Combining emissions trading and emissions taxes in a multi-objective world

Lehmann, Paul

Helmholtz Centre for Environmental Research - UFZ Leipzig

April 2010

HELMHOLTZ
ZENTRUM FÜR
UMWELTFORSCHUNG
UFZ

UFZ-Diskussionspapiere

Department of Economics

4/2010

Combining Emissions Trading and Emissions Taxes in a Multi-objective World

Paul Lehmann

April 2010

Herausgeber:
Helmholtz-Zentrum für Umweltforschung GmbH - UFZ
Permoserstr. 15
04318 Leipzig

ISSN 1436-140X

Combining Emissions Trading and Emissions Taxes in a Multi-objective World

Paul Lehmann

April 2010

Helmholtz-Centre for Environmental Research – UFZ
Department of Economics
Permoserstr. 15
04318 Leipzig, Germany
paul.lehmann@ufz.de

Combining Emissions Trading and Emissions Taxes in a Multi-objective World

Abstract:

The combination of emissions trading and emissions taxes is usually rejected as redundant or inefficient. This conclusion is based on the restrictive assumption that both policies are exclusively meant to control pollution. However, particularly taxes may pursue a variety of other policy objectives as well, such as raising fiscal revenues or promoting equity. Multiple objectives may justify multiple policies. In this case, welfare losses with respect to pollution control may be traded off by benefits from attaining other policy objectives. Consequently, pragmatic policy recommendations have to be based on an in-depth understanding of interactions in the policy mix. This article makes three contributions that are relevant in this respect. (1) The most important factors distorting pollution abatement under the policy mix are identified. This insight is required to estimate the actual extent of inefficiency in controlling pollution, and to compare it with benefits of attaining other objectives of the tax. (2) The policy mix is not only compared to the unrealistic ideal of an efficient single emissions trading scheme but also to a suboptimal heterogeneous emissions tax. It is shown that if the tax is required to address multiple policy objectives, the implementation of an emissions trading scheme in addition may in fact increase the efficiency of pollution control. (3) It is demonstrated that welfare losses can be minimized within a policy mix by modifying emissions trading design.

Keywords: policy mix, emissions trading, emissions tax, efficiency

JEL Codes: H23, H32, Q58

1 Introduction

Emissions trading and emissions taxes are usually understood as alternatives for pollution control. Considerable efforts have been invested to study under which conditions quantity controls should be preferred to price controls and vice versa (see, for example, Weitzman, 1974; Milliman and Prince, 1989; Goulder et al., 1999; Montero, 2002; Fischer et al., 2003; Krysiak, 2008). This literature seems to imply that combining emissions trading and emissions taxes is redundant at best and inefficient at worst. The underlying assumption is that both policies are exclusively meant to address a single pollution problem only. However, real-world policy-making may be more complex. Policy instruments often pursue multiple objectives. In this case, the classic Tinbergen (1952) rule applies: the number of policy instruments has to equal the number of policy objectives. In other words, the simultaneous attainment of multiple objectives under a policy mix may justify a certain degree of inefficiency with respect to pollution control. Consequently, pragmatic analyses of a policy mix need to take multiple objectives into account. They have to be based on a careful evaluation of welfare gains and losses of the policy mix in a multi-objective world. Such evaluation first of all requires a proper understanding of interactions in the policy mix. What is their actual impact on the efficiency of pollution control? And what are corresponding policy recommendations that are appropriate in a multi-objective world? These questions have received little attention so far.

The article analyzes a policy mix of an emissions trading scheme overlapping with an emissions tax. Firms have to hold a sufficient amount of permits and pay an emissions tax in addition. It is assumed that the emissions trading scheme primarily addresses the pollution problem. The tax is meant to control pollution as well. However, it is also driven by a multiplicity of other policy objectives, criteria and constraints. Sorrell and Sijm (2003, pp. 427-428) emphasize that the perhaps most important goal of taxation is to raise fiscal revenues. Johnstone (2003, p. 18) points out that emissions taxes may also be guided by distributional concerns. Both objectives of taxation may be particularly important when the design of the emissions trading scheme is suboptimal. When emission permits are not auctioned but allocated for free, the tax can be employed to generate fiscal revenues nevertheless and to capture windfall profits of firms. Moreover, the existence and maintenance of multiple policy instruments may also be attributed to the political economy of policy-making. Goulder and Parry (2008, p. 170) argue, for example, that policy choices may be determined by multi-level decision-making of possibly competing jurisdictions.

This article makes three contributions to improving the understanding of a policy mix which are relevant in the presence of multiple policy objectives. First of all, the article clarifies which factors actually determine the level of welfare losses when an emissions trading scheme is combined with an emissions tax. This insight is necessary to compare losses from combining both policy instruments with respect to pollution control with gains from addressing other objectives and criteria. It is shown that the decisive driver of welfare losses is the heterogeneity of taxation across participants in emissions trading. Moreover, losses depend on the slope of the marginal abatement cost curve, the total number of firms participating in emissions trading and the size of trading sectors with different tax rates. Secondly, the policy mix is not only compared to the ideal of a single first-best emissions trading scheme but also to a suboptimal heterogeneous emissions tax implemented in isolation. This comparison allows examining whether the implementation of an emissions trading scheme on top of a pre-existing emissions tax is at all welfare-improving. This question is relevant when the tax cannot be abolished because it also addresses other objectives than pollution control. The comparison reveals that the welfare loss under the policy mix corresponds perfectly to the loss under the single suboptimal tax when marginal abatement costs are linear. This insight leads to the surprising finding that the welfare loss is not attributable to interactions in the policy mix but only to the inefficient design of the tax. In fact, implementing an emissions trading scheme on top of an emissions tax increases overall welfare if the trading scheme is more stringent and produces additional benefits from emission reductions. The analysis moreover shows that interactions under the policy mix even reduce the welfare loss from heterogeneous taxation under the plausible assumption of convex marginal abatement costs. As a third contribution, the article sheds light on the question whether modifications in the design of emissions trading can help to reduce the inefficiency of the policy mix – given that modifications of the tax are not an option. A pragmatic approach is developed which restricts permit trading between sectors with different tax rates. The sector with the higher tax rate receives a deliberate over-allocation of permits. In turn, firms in the sector with the lower tax rate are allowed to buy permits from the other sector at a trading ratio higher than one. This approach is cost-effective in controlling pollution and involves only modest information requirements on part of the regulator.

There is a limited body of studies which analyze the combination of emissions trading and emissions taxes. It is shown that this policy mix may raise efficiency of pollution control compared to single policy instruments under a very strict assumption only: when firms are free to choose between emissions trading and taxation. Roberts and Spence (1976) point out that this policy mix may outperform single policy instruments when the regulator is uncertain about the marginal abatement cost curve. Referring to Weitzman's (1974) finding, they argue that underestimating the true marginal abatement costs may result in inefficiently high abatement levels under emissions trading as well as under an emissions tax (although the extent varies across instruments). Alternatively, Roberts and Spence suggest a superior hybrid approach. The regulator may cap the permit price – and limit welfare losses – by allowing firms to pay an emissions tax instead (or by selling additional permits at a fixed price). Firms participate in emissions trading as long as the market price for permits is below the tax rate, and pay the tax otherwise.[1] Lately, this so-called "safety valve"-approach has been particularly promoted to mitigate climate change efficiently (see, for example, Pizer, 2002; Newell et al., 2005; Burtraw et al., 2009). Johnstone (2003, p. 17) emphasizes that emissions trading and emissions taxes may also be combined when enforcement is difficult. The tax may be imposed as a fine per unit of emission which is not covered by permits. In this case, the tax reduces incentives for non-compliance and thereby facilitates the implementation of emissions trading. However, these studies differ significantly from the analysis carried out in this paper. Here, it is assumed that firms cannot escape one policy but have to meet the obligations of the emissions trading scheme and the emissions tax simultaneously.

