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Environmental policy and technology diffusion under imperfect competition

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Chapter 9

Instrument comparison

9.1 Introduction

The numerical examples given in the previous chapters mainly concentrated on illustrating the various functional relationships with respect to the diffusion process under the different pollution control policies. The aim of this chapter is to provide a more thorough comparison of the instruments of environmental policy in order to make a more justifiable judgement on which instrument is best in terms of diffusion enhancement. In order to avoid an arbitrary comparison, we determine the equilibrium penetration of clean technology in such a way that all policy measures generate an equal amount of emissions in this equilibrium. We call these equilibria the '*constrained* evolutionary equilibria' (CEE). By calculating the CEE we do not have to worry about adjusting for emission afterwards and can directly evaluate and compare the instruments on their diffusion incentive effects, given total emissions are equal among the instruments in the corresponding equilibrium.

In policy terms the problem setting is as follows. Take for granted that the control authority wants to keep emissions below a predetermined target level and that, a priori, diffusion of clean technology is a good thing. Given such a setting, the question to be answered is which environmental policy instrument performs best. The answer is given in section 9.2. However, from an economic point of view this question is not the most interesting. Why should diffusion of clean technology have value in itself? The more conventional economic approach is to ask how different instruments of environmental policy contribute to welfare through their impact on the diffusion of clean technology, given a constraint on total emissions. This economically more interesting question will be tackled in section 9.3, comparing the different instruments under four different scenarios based on different assumptions on cost asymmetry and the relative pollution intensiveness of the two technologies. The chapter finalizes with conclusions in section 9.4.

9.2 Instrument ranking based on diffusion incentives

Knowing the parameter restrictions that yield a unique dynamically stable equilibrium (see chapter 6), an attempt can be made to rank the environmental policy instruments emission taxation, subsidies, permits and credits to the extent they stimulate diffusion of clean technology. The evolutionary equilibria serve as an indicator of this diffusion incentive since they measure the long-run penetration of clean technology firms. However, evaluating the evolutionary equilibria in the form as given in tables 7.2 and 8.1, will in principle not provide correct rankings. The reason is that these equilibria were calculated without considering the quality of the environment in terms of an industry emission target. Let's call these the '*unconstrained* evolutionary equilibria' (UEE). They are the equilibrium levels of diffusion contingent on the instruments, i.e., the emission tax rate, subsidy rate, emission ceiling and emission standard.

By looking at the diffusion incentive without explicitly considering a pollution externality, one can imagine that any degree of diffusion can be met as long as one sets the corresponding instrument variable (tax rate, subsidy rate, emission ceiling and emission standard) high enough. Determining which instrument yields the highest degree of diffusion is then quite arbitrary. Therefore, in order to provide a more correct basis for a comparison of the pollution control policies, we first determine the evolutionary diffusion equilibria given they all meet the same emission goal in this final equilibrium, i.e., the CEE. Subsequently, given the quality of the environment being equal under the four policy regimes, we can determine which policy yields the highest penetration of clean technology.

The first step in the procedure is to fix an emission target $\bar{E}$, which is equal for all policy regimes. Next we have to set the height of the instrument τ, υ, L and δ in such a way that they all generate $\bar{E}$ in the corresponding evolutionary equilibria. The tradable permit policy is the easiest case because the emission ceiling L automatically coincides with $\bar{E}$. Since industry emissions under permits are equal to L for all diffusion states $s \in [0,1]$, the UEE under permits is equivalent to the CEE under permits (see table 8.1). How to determine the level τ, υ and δ? For this we make use of the UEE. We will illustrate this for emission taxation. The same procedure can be applied to determine υ and δ for the subsidy and credit regime respectively.

All variables are a function of diffusion s. By setting $s = \tilde{s}^{tax}$ without fixing τ, we get the UEE $\tilde{s}^{tax}(\tau)$ as given in table 7.2. Substituting this into the model, all variables become dependent on τ and E^{tax}. The only thing we have to do now is to find the emission tax $\bar{\tau}$ such that $E^{tax} = \bar{E}$. Substitution of $\bar{\tau}$ back into $\tilde{s}^{tax}$ gives us the CEE under taxation ($\bar{s}^{tax}$) in which industry emissions are equal to $\bar{E}$. In the same way $\bar{\upsilon}$ and $\bar{\delta}$ and subsequently the CEE $\bar{s}^{sub}$ and $\bar{s}^{cre}$ can be found. Table 9.1 contains the analytical expressions for the CEE $\bar{s}^k$ $(k = tax, sub, per, cre)$.

