$$U_y^{NS} = \frac{2(A-r)^2(16-7r\beta)^2}{(16-7r^2\beta^2)^2}, \tag{79}$$

$$CS^{NS} = \frac{(A-r)^2(272+r\beta(256-65r\beta))}{2(16-7r^2\beta^2)^2}, \tag{80}$$

$$W^{NS} = \frac{(A-r)^2(23-14r\beta)}{2(16-7r^2\beta^2)}. \tag{81}$$

Furthermore, according to Eq. (68) (74)–(75), and (78)–(81), we have Proposition 2.

Proposition 2. If $r\beta < 1$, there exists a positive compensative subsidy that increases the consumer surplus, union utility and the firm's profit in the polluted sector, and the social welfare, but causes harm to the union utility and firm's profit in the polluting sector.

5.4. Emission tax with compensative subsidy

In this subsection, we consider emission tax and compensative subsidy in the policy stage game. Substituting Eqs. (22) and (23) into Eq. (5), and solving the welfare optimization problem, we have:

$$t^{TS} = \frac{(A-r)(r\beta(22-7r\beta)-6)}{18-23r^2\beta^2}, \tag{82}$$

$$s^{TS} = \frac{(A-r)(108-r\beta(78-r\beta(4+5r\beta)))}{2(18-23r^2\beta^2)}. \quad (83)$$

The superscript '*TS*' indicates the equilibrium of emission tax with subsidy under centralized union. Consequently, the pollution of the polluted firm is positive, if $r\beta < 0.4530$. There is a positive emission tax, if $r\beta > 0.3016$. A non-negative constraint is imposed on the emission tax. However, if $r\beta < 0.3016$, we have $t^{TS} = 0$ and $s^{TS} = s^{NS}$.

Accordingly, from Eqs. (82) and (83), we have Lemma 5.

Lemma 5. *The equilibrium outcomes of emission tax with compensative subsidy*

$$q_x^{TS} = \frac{(A-r)(6-r\beta(10+r\beta))}{18-23r^2\beta^2}, \quad (84)$$

$$q_y^{TS} = \frac{6(A-r)(3-2r\beta)}{18-23r^2\beta^2}, \quad (85)$$

$$a_x^{TS} = \frac{(A-r)(r\beta(22-7r\beta)-6)}{36-46r^2\beta^2}, \quad (86)$$

$$e_x^{TS} = \frac{(A-r)(18-r\beta(42-5r\beta))}{36-46r^2\beta^2} > 0, \text{ if } r\beta < 0.4530, \quad (87)$$

$$\pi_x^{TS} = \frac{(A-r)^2(180-r\beta(744-r\beta(920-r\beta(228-53r\beta))))}{4(18-23r^2\beta^2)^2}, \quad (88)$$

$$\pi_y^{TS} = \frac{36(A-r)^2(3-2r\beta)^2}{(18-23r^2\beta^2)^2}, \quad (89)$$

$$U_x^{TS} = \frac{2(A-r)^2(1+r\beta)(6-7r\beta)(6-r\beta(10+r\beta))}{(18-23r^2\beta^2)^2}, \quad (90)$$

$$U_y^{TS} = \frac{72(A-r)^2(3-2r\beta)^2}{(18-23r^2\beta^2)^2}, \quad (91)$$

$$W^{TS} = \frac{(A-r)^2(54-r\beta(48+7r\beta))}{72-92r^2\beta^2} \quad (92)$$

According to the above mentioned, we have Proposition 3.

Proposition 3. If $0.3016 < r\beta < 0.4530$, a positive emission tax and a positive compensative subsidy both increase the union utility and firm's profit in the polluted

Table 1. The equilibrium and $r\beta$ space.

$r\beta$ Regime	0 ~ 0.3016	0.3016 ~ 0.4530	0.4530 ~ 0.7720	0.7720 ~ 1	1 ~ 1.1122
TN		$t^{TN}=0$ $e^{TN}=e^{NN}=\frac{A-r}{4+r\beta}$		$t^{TN}=\frac{2(A-r)(4-r\beta)^2(-6+r\beta(7+r\beta))}{576-300r^2\beta^2+3r^4\beta^4}$ $e^{TN}=\frac{(A-r)(96+r\beta(-92+r\beta(4+r\beta)))}{192-100r^2\beta^2+r^4\beta^4}$	
NS			$s^{NS}=\frac{3(A-r)(4-r\beta)^2}{16-7r^2\beta^2}$ $e^{NS}=\frac{4(A-r)(-1+r\beta)}{-16+7r^2\beta^2}$		NA
TS	$t^{TS}=0$ $s^{TS}=s^{NS}$	$t^{TS}=\frac{(A-r)(r\beta(22-7r\beta)-6)}{18-23r^2\beta^2}$ $s^{TS}=\frac{(A-r)(108-r\beta(78-r\beta(4+5r\beta)))}{2(18-23r^2\beta^2)}$ $e^{TS}=-\frac{(A-r)(18+r\beta(-42+5r\beta))}{-36+46r^2\beta^2}$	NA	NA	NA

Source: Authors.

sector and the social welfare, and enhance the consumer surplus, the union utility and firm's profit in the polluting sector

6. Discussion

We summarize the various policy regimes in the different parameters ($r\beta$) space in Table 1. If the negative externality of industry x is extremely large ($r\beta > 1.1122$), there is no environmental policy that ensures the output and pollution emission of the polluting firm x is positive. In other words, the polluting firm x will be driven out of the market, if the degree of negative externality is extremely large.