Böhringer et al. (2008) examine an international emissions trading scheme overlapping with national emissions taxes. They argue that in this case the policy mix is indeed redundant at best and inefficient at worst. If the tax is homogenous across all countries, the policy mix will not impair welfare. Given that the tax is less stringent than the trading scheme, the permit price is exactly reduced by the tax rate.[2] Compared to a single emissions trading, the emission abatement effect of taxation is zero. Welfare losses occur when not all countries participating in emissions trading implement taxes, i.e. when taxation is heterogeneous. The tax then drives marginal abatement costs apart. Compared to a single emissions trading scheme, the policy mix inefficiently shifts emissions from countries with taxation to tax-free countries. Consequently, Böhringer et al. strongly recommend abolishing the tax.[3] The important restriction of their study is that it assumes both policy instruments to address pollution control only. In contrast, this article assumes a multi-objective world in which the conclusion to abolish the emissions tax may be flawed. As this scenario is not considered by Böhringer et al., they do not address the issues raised in this article.

Finally, this article is related to the discussion on environmental policy choices in the presence of pre-existing tax distortions. Several studies show that pre-existing taxes increase abatement costs under emissions trading schemes (see, for example, Goulder et al., 1997; Parry, 1997; Goulder et al., 1999; Parry and Williams, 1999). Pre-existing taxes are levied on income or sales, for example. Welfare losses result from general equilibrium effects of environmental policy instruments. These deteriorate the factor-market distortions created by pre-existing taxes. In contrast, this article

[1] Weitzman (1978) later also emphasized the advantages of this approach.

[2] If the emissions tax is more stringent than the emissions trading scheme, the permit price will fall to zero. In this case, the efficiency properties of the tax dominate. The emissions level under the policy mix is equal to that with a single emissions tax.

[3] Eichner and Pethig (2007) analyze the combination of international emissions trading with country-level emissions taxes in the light of trade theory. They find that countries may use taxes as a surrogate for tariffs to manipulate the terms of permit trade in their favour.

analyzes interactions between emissions trading and a (pre-existing) tax which explicitly targets emissions. The focus is not on distortions in classical factor markets, such as for labour. Instead, the article sheds light on partial-equilibrium effects of the policy mix in the emissions market established by the emissions trading scheme.

The article is organized as follows. Section 2 introduces a simple partial-equilibrium model which is used to analyze the combination of emissions trading and an emissions tax. Section 3 compares the efficiency properties of the policy mix with those of a first-best single emissions trading scheme. This comparison reveals major drivers of the welfare loss under a policy mix. Section 4 compares welfare effects of the policy mix with those of a single heterogeneous emissions tax. This section examines whether the implementation of an emissions trading scheme on top of a pre-existing tax is economically desirable or not. Section 5 analyzes options to modify the emissions trading scheme in order to improve the efficiency of the entire policy mix. Section 6 puts the results into perspective and concludes.

2 Model

The policy mix of emissions trading and an emissions tax is analyzed in a partial equilibrium model. The model supposes an industry with n identical firms and two sectors i (with $i = 1,2$). Sector 1 encompasses αn firms and sector 2 $(1-\alpha)n$ firms (with $0 \le \alpha \le 1$).

Along with the production of output, firms in both sectors generate emissions of a pollutant e_i. Emissions of each firm are assumed to be independent of the firm's output, i.e. pollution and production are fully separable activities. Consequently, firms' emissions choices can be analyzed without considering their output choices. Firms can reduce their emissions by abatement with cleaner technologies or cleaner inputs. To reduce their emissions, firms have to incur abatement costs $c_i(e_i)$. In order to be able to solve the model analytically, the abatement cost function is assumed to have the following quadratic form:

$$c_i(e_i) = \frac{a}{2}e_i^2 - be_i + \frac{b^2}{2a} \text{ with } e_i \in \left[0; \frac{b}{a}\right] \tag{1}$$

Parameters a and b are assumed to be positive. The upper limit of the interval for emissions, b/a, represents the unique global minimum of costs as well as the unique zero of the quadratic function. It can be interpreted as the "natural" emissions level which is observed when firms undertake no abatement at all. Within the interval given above, abatement costs are positive, decreasing in emissions and convex. The marginal abatement cost function for firms in both sectors, $c_i'(e_i)$, can be derived from equation (1). It is linear and writes as:

$$c_i'(e_i) = ae_i - b \text{ with } e_i \in \left[0; \frac{b}{a}\right] \tag{2}$$

Rearranging equation (2) gives the emissions level in each sector as a function of marginal abatement costs:

$$e_i = \frac{c_i'(e_i) + b}{a} \tag{3}$$

Total emissions E of the entire industry are the sum of each sector's emissions. Sectoral emissions compute as the product of the representative firm's emissions times the number of firms in the sector. Using equation (3), total emissions of the entire industry can thus be rewritten as:

$$E = \alpha n \frac{c_1'(e_1) + b}{a} + (1-\alpha) n \frac{c_2'(e_2) + b}{a} \tag{4}$$

In order to reduce emissions, two policies are implemented. An emissions trading scheme sets a cap $\overline{E}$ on total emissions of the entire industry. The emissions cap is assumed to be efficient, i.e. marginal abatement costs at $\overline{E}$ equal the marginal damage of emissions. The regulator is assumed to issue a corresponding amount of permits and to allocate a fixed number of $\overline{a}_i$ permits free of charge to firms in both sectors. Each firm is obliged to hold a sufficient amount of permits to cover its emissions. Subject to this constraint, each firm is free to choose whatever level of abatement. Firms may buy extra permits or sell excess permits in an emissions market at equilibrium price t. Firms are assumed to take this price as given. Since firms in both sectors are identical, each sector's share in the total number of firms, α and $(1-\alpha)$, can also be interpreted as the respective shares of sector one and two in the emissions market. In addition to emissions trading, the regulator imposes a tax on firms in each sector at rate τ_i for each unit of emission generated by them. The tax rate may be homogeneous across sectors, i.e. $\tau_1 = \tau_2$, or heterogeneous, i.e. $\tau_1 \neq \tau_2$. The tax is assumed to be less stringent than the emissions trading scheme, i.e. the emissions level resulting if only the tax was in place is below the emissions cap.[4]

Given this regulatory framework, firms in both sectors face the problem of minimizing their emission-related costs κ, i.e. the sum of abatement costs, net permit costs and tax payments:

---

[4] Interactions of emissions trading and emissions taxes in the emissions market are only relevant given this assumption. As has already been emphasized in footnote 2, the permit price would drop to zero if the tax was more stringent than the emissions trading scheme. The properties of the tax would be decisive for the efficiency of abatement. The emissions market would become obsolete and disappear.

$$\min_{e} \kappa = c_i\left(e_i\right) + t\left(e_i - \overline{a}_i\right) + \tau_i e_i \tag{5}$$

The straightforward first-order condition for firms in both sectors is as follows:

$$-c_i'\left(e_i^{PM}\right) = t^{PM} + \tau_i \tag{6}$$

where superscript PM denotes equilibrium values for the policy mix.[5] Thus, firms reduce their emissions until inverse marginal abatement costs equal the sum of the permit price and the tax rate.