Table 9.1: *Constrained evolutionary equilibria.*

Policy	$\bar{s}$
Taxation	$\frac{\zeta_d(\zeta_d\theta_c N - z_1) + \zeta_c(z_2 - \zeta_d\theta_d N)}{N[\zeta_d(z_3 + \zeta_d\theta_c) + \zeta_c(z_3 - \zeta_d(\theta_c + \theta_d)) + \zeta_c^2\theta_d]}$
Subsidy	$\frac{z_2 - \zeta_d\theta_d N}{N(z_3 + (\zeta_c - \zeta_d)\theta_d)}$
Permits	$\frac{\zeta_d z_1 - \zeta_c z_2 + \zeta_d N(\zeta_c\theta_d - \zeta_d\theta_c)}{N[(\zeta_d - \zeta_c)(\zeta_c\theta_d - \zeta_d\theta_c) - z_3(\zeta_d + \zeta_c)]}$
Credits	$\frac{d_1 \sqrt{(\zeta_c - \zeta_d)^2 N(d_2 + d_3)}}{2N(\zeta_c - \zeta_d)[(\zeta_c - \zeta_d)(\theta_c - \theta_d) - 2z_3]}$

The constants included in table 9.1 read as follows:

$$
\begin{aligned}
z_1 &= (\beta + \gamma N)\bar{E}, \\
z_2 &= \beta(N+1)\bar{E}, \\
z_3 &= (\beta - \gamma)\bar{E}, \\
d_1 &= -(\zeta_c - \zeta_d)N(2z_3 + \zeta_d\theta_c - (2\zeta_d - \zeta_c)\theta_d), \\
d_2 &= 4z_2\zeta_d\theta_d - (2z_3 + \zeta_d\theta_c)(2\bar{E}(\beta(N+2) + \gamma N)) + \zeta_c^2\theta_d^2 N, \\
d_3 &= 2\zeta_c(2z_2\theta_c - (2z_1 + \zeta_d\theta_c N)\theta_d).
\end{aligned}
$$

The associated levels of the specific instruments that yield the above CEE are given in table 9.2.

Table 9.2: *Constrained instrument levels.*

$$\tau = \frac{\beta(N+1)(\zeta_d\theta_d+\zeta_c\theta_c)-(\beta+\gamma N)(\zeta_d\theta_c+\zeta_c\theta_d)-(\beta-\gamma)\bar{E}(\gamma N+\beta(N+2))}{\beta(N+1)(\zeta_c^2+\zeta_d^2)-2(\beta+\gamma N)\zeta_c\zeta_d}$$

$$\upsilon = \frac{\beta(N+1)(\zeta_d\theta_d+\zeta_c\theta_c)-(\beta+\gamma N)(\zeta_d\theta_c+\zeta_c\theta_d)-(\beta-\gamma)\bar{E}(\gamma N+\beta(N+2))}{(\zeta_c-\zeta_d)[\beta(N+1)\zeta_c-(\beta+\gamma N)\zeta_d]}$$

$$L = \bar{E}$$

$$\delta = \frac{\theta_c(\zeta_d^2-\zeta_c\zeta_d)+\theta_d(\zeta_c^2-\zeta_c\zeta_d)+2(\beta-\gamma)\bar{E}+\sqrt{(\zeta_c-\zeta_d)^2N(d_2+d_3)}}{2N[2(\beta-\gamma)\bar{E}-(\zeta_c-\zeta_d)(\theta_c-\theta_d)]}$$

If we want to rank the instruments on the basis of the extent to which they enhance the penetration of clean technology, we can simply compare the four CEE and see which one is larger compared to the other. This leads us to the following proposition:

Proposition 5 *The ranking of the constrained evolutionary equilibria (CEE) is:*

$$\bar{s}^{tax} = \bar{s}^{per} \gtreqless \bar{s}^{cre} \gtreqless \bar{s}^{sub} \Longleftrightarrow h_1\theta_c - h_2\theta_d \lesseqgtr a,$$

where

$$\begin{aligned} h_1 &= \beta(N+1)\zeta_c - (\beta+\gamma N)\zeta_d \lesseqgtr 0, \\ h_2 &= (\beta+\gamma N)\zeta_c - \beta(N+1)\zeta_d < 0, \\ a &= (\beta-\gamma)\bar{E}(\gamma N + \beta(N+2)) > 0. \end{aligned}$$

Proof. We compared the instruments analytically in pairs. That is, we determined analytically when $\bar{s}^{tax} - \bar{s}^{sub} \lesseqgtr 0$, then $\bar{s}^{tax}$ versus $\bar{s}^{cre}$ and so on. By evaluating in this way, the common parameters h_1, h_2 and a are found. It is then straightforward to obtain the ranking. ■

Furthermore, $a > 0, h_1 \gtreqless 0, h_2 < 0$ and $h_1 > h_2$, provided $\zeta_c < \zeta_d$ and $\beta > \gamma$. Proposition 5 states that emission taxation and permits provide exactly the same diffusion incentive. In this case, it follows directly that the emission tax rate τ is equal to the equilibrium permit price $\tilde{\sigma}$. This can be checked by substituting the evolutionary equilibrium $\tilde{s}^{per}$ into the permit price function (8.6)[1]. Then, by looking at the final diffusion equilibrium, taxation and permits yield also the same outcome whenever $\tau = \tilde{\sigma}$. In case emissions can vary freely under taxation without a fixed outcome in the evolutionary equilibrium (the UEE situation), it then is evident that emission taxation yields a higher (lower) equilibrium degree of diffusion of clean technology whenever the tax rate is set higher (lower) to the equilibrium permit price[2].