If the negative externality of industry x is very large ($1 < r\beta < 1.1122$), the equilibrium of a compensative subsidy does not exist. The welfare maximization policy is imposing an emission tax on the polluting firm to reduce the pollution and raise the social welfare. We have $e^{TN} < e^{NN}$ due to the government's imposing an emission tax.

If the negative externality of industry x is relatively large ($0.4530 < r\beta < 1$), comparing the social welfare and pollutant between two policy combinations under centralized union, we obtain:

$$W^{NS}-W^{TN}=\frac{(A-r)^2(4-r\beta)^2(288-r\beta(60+r\beta(178-7r\beta(6+r\beta))))}{6(16-7r^2\beta^2)(192-100r^2\beta^2+r^4\beta^4)}, \tag{93}$$

$$e^{NS}-e^{TN}=(A-r)\left(\frac{4-4r\beta}{16-7r^2\beta^2}-\frac{96+r\beta(-92+r\beta(4+r\beta))}{192-100r^2\beta^2+r^4\beta^4}\right). \tag{94}$$

By (i) due to the fact that $0.7720 < r\beta < 1$, we have $W^{NS} > W^{TN}$ and $e^{NS} < e^{TN}$. (ii) if $0.4530 < r\beta < 0.7720$, we have $t^{TN}=0$, $W^{TN}=W^{NN}$ and $e^{TN}=e^{NN}$. (iii) due to the interior solution of compensative subsidy, we have $W^{NS} > W^{NN}$ and $e^{NS} <$

e^{NN}. From (i) to (iii), we obtain $W^{NS} > W^{TN} = W^{NN}$ and $e^{NS} < e^{TN} = e^{NN}$, if $0.4530 < r\beta < 1$. Consequently, the best policy is imposing a compensative subsidy on the polluted firm y to raise both the output and the social welfare.

If the negative externality of industry x is relatively small ($0.3016 < r\beta < 0.4530$), comparing the social welfare and pollutant between two policy combinations under centralized union, we obtain that:

$$W^{NS} - W^{TS} = -\frac{(A-r)^2(6 + r\beta(-22 + 7r\beta))^2}{4(288 - 494r^2\beta^2 + 161r^4\beta^4)}, \tag{95}$$

$$e^{NS} - e^{TS} = \frac{(A-r)(-24 + 5r^2\beta^2)(6 + r\beta(-22 + 7r\beta))}{576 - 988r^2\beta^2 + 322r^4\beta^4}. \tag{96}$$

Due to the fact that $0.3016 < r\beta < 0.4530$, we have $W^{NS} < W^{TS}$ and $e^{NS} > e^{TS}$. The best policy is imposing an emission tax on the polluting firm and subsidizing a compensative subsidy on the polluted firm.

If the negative externality of industry x is very *small* ($r\beta < 0.3016$), we have $t^{TS} = 0$, $s^{TS} = s^{NS}$, $W^{NS} = W^{TS}$ and $e^{NS} = e^{TS}$. The policy pair of emission tax and compensative subsidy degenerate to a single compensative subsidy policy; the best policy is to impose a compensative subsidy on the polluted firm.

From the above analysis, we have the following proposition immediately.

Proposition 4. From the points of welfare maximization and pollutant minimization, if the negative externality of industry x is very large ($1 < r\beta < 1.1122$), the best policy is emission tax; if the negative externality of industry x is relatively large ($0.4530 < r\beta < 1$), the best policy is compensative subsidy; if the negative externality of industry x is relatively small ($0.3016 < r\beta < 0.4530$), the best policy is emission tax with compensative subsidy; and if the negative externality of industry x is very small ($r\beta < 0.3016$), the best policy is compensative subsidy.

With a negative production externality, an emission tax and a compensative subsidy could be imposed on the polluting and polluted sectors respectively, which is different from the case of emission tax without compensative subsidy under centralized union.

The economic intuition of Proposition 4 is that the emission tax reduces the output of polluting firm, harms consumer surplus, and worsens employment. Although the pollution tax reduces pollution, it causes high social costs.