3 The Policy Mix Compared to Emissions Trading

In this section, the policy mix of emissions trading and an emissions tax is compared to a single efficient trading scheme. This comparison allows identifying the most important drivers determining the extent of welfare losses under the policy mix.

Substituting inverse marginal abatement costs of each sector by using equation (6) and setting total emissions equal to the emissions cap, equation (4) can be rewritten as:

$$\overline{E} = \alpha n \frac{b - t^{PM} - \tau_1}{a} + \left(1-\alpha\right) n \frac{b - t^{PM} - \tau_2}{a} \tag{7}$$

Reorganizing equation (7) gives the equilibrium permit price under the policy mix:

$$t^{PM} = b - \frac{a}{n}\overline{E} - \alpha\tau_1 - \left(1-\alpha\right)\tau_2 \tag{8}$$

Setting tax rates in both sectors zero reveals the equilibrium permit price which would emerge if only an emissions trading scheme was in place: $t^{ET} = b - \left(a/n\right)\overline{E}$, where superscript ET denotes equilibrium values under a single emissions trading scheme. Thus, implementing an emissions tax on top of emissions trading reduces the equilibrium permit price by the average tax rate. The average tax rate is the sum of the sectors' heterogeneous tax rates weighted with sectors' shares in the emissions market. If taxation of sectors is homogeneous, i.e. $\tau_1 = \tau_2 = \tau$, the permit price under the policy mix is just the permit price under the single emissions trading scheme reduced by the tax rate: $t^{PM} = t^{ET} - \tau$. If firms in sector 2 are exempt from taxation, i.e. $\tau_2 = 0$, the permit price equals the difference of the permit price under emissions trading only and the tax rate for sector 1 multiplied by its emissions market share: $t^{PM} = t^{ET} - \alpha\tau_1$.

---

[5] With auctioning, firms would not receive permits free of charge but would have to buy all permits, i.e. $\overline{a}_i = 0$. This would not change the first-order conditions though because $\overline{a}_i$ is a constant that cancels out with derivation.permit.

Inserting equations (6) and (8) into (3) gives the individual emissions levels chosen by firms in both sectors in equilibrium:

$$e_1^{PM} = \frac{\overline{E}}{n} + \frac{(1-\alpha)(\tau_2 - \tau_1)}{a} \tag{9}$$

$$e_2^{PM} = \frac{\overline{E}}{n} + \frac{\alpha(\tau_1 - \tau_2)}{a} \tag{10}$$

Setting tax rates zero reveals that firms' emissions levels would be identical in both sectors under a single emissions trading, corresponding to the n-th share in the emissions cap:

$$e_i^{ET} = \frac{\overline{E}}{n} \tag{11}$$

These emissions levels also emerge when taxation is homogeneous across sectors, as can be seen from equations (9) and (10). If taxation is heterogeneous, however, emissions choices are distorted. Firms in the sector with higher taxation will reduce their emissions under the policy mix compared to a single emissions trading scheme. In contrast, firms subject to the lower tax rate will choose a higher emissions level. However, the overall level of emissions is determined by the emissions cap and remains unchanged. Thus, the implementation of heterogeneous emissions tax on top of an emissions trading scheme only results in a shift of emissions between sectors.

The shift of emissions comes at increasing overall costs of abatement. Condition (6) shows the well-known result that marginal abatement costs vary between sectors when tax rates are heterogeneous. Thus, with the implementation of a heterogeneous tax in addition to the emissions trading scheme, the emissions cap cannot be attained cost-effectively. Compared to a situation with emissions trading only, the higher-taxed sector incurs higher overall abatement costs while the lower-taxed sector faces lower abatement costs. The difference between the cost increase in one sector and the cost decrease in the other sector is the efficiency loss due to the policy mix. Analytically, the efficiency loss ΔW due to the policy mix can be understood as the absolute value of the sum of the definite integrals of the inverse marginal abatement costs functions for firms in both sectors on the interval $\left[e_i^{PM}, e_i^{ET}\right]$, multiplied by the number of firms in each sector:

$$\Delta W = \left| \alpha n \int_{e_1^{PM}}^{e_1^{ET}} \left(c_1'(e_1)\right) de_1 + (1-\alpha) n \int_{e_2^{PM}}^{e_2^{ET}} \left(c_2'(e_2)\right) de_2 \right| \tag{12}$$

Solving the integrals using equations (1), (9), (10) and (11) yields the welfare loss under a policy mix of emissions trading and a heterogeneous emissions tax compared to the case of a single emissions trading scheme:

$$\Delta W = \frac{\alpha(1-\alpha)n(\tau_1 - \tau_2)^2}{2a} \tag{13}$$

Proposition 1: *The welfare loss under the policy mix is driven by four factors: (1) the heterogeneity of taxation,* $|\tau_1 - \tau_2|$*, (2) the slope of the marginal abatement cost curve,* a*, (3) the total number of identical firms,* n*, and (4) the sectors' shares in the emissions market,* α*.*

(1) The larger is the heterogeneity of taxation, i.e. the absolute value of the difference between both tax rates, the larger will be the inefficiency under the policy mix. As equations (9) and (10) illustrate, firms subject to the higher tax rate will abate even more excessively with increasing heterogeneity of taxation. At the same time, firms facing the lower tax rate have a stronger incentive to abate below optimal levels. It is worth highlighting that the welfare loss does not increase linearly but exponentially in heterogeneity of taxation. Heterogeneity of taxation may therefore be considered the most important driver of welfare losses in the policy mix.

(2) As one would expect, the inefficient distortion of abatement is deteriorated as the slope of the marginal abatement cost curve becomes flatter. This is because the same price distortion induced by the tax rate will have a stronger impact on emissions with a relatively flat marginal abatement cost curve than with a relatively steep one.

(3) The inefficiency of the policy mix becomes more severe with an increasing total number n of firms. This is because an increase in the total number of firms implies a rise in total as well as sectoral emissions. Consequently, the total of distorted emissions abatement and emissions inefficiently shifted from one sector to another will increase as well.

(4) Assuming all other variables to be constant, the welfare loss will be largest when both sectors have the same share in the emissions market. This finding can be proven analytically since the function $f(\alpha) = \alpha(1-\alpha)$ has a global maximum at $\alpha = 0.5$. Thus, the larger is the difference in market shares, the smaller will be the inefficiency of the policy mix. This can be illustrated for the example of a tax imposed on sector 1 only. It will first be assumed that sector 1 is very big and sector 2 is very small. As has been explained above, taxing sector 1 reduces emissions in this sector and provides for a reduction of demand for permits. Firms in sector 2 can benefit from the resulting decrease of the permit price and extend their emissions. However, if sector 2 is very small, this increase in demand for permits will hardly compensate the reduction brought about by sector 1. Consequently, the reduction of the permit price will be close to that arising in the presence of emissions trading and homogeneous taxation. Firms in sector 2, which are not subject to the tax, will abate too little due to the decreasing permit price. However, the inefficiency of the policy mix is small, since most firms (those in sector 1) face nearly efficient abatement incentives set out by the reduced permit price and the tax rate. Analogous results can be derived if one assumes that sector 1 is very small and sector 2 is very big. In this case, the

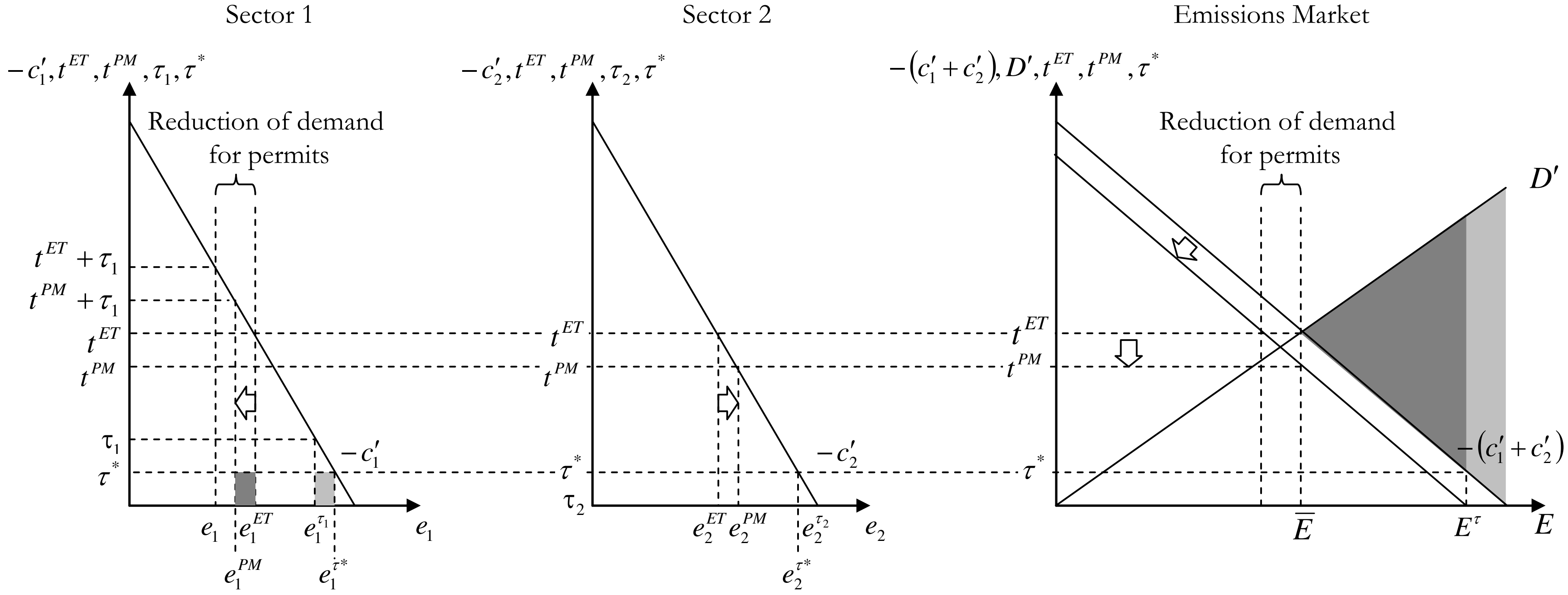
implementation of a sectoral emissions tax on top of the emissions trading scheme will result in additional abatement in sector 1. However, the resulting decrease of demand for permits will hardly affect the permit price since sector 1 is small. The permit price will therefore be close to the level arising in the presence of emissions trading only. Firms in sector 1 will abate too much since they are subject to the high permit price and the emissions tax. Yet, the policy mix is almost efficient since most firms (those in sector 2) face the nearly efficient incentives of the emissions trading scheme.

The analytical results can be illustrated by using the simple example with both sectors composed of one firm each and an emissions tax imposed on the sector-1 firm only. The tax is imposed on top of a pre-existing emissions trading scheme. This case is depicted in

Figure 1. The first two graphs represent the inverse marginal abatement cost curves for sectors 1 and 2, which can be interpreted as sector-specific demand functions for permits. The aggregated curve of inverse marginal abatement costs of the industry in the third graph then represents the demand function for the entire emissions market. Facing the preexisting permit price t^{ET} and the tax rate τ_1, the firm in sector 1 is initially stimulated to reduce its emissions from e_1^{ET} to e_1. The firm in sector 2 does initially not have an incentive to deviate from its emissions level e_2^{ET}. However, both emissions levels do not represent equilibrium values. Due to a declining demand for permits in sector 1, the demand function of the entire emissions market is shifted to the left. Since the emissions cap $\overline{E}$ will always be met, the equilibrium permit price declines to t^{PM}. However, in contrast to the case of emissions trading with homogeneous taxation, the reduction in the permit price will be less than the tax rate. This is because the firm in sector 2, which is not subject to the tax, will take advantage of the permit price reduction, demand more permits and therefore compensate some of declining demand of the firm in sector 1. Consequently, firms in sector 1 will have higher incentives to reduce their emissions than with emissions trading only: $t^{PM} + \tau > t^{ET}$ and $e_1^{PM} < e_1^{ET}$. In turn, firms in sector 2 will have fewer incentives to reduce their emissions than under a single emissions trading scheme since they only face the reduced permit price. Therefore, emissions of firms in sector 2 will increase, i.e. $e_2^{PM} > e_2^{ET}$. The resulting welfare loss is depicted as the dark-shaded rectangle in

Figure 1.

Figure 1: Welfare effects of combing emissions trading and a heterogeneous emissions tax compared to a single emissions trading scheme and a single heterogeneous emissions tax: The case of linear marginal abatement costs



4 The Policy Mix Compared to an Emissions Tax

As has been pointed out before, comparing the policy mix to a single efficient emissions trading scheme may be a rather theoretical exercise. An emissions tax may be in place already and needed to address multiple policy objectives – even though it is heterogeneous and distorts pollution abatement. From this pragmatic perspective, the decisive questions are: Which impact does the implementation of an emissions trading scheme on top of an emissions tax have on the efficiency of pollution control? Is it all desirable to supplement the tax by an emissions trading scheme? In order to answer these questions, the policy mix has to be compared to a single heterogeneous emissions tax.