The advantages of compensating for damaged sectors can be emphasized again. When a combination of emission tax with compensative subsidy is adopted by the government, the compensative subsidy can effectively increase the marginal revenue of the polluted firm and expand the output of the polluted sector, thereby offsetting the productivity losses caused by the pollutant emission. The emission tax can effectively reduce the output and pollutant emission of the polluting firm and increase the productivity of the polluted sector, thereby leading to an increase in the output of the polluted sector.

Based on the above analysis, we see that the emission tax rate will always be positive, accompanied by a compensative subsidy. The production creates a negative externality that damages the polluted sector and leads to lower market output. The emission tax coupled with a compensative subsidy will regulate the externalities and raise the social welfare accordingly.

Finally, we compare the pollutant emission among different regime, and it is not surprising, if the negative externality of pollution is very large, that the government will use an emission tax to reduce the output of the polluting firm, to get prices right and thereby reduce environmental pressures. However, if the negative externality of pollution is relatively large, the emission tax policy and compensative subsidy policy are both available and comparable. It is surprising that the pollutant emission under compensative subsidy is lower than the one under emission tax. The intuition of these findings is as follows. Since the compensative subsidy raises the marginal revenue of the polluted firm, from lemma 1, a compensative subsidy will raise the total labor demand, and both the wages of the polluting sector and the polluted sector are increasing with the compensative subsidy in a centralized union. As mentioned in Bárcena-Ruiz (2011), in a centralized union, the union internalizes the damage caused by the polluting firm and raises the wage of the polluting firm to reduce the negative externality. With the same intuition, a compensative subsidy imposed on the polluted firm in a centralized union increases not only its own labor demand but also the whole labor market and causes a wage increase in the polluting sector, thereby decreasing the output of the polluting firm. This is different from the framework in Cheng et al. (2019) in which a compensative subsidy imposed on the polluting firm in a decentralized union will not cause a decrease in its output.

7. Conclusion

In mid-July 2014, the EEA issued a report, arguing that ‘green fiscal’ reforms can boost employment while protecting the environment, such as reducing taxes on labor. In turn, tax is imposed on industries that damage the environment. Hans Bruyninckx, executive director of the Environment Agency, said well-designed environmental taxes can reduce pollution and increase resource efficiency in a very cost-effective way, and at the same time promote employment, economic growth and social fairness (Hall, 2014). This paper utilizes a cross-industry pollution externality model to show that it might be able to levy an emission tax on the polluting firm and use the income to compensate the polluted industry, thereby improving total welfare.

We have the following conclusions: To achieve welfare maximization, firstly, if the negative externality of industry x is very large, the best policy is emission tax; secondly, if the negative externality of industry x is relatively large, the best policy is compensative subsidy; thirdly, if the negative externality of industry x is relatively small, the best policy is emission tax with compensative subsidy; and finally, if the negative externality of industry x is very small, the best policy is compensative subsidy. However, if the negative externality of pollution is relatively large and the

Table 2. Welfare ranking in different $r\beta$ spaces.

$r\beta$ Regime	0 ~ 0.3016	0.3016 ~ 0.4530	0.4530 ~ 0.7720	0.7720 ~ 1	1 ~ 1.1122
Welfare Maximization Regime	NS	TS	NS	NS	TN
Welfare Compare	$W^{NS} = W^{TS} > W^{TN} = W^{NN}$	$W^{TS} > W^{NS} > W^{TN} = W^{NN}$	$W^{NS} > W^{TN} = W^{NN}$	$W^{NS} > W^{TN}$	$W^{TN} > W^{NN}$
Pollutant Minimization Regime	NS	TS	NS	NS	TN
Pollutant Compare	$e^{NS} < e^{NN}$	$e^{TS} < e^{NS} < e^{NN}$	$e^{NS} < e^{NN}$	$e^{NS} < e^{TN} < e^{NN}$	$e^{TN} < e^{NN}$

Source: Authors.

emission tax policy and compensative subsidy policy are both available, the pollutant emission under compensative subsidy is lower than the one under emission tax.

Our findings complement the results of Bárcena-Ruiz (2011) and Cheng et al. (2019). With negative cross-industry externality, a positive emission tax may still be imposed; however, the advantages of compensating for damaged sectors have been emphasized in our framework. A negative externality created by the polluting firm damages the productivity of the polluted sector, and an incomplete market structure leads to lower market output through emission tax. Therefore, the implementation of emission tax with compensatory subsidy will correct these distortions, meanwhile enhancing consumer surplus and raise social welfare. More importantly, the magnitude of negative externality plays a critical role. When the negative externality is sufficiently large, the government should tax the firm to reduce the pollution of the polluting sector. However, when the negative externality is sufficiently small, the government should subsidize the polluted firm to increase output and enhance consumer surplus.

Our results echo 'green fiscal' reforms, the emission tax coupled with a compensative subsidy will regulate the externalities to get prices right and thereby reduce environmental pressures, and raise the social welfare accordingly (Tables 1 and 2).

Disclosure statement

No potential conflict of interest was reported by the authors.

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