For the purpose of this comparison, it is necessary to shed light on the welfare effects of a single heterogeneous emissions tax. Assuming that firms determine their optimal abatement levels under taxation such that $-c_i'\left(e_i^{\tau_i}\right)=\tau_i$, emissions levels of firms in both sectors can be derived from equation (3):

$$e_i^{\tau_i}=\frac{b-\tau_i}{a} \tag{14}$$

where superscript τ_i indicates equilibrium values under the emissions tax. The overall emissions level of the industry under the tax, E^{τ}, writes analogously to equation (4):

$$E^{\tau}=n\frac{b-\alpha\tau_1-(1-\alpha)\tau_2}{a} \tag{15}$$

The same emissions level can be attained by a tax rate τ^* that is homogeneous across sectors. Substituting τ_1 and τ_2 by τ^* and reorganizing equation (15) yields:

$$\tau^*=b-\frac{a}{n}E^{\tau} \tag{16}$$

Combining equations (15) and (16) gives the homogeneous tax rate depending on the heterogeneous sectoral tax rates:

$$\tau^*=\alpha\tau_1+(1-\alpha)\tau_2 \tag{17}$$

Thus, the homogenous tax rate computes as the simple mean average of the heterogeneous tax rates weighted with the shares of the respective sectors in the total number of firms. Assuming that firms determine their optimal abatement levels under taxation now such that $-c_i'\left(e_i^{\tau_i}\right)=\tau^*$ and using equations (3) and (17), the resulting emissions level of firms in both sectors is:

$$e_i^{\tau*}=\frac{b-\alpha\tau_1-(1-\alpha)\tau_2}{a} \tag{18}$$

where superscript τ^* indicates equilibrium values under the homogeneous emissions tax.

The heterogeneous tax is not cost-effective in attaining the emissions level E^τ since abatement incentives are not equalized across sectors. The welfare loss from heterogeneous taxation can be determined by comparing the welfare effects with those under a cost-effective homogeneous tax rate τ^*. Analytically, the welfare loss can be computed as the absolute value of the sum of the definite integrals of the marginal abatement cost functions for both sectors on the interval $\left[e_i^{\tau_i}, e_i^{\tau^*}\right]$ multiplied by the number of firms in each sector:

$$\Delta W = \left| \alpha n \int_{e_i^{\tau_1}}^{e_1^{\tau^*}} \left(c_1'(e_1)\right) de_1 + (1-\alpha) n \int_{e_2^{\tau_2}}^{e_2^{\tau^*}} \left(c_2'(e_2)\right) de_2 \right| \tag{19}$$

Solving the integrals using equations (1), (14) and (18) gives the welfare loss under heterogeneous taxation compared to homogeneous taxation:

$$\Delta W = \frac{\alpha(1-\alpha)n(\tau_1 - \tau_2)^2}{2a} \tag{20}$$

Proposition 2: *Given linear marginal abatement costs, the welfare loss from heterogeneous taxation under a single emissions tax corresponds perfectly to the welfare loss under a policy mix with emissions trading and an emissions tax.*

This conclusion becomes obvious when equation (20) is compared to equation (13). It reveals a surprising insight: From the perspective employed in this section, the welfare loss under the policy mix cannot be attributed to interactions between both policies. The loss is only due to inefficient, heterogeneous design of the tax. The corresponding distortions arise no matter whether the tax is complemented by an emissions trading scheme or not. The welfare loss under a single heterogeneous emissions tax is depicted as the light-shaded rectangle in Figure 1.

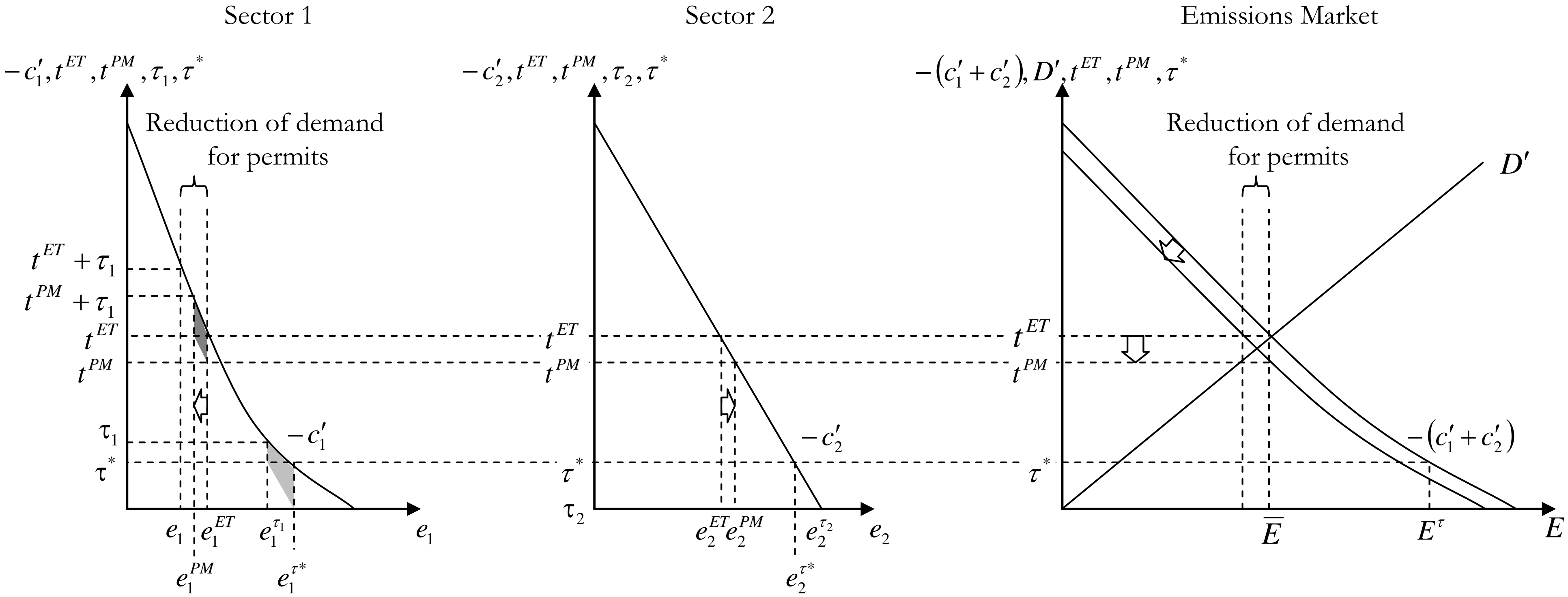
Figure 1 also reveals another important result: While the welfare loss from heterogeneous taxation remains unchanged in absolute terms, implementing an emissions trading scheme on top of the tax reduces the relative importance of the welfare loss. The heterogeneous emissions tax provides for total emissions to decline to E^τ. In this case, the welfare loss from heterogeneous taxation compares with relatively modest net gains from internalization. Net gains compute as the difference between mitigated damage from emissions and corresponding abatement costs. Net gains are depicted as the light-shaded trapezoid between the marginal damage curve, D', and the aggregated marginal abatement cost curve in Figure 1. If a more stringent, efficient emissions trading scheme is implemented on top of the tax, total emissions will be reduced more significantly to the emissions cap $\overline{E}$. The net gains from internalization under the policy mix then amount to sum of the dark-shaded triangle and the light-shaded trapezoid in Figure 1. This larger welfare gain compares with a welfare loss from heterogeneous taxation which is still as large as under the single tax. Thus, the implementation of an emissions trading scheme on top of the heterogeneous emissions tax is desirable from an efficiency point of view. It increases the net gains from reducing emissions while leaving the welfare loss from heterogeneous taxation unaffected.

The discussion so far has been based on the assumption of linear marginal abatement costs. However, marginal abatement costs may well turn out to be non-linear. For greenhouse gas emissions, for example, empirical studies have found marginal abatement costs to be convex (see, e.g., Ellerman and Decaux, 1998; Criqui et al., 1999; Klepper and Peterson, 2006) as well as concave (see, e.g., Morris et al., 2008).

Proposition 3: *The welfare loss from heterogeneous taxation is smaller (larger) under a policy mix with emissions trading and an emissions tax than under a single emissions tax when marginal abatement costs are convex (concave).*

This proposition can be explained by using Figure 2 – a modification of Figure 1 – for the case of convex marginal abatement costs. For simplicity reasons, convexity of marginal abatement costs is assumed for sector 1 but not for sector 2. If only the tax for sector 1 is in place, the emissions level of firms in sector 1 and 2 will be relatively high. The inefficient reduction of emissions in sector 1 due to the heterogeneous emissions tax occurs in the relatively flat section of the inverse marginal abatement cost curve. In this section, the tax rate has a relatively strong impact on the emissions level chosen. The resulting welfare loss – depicted as the light-shaded area in Figure 2 – will be relatively high. If an emissions trading scheme is implemented in addition to the emissions tax, emissions will be reduced in both sectors compared to the situation with the tax only. This implies that the emission distortion caused by the tax rate now occurs in the relatively steep section of sector 1's inverse marginal abatement cost curve. In this section, the same tax rate will have a smaller effect on emissions than in the flat section. The resulting welfare loss – depicted as the dark-shaded area in Figure 2 – will be less important than under the single heterogeneous emissions tax. In contrast to the linear case, the emissions cap now has an impact on the welfare loss stemming from heterogeneous taxation under the policy mix. The welfare loss will be the smaller, the closer the emissions cap is to the optimal emissions cap, i.e. $\overline{E}$ in Figure 2. Reducing the emissions cap (if it is set above the optimal level) will shift the inefficient distortion of the tax towards a steeper section of the inverse marginal abatement cost function and reduce the extent of over-abatement in sector 1.

Figure 2: Welfare effects of combing emissions trading and a heterogeneous emissions tax compared to a single emissions trading scheme and a single heterogeneous emissions tax: The case of convex marginal abatement costs



With concave marginal abatement costs, the findings for convex marginal abatement costs are reversed. With a heterogeneous emissions tax only, the inefficient distortion arises at a relatively high emissions level where the marginal abatement cost curve is relatively steep. In this section, the impact of price distortion will be relatively small. Implementing the emissions trading scheme on top of the emissions tax reduces the emissions level. Consequently, the inefficient price distortion now occurs in the relatively flat section of the marginal abatement cost curve. In this section, the same tax rate will have a relatively strong effect on emissions. Given concave marginal abatement costs, the policy mix will increase the welfare loss stemming from heterogeneous taxation. Whether or not the policy mix is overall superior to the single tax depends on how the increasing welfare losses due to heterogeneous taxation compare with the internalization gains due to overall larger emission reductions.

The assumption of non-linear marginal abatement costs thus yields further important results. Interactions between the emissions trading scheme and the emissions tax are now decisive for the extent of the welfare loss resulting from heterogeneous taxations. Surprisingly, interactions in fact decrease the welfare loss compared to a single tax when marginal abatement costs are convex. However, the reverse is true when concave marginal abatement costs are assumed. The implementation of an emissions trading scheme on top of an existing heterogeneous tax is therefore strictly welfare-increasing in the convex case. In the concave case, the overall evaluation of the policy mix is ambiguous.

5 Modifications of Emissions Trading to Increase the Efficiency of the Policy Mix

When abolishing or modifying the heterogeneous emissions tax is not a policy option, it is worthwhile to investigate whether modifications of the emissions trading scheme may reduce welfare losses under the policy mix. It has been shown that the inefficiency under the policy mix arises because emissions are inefficiently shifted from the high-taxed to the low-taxed sector. An intuitive solution to this problem is to restrict emissions trading between sectors. This implies that the policy mix will in fact consist of three policies: an emissions trading scheme for each sector and a heterogeneous tax. The emissions trading schemes may be perfectly separated or linked to a certain extent only.

The solution is trivial given the assumption of marginal abatement cost functions which are identical across all firms and sectors – as has been assumed so far. In this case, trades across sectors do not result in welfare gains. An optimal policy mix then encompasses two perfectly separated emissions trading schemes for sector 1 and 2. No trade should be allowed across sectors. The emissions cap should be divided into two sectoral caps according to the sectors' shares in the emissions market, i.e. $\overline{E}_1 = \alpha\overline{E}$ and $\overline{E}_2 = (1-\alpha)\overline{E}$. Consequently, separate permit prices, t_1 and t_2, would emerge in each sector's emissions market. Designing such a policy mix is easy for the regulator as he does not have to obtain any knowledge about the marginal abatement cost functions of the sectors.

Separating emissions markets for sectors efficiently is more tedious when marginal abatement cost functions are heterogeneous across sectors and firms. In this case, a detailed understanding of marginal abatement costs is necessary in order to determine each sector's emissions cap optimally. Yet, the regulator usually only has a rough understanding of these functions due to high transaction costs of gathering necessary information. Consequently, sectors are likely to receive an inefficient over- or under-allocation of permits.[6] In order to provide for an equalization of marginal abatement costs, the regulator may decide to allow trading of permits between both sectors. Allowing trading on a one-to-one basis would exactly correspond to the case of an unrestricted emissions trading scheme combined with a heterogeneous emissions tax – as it has been described above. Instead of an exchange on a one-to-one basis, the regulator may allow trading of permits at a certain ratio only. Given an only rough understanding of marginal abatement costs, the efficiency of the policy mix in this case depends on the heterogeneity of taxation as well as the level of over- or under-allocation of permits to each sector.

Proposition 4: *When a regulator has only a rough understanding of marginal abatement costs, he should deliberately over-allocate permits to the sector with the high tax rate and allow firms in the low-taxed sector to buy permits from the high-taxed sector at the trading ratio larger than one.*

In order to illustrate this proposition, two scenarios are distinguished: permits may be over-allocated either to the sector with the higher tax rate or to the sector with the lower tax rate. First of all, it will be assumed that sector 1 faces a higher tax rate, i.e. $\tau_1 > \tau_2$, and receives an over-allocation of permits. Prohibiting any trades between sectors will result in abatement incentives to be too low for sector 1 and too high for sector 2: $t_1 + \tau_1 < t_2 + \tau_2$. In order to attain an efficient level of abatement, permits (and thus emissions) should be traded from sector 1 to sector 2. However, an emissions trading scheme based on one-to-one trades can neither provide an efficient outcome. In fact, the results are reversed. Since permit prices are equalized across both sectors, sector 1 now has higher incentives to abate than sector 2: $t_1 + \tau_1 > t_2 + \tau_2$. This implies that allowing unrestricted trading between sectors would result in too many permits to be traded from sector 1 to sector 2. This inefficiency arises because due to heterogeneous taxation, sector-1 and sector-2 firms do not have the same incentive to abate if they hold one sector-1 permit. In fact, this incentive is lower in sector 2 than in sector 1. Consequently, the incentive to buy a

[6] The level and heterogeneity of tax rates does not have an effect on this inefficiency as taxation is homogeneous within sectors and sectoral trading schemes are not linked.

sector-1 permit is higher for sector-2 firms than for sector-1 firms. This deficiency can be overcome by introducing the trading ratio β. The ratio determines how many sector-1 permits the firms in sector 2 have to hold in order to cover one unit of their emissions. The new first-order condition for sector 2 then is:

$$-c_2'(e_2) = \min[\beta t_1 + \tau_2, t_2 + \tau_2] \tag{21}$$

In contrast, the first-order condition for optimal abatement for sector 1 is:

$$-c_1'(e_1) = t_1 + \tau_1 \tag{22}$$

The ratio has to provide for firms in sector 1 and 2 to have the same incentives to abate if they buy a permit on the emissions market of sector 1. From equations (21) and (22) thus follows:

$$t_1 + \tau_1 = \beta t_1 + \tau_2 \tag{23}$$

Reorganizing equation (23) yields the optimal trading ratio:

$$\beta = 1 + \frac{\tau_1 - \tau_2}{t_1} \tag{24}$$

The trading ratio provides that firms in sector 2 implicitly pay the sector-1 permit price and the difference by which the sector-1 tax rate is higher than the sector-2 tax rate. Since the sector-1 tax rate exceeds the sector-2 tax rate, the trading ratio will be larger than one. Consequently, firms in sector 2 have to buy more than one sector-1 permit to cover one unit of their emissions. They will do as long as $t_1 + \tau_1 = \beta t_1 + \tau_2 < t_2 + \tau_2$. Gains from trade vanish when $t_1 + \tau_1 = \beta t_1 + \tau_2 = t_2 + \tau_2$. In this case, marginal abatement costs will be equal across sectors. Thus, the trading ratio provides for cost-effective abatement in the entire industry by restricting the amount of permits traded from sector 1 to 2.

This result is not necessarily attained under the second scenario where the low-taxed sector receives excess permits. It is now assumed that the tax rate is lower in sector 1 than in sector 2: $\tau_1 < \tau_2$. Sector 1 again receives an over-allocation of permits. Without trading between sectors, abatement incentives will be lower in sector 1 than in sector 2: $t_1 + \tau_1 < t_2 + \tau_2$. As in the first scenario, permits (and thus emissions) should be transferred from sector 1 to sector 2. However, allowing trades from sector 1 to sector 2 on a one-to-one basis will not yield a cost-effective outcome. The explanation is different to the case in which the high-taxed sector receives the over-allocation. If the permit price is lower in sector 1 than in sector 2, i.e. $t_1 < t_2$, trades of permit from sector 1 to sector 2 will equalize the permit prices in both sectors. In this case, however, firms in sector 2 still have higher incentives to abate than sector 1 due to the higher tax rate. Thus, they buy too few permits from sector 1 from a cost-effectiveness point of view. There may be even cases where the permit price in sector 1 is higher than in sector 2, i.e. $t_1 > t_2$, despite the over-allocation of permits to sector 1. This situation arises when the tax rate for sector 2 is significantly higher than that for sector 1: $\tau_1 << \tau_2$. Firms in sector 2 then do not have any incentive to buy permits from sector 1. In contrast, sector-1 firms have an incentive to buy permits from sector 2. The resulting uniform permit price will be lower than that existing in absence of trading between the sectors. The resulting overall incentives to abate are even lower for sector 1 after trading is allowed. Consequently, emissions are shifted from sector 2 to sector 1. This is contrary to what would be necessary from an efficiency point of view. The implementation of a trading ratio can only overcome this imperfection if the difference of the tax rate in sector 2 (the higher tax rate) and that in sector 1 (the lower tax rate) is below the permit price which prevails in sector 1 before inter-sectoral trading is allowed, i.e. if $\tau_2 - \tau_1 > t_1$. Under this condition, the trading ratio given in equation (24) is positive and between zero and one. This implies that firms in sector 2 have to hold less than one sector-1 permit to cover its emissions. Sector-2 firms have a stronger incentive to buy sector-1 permit than firms in sector 1. Consequently, more emissions will be shifted from sector 1 to sector 2 than with one-to-one trades. The trading ratio would become negative if the difference between the sectors' tax rates is sufficiently high. In fact, this will be the case if the difference of the tax rate in sector 2 (the higher tax rate) and that in sector 1 (the lower tax rate) exceeds the permit price which prevails in sector 1 before inter-sectoral trading is allowed, i.e. if $\tau_2 - \tau_1 > t_1$. However, a negative trading ratio cannot emerge on an emissions market. It would imply that sector-2 firms had to pay a negative price – or rather receive remuneration – for each sector-1 permit they purchase. Yet, sector-1 firms do not have any incentive to sell their permits at a negative price. The trading ratio thus falls to zero but not below. Consequently, sector-2 firms will choose not to buy any permits from sector 1 – but neither sector-2 permits. The permit price in sector 2 falls to zero. Eventually, firms in sector 2 only face the emissions tax. However, this tax rate is still higher than the sum of the permit price and the tax rate in sector 1. Therefore, firms in sector 2 still abate too much and too costly compared to the social optimum.

In summary, there are indeed options to modify an emissions trading scheme such that the welfare loss under a combination with a heterogeneous emissions tax is reduced. The regulator should establish two sectoral emissions trading schemes. If the regulator has perfect knowledge about the marginal abatement costs, he may simply determine the optimal emissions caps for each sector and prohibit any trades between sectors. If the regulator has only a rough understanding of marginal abatement costs, a more pragmatic approach may be based on allowing the transfer of permits between sectors at a certain trading ratio only. This approach assures a cost-effective outcome if the sector with the higher tax rate receives a deliberate over-allocation of permits. Over-allocating permits to the sector with the lower tax rate only yields a cost-effective outcome if the difference between the tax rates is sufficiently low.

6 Conclusion

A policy mix of emissions trading and emissions taxes is usually rejected when both policies overlap, i.e. when firms have to hold permits to cover their emissions and pay a tax in addition. Given that the emissions trading scheme is designed efficiently and that the tax is less stringent, the abolition of the tax is usually recommended. This paper addresses an important restriction which underlies this conclusion: Existing policy mix studies usually assume that emissions trading as well as emissions taxes are exclusively meant to address a pollution problem. In reality, however, policies may pursue multiple objectives. In particular, emissions taxes often address pollution control as well as other goals, such as raising fiscal revenues. In the presence of multiple objectives, the abolition of the tax may not necessarily be a desirable option. The inefficiency in controlling pollution may in fact be the "price" of attaining multiple objectives simultaneously. Consequently, a pragmatic policy mix analysis has to take multiple objectives into account if it aims to provide useful policy evaluation and recommendation. A general rejection of a policy mix is not appropriate. Rather, a proper understanding of interactions in the policy mix is required. In this respect, this article makes three necessary contributions to improving the understanding of policy interactions – and to increasing the relevance of economic policy mix theory for real-world policy problems.

Firstly, the key drivers of inefficiency under the policy mix are identified. The heterogeneity of taxation is found to be the decisive driver. Other important driving factors include the slope of the marginal abatement cost curve, the number of firms in the entire industry as well as the share of sectors with different tax rates in the emissions market. This insight can be used to determine the actual extent of welfare losses under the policy mix. In a subsequent step of analysis, these losses may then be compared with benefits from attaining other policy objectives. With this comparison, the overall efficiency of the policy mix in the presence of multiple policy objectives can be assessed.

Secondly, the policy mix is compared to a single heterogeneous emissions tax. This analysis helps to determine whether the implementation of an emissions trading scheme is at all economically desirable when an emissions tax is already in place and shall not be abolished. From this perspective, the analysis yields the surprising result that the policy mix does not necessarily reduce welfare. It is shown that interactions between the emissions trading scheme and the emissions tax are in fact welfare-increasing when marginal abatement costs are linear or convex. Thus, the implementation of the trading scheme on top of the suboptimal tax is economically desirable. Only with concave marginal abatement costs, the result is ambiguous.

Thirdly, the article examines the important question whether a modification of the emissions trading scheme may mitigate welfare losses under a policy mix – given that modifications of a heterogeneous tax are ruled out. A pragmatic approach, which requires only a rough understanding of marginal abatement costs, may consist in restricting permit trades across sectors. The sector subject to a higher tax rate should receive a deliberate over-allocation of permits. In turn, firms in the sector with the lower tax rate should be allowed to buy permits from the other sector at a trading ratio higher than one. In a real policy context with a broad array of policy objectives and criteria, such an approach may be debatable. It may raise distributional concerns as it produces windfall profits to firms which benefit from an over-allocation of permits. However, regulators often also aim to place a smaller burden of environmental regulation on some selected sectors which depend largely on exports. If such sector faces a higher tax rate than other sectors, the modification of the emissions trading scheme produces a synergy: it increases the efficiency of the policy mix and, simultaneously, protects a national industry.

Two extensions of the analysis may be promising. First of all, the multiplicity of policy objectives is translated into a modelling constraint in this article for simplicity reasons. The policy mix is analyzed under the restriction that the emissions tax has to be maintained. Instead, multiple policy objectives can also be taken into account more explicitly in the policy mix model. This approach allows for an overall analytical assessment of the policy mix which considers welfare losses with respect to pollution control as well as benefits from attaining other objectives. Possibly, such analysis should be conducted in a general equilibrium framework rather than on the basis of a partial equilibrium approach as in this article.

A second extension can depart from the assumption that the tax is directly levied on emissions. Often, emissions are addressed rather indirectly by taxing output. Output taxes may result in additional welfare losses when output and emissions are related at a variable emissions rate. An output tax sets incentives to reduce output but not the emissions rate. In order to account for these distortions, the assumption of fully separable pollution and production activities – as it is used in this article – has to be relaxed. Given this modification, it may then be interesting to analyze the welfare implications of implementing an emissions trading scheme on top of a tax. Are distortions from output taxation ameliorated or deteriorated under a policy mix? Moreover, a model with emissions depending on output allows analyzing interactions in output markets, which may also influence the efficiency of the policy mix.

References

Böhringer, C., Koschel, H., Moslener, U., 2008. Efficiency Losses from Overlapping Regulation of European Carbon Emissions. Journal of Regulatory Economics 33, 299-317.

Burtraw, D., Palmer, K.L., Kahn, D.B., 2009. A Symmetric Safety Valve, RFF Discussion Paper 09-06. Resources for the Future (RFF), Washington, D.C.

Criqui, P., Mima, S., Viguier, L., 1999. Marginal abatement costs of CO_2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model. Energy Policy 27, 585-601.

Eichner, T., Pethig, R., 2007. Efficient CO_2 emissions control with national emissions taxes and international emissions trading, CESifo Working Paper No. 1967. Centre for Economic Studies and Ifo Institute for Economic Research, Munich.

Ellerman, A.D., Decaux, A., 1998. Analysis of Post-Kyoto CO2 Emission Trading Using Marginal Abatement Curves, Joint Program on the Science and Policy of Global Change Report. Massachusetts Institute of Technology (MIT), Cambridge, MA.

Fischer, C., Parry, I.W.H., Pizer, W.A., 2003. Instrument Choice for Environmental Protection When Technological Innovation is Endogenous. Journal of Environmental Economics and Management 45, 523-545.

Goulder, L.H., Parry, I.W.H., 2008. Instrument Choice in Environmental Policy. Review of Environmental Economics and Policy 2, 152-174.

Goulder, L.H., Parry, I.W.H., Burtraw, D., 1997. Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-Existing Tax Distortions. RAND Journal of Economics 28, 708-731.

Goulder, L.H., Parry, I.W.H., Williams, R.C.I., Burtraw, D., 1999. The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. Journal of Public Economics 72, 329-360.

Johnstone, N., 2003. The Use of Tradable Permits in Combination with Other Policy Instruments. Organisation for Economic Cooperation and Development (OECD), Paris.

Klepper, G., Peterson, S., 2006. Marginal abatement cost curves in general equilibrium: The influence of world energy prices. Resource and Energy Economics 28, 1-23.

Krysiak, F.C., 2008. Prices vs. quantities: The effects on technology choice. Journal of Public Economics 92, 1275-1287.

Milliman, S.R., Prince, R., 1989. Firm Incentives to Promote Technological Change in Pollution Control. Journal of Environmental Economics and Management 17, 247-265.

Montero, J.P., 2002. Prices versus quantities with incomplete enforcement. Journal of Public Economics 85, 435-454.

Morris, J., Paltsev, S., Reilly, J., 2008. Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Reductions: Results from the EPPA Model, Joint Program on the Science and Policy of Global Change Report. Massachusetts Institute of Technology (MIT), Cambridge, MA.

Newell, R.G., Pizer, W.A., Zhang, J., 2005. Managing Permit Markets to Stabilize Prices. Environmental and Resource Economics 31, 133-157.

Parry, I.W.H., 1997. Environmental taxes and quotas in the presence of distorting taxes in factor markets. Resource and Energy Economics 19, 203-220.

Parry, I.W.H., Williams, R.C.I., 1999. A second-best evaluation of eight policy instruments to reduce carbon emissions. Resource and Energy Economics 21, 347-373.

Pizer, W.A., 2002. Combining price and quantity controls to mitigate global climate change. Journal of Public Economics 85, 409-434.

Roberts, J., Spence, M., 1976. Effluent charges and licenses under uncertainty. Journal of Public Economics 5, 193-208.

Sorrell, S., Sijm, J., 2003. Carbon Trading in the Policy Mix. Oxford Review of Economic Policy 19, 420-437.

Tinbergen, J., 1952. On the Theory of Economic Policy. North-Holland, Amsterdam.

Weitzman, M.L., 1974. Prices vs. quantities. Review of Economic Studies 41, 477-491.

Weitzman, M.L., 1978. Optimal rewards for economic regulation. American Economic Review 68, 683-691.

Woerdman, E., 2004. The Institutional Economics of Market-Based Climate Policy. Elsevier Science, Amsterdam.