Table 9.3 contains a summary of the ranking, given the inequality $h_1\theta_c - h_2\theta_d \lesseqgtr a$ in proposition 5. Rank number 1 means that the instrument stimulates diffusion most, i.e., it leads to the highest equilibrium degree of diffusion. When $h_1\theta_c - h_2\theta_d < a$, taxation and permits are best, followed by credits and subsidies respectively. In a situation of $h_1\theta_c - h_2\theta_d > a$ subsidies switch position with taxation and permits, i.e., subsidies yield the biggest incentive, followed by credits. Taxation and permits then provide the lowest diffusion incentive.

Table 9.3: *Ranking constrained evolutionary equilibria.*

Policy	$h_1\theta_c - h_2\theta_d < a$	$h_1\theta_c - h_2\theta_d > a$
Taxation	1	3
Subsidy	3	1
Permits	1	3
Credits	2	2

What does this result tell us? In the first place that the ranking depends on the underlying market structure in terms of the degree of product substitutabil-

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[1] This holds for both the constrained and unconstrained evolutionary equilibria.

[2] Be aware that by setting the emission tax τ such that the diffusion incentive is equivalent to permits, requires the control authority to have perfect information. Given the initial overall endowment of permits L, the control authority has to calculate the long-run diffusion incentive under permits and set the tax accordingly. If it is set such that $\tau = \widetilde{\sigma}$ the output at the firm level under both taxation and permits are also equal and hence the aggregate level of emissions in $\tilde{s}^{tax} = \tilde{s}^{per}$ are equivalent too, i.e., $\widetilde{E}^{tax}(\tilde{s}) = \widetilde{E}^{per}(\tilde{s}) = L$.

ity (measured by the difference between β and γ). Moreover, it depends on whether the clean or dirty firm has a net absolute advantage (measured by θ_j), which is conditional on the demand structure measured by α_j and the firm's cost structure ϑ_j. Finally, it depends on the relative pollution intensiveness of the clean and dirty technology (ζ_c versus ζ_d). So to implement the right policy instrument in terms of establishing the highest long-run penetration of clean technology, the policy maker inevitably has to take the market structure and the relative pollution intensiveness of the two technologies into account.

To illustrate how a switch in the relative instrument ranking may be established suppose, for instance, that the products are perfect substitutes implying that the direct and cross price effect coincide ($\beta = \gamma$). Consequently:

Corollary 6 *When products are perfect substitutes the relative instrument ranking is:* $\bar{s}^{tax} = \bar{s}^{per} \gtreqless \bar{s}^{cre} \gtreqless \bar{s}^{sub} \Longleftrightarrow \theta_d \lesseqgtr \theta_c$.

Proof. If $\beta = \gamma$ it follows that $a = 0$ and $h_1 = h_2 = h < 0$. Substituting this into the ranking rule of proposition 5 we obtain $h(\theta_c - \theta_d) \lesseqgtr 0$. Since $h < 0 \Longrightarrow h\theta_d \lesseqgtr h\theta_c \Longleftrightarrow \theta_d \lesseqgtr \theta_c$. ■

What does this imply? When products are perfect substitutes and the clean firm has a net absolute advantage over the dirty firm ($\theta_d < \theta_c$), (1) permits and emission taxation provide the highest penetration of clean technology followed by (2) credits and (3) subsidies. When the reverse holds ($\theta_d > \theta_c$), the subsidy instrument switches with permits and taxation, whereas credits maintains its second rank. Why is it that subsidies provide the biggest diffusion incentive when $\theta_d > \theta_c$? In this situation, the potential profits tend to be higher for dirty production relative to clean production, as we have seen under a laissez faire policy. An emission reduction subsidy does not increase the price of dirty output directly, but only indirectly by decreasing the price of the clean product. Therefore, total output tends to be higher and the emission target $\bar{E}$ can only be reached by a deep penetration of clean technology. Permits and taxes discourage dirty production by directly increasing the price of the dirty product thus relaxing the need for strong diffusion of clean technology. There already exists a 'natural' positive incentive to switch from the dirty to the clean technology if $\theta_c > \theta_d$. In such a case, the subsidy level does not have to be as high as when $\theta_c < \theta_d$, where the imposed high subsidies do generate an additional incentive in order to achieve the emission goal $\bar{E}$.

The preceding outline was more or less embedded into a 'technical' rationale. However, an aspect central to the policy maker is how the various instruments affect welfare. This component has not been discussed extensively so far. As a next step, we would like to include a welfare measure and examine some different scenarios.

9.3 The scenarios

9.3.1 The setup

In order to make an adequate comparison of the policy instruments possible, we follow the preceding route of setting an industry emission target $\bar{E}$, which is *equal* for *all* four policy regimes. We then calculate the emission tax τ, the subsidy rate υ and emission standard δ in such a way that the emission goal is fulfilled in diffusion equilibria $\tilde{s}^k$ $(k = tax, sub, per, cre)$. The permit regime is quite easy in this sense since the emission target $\bar{E}$ coincides with the emission ceiling L and is constant for all diffusion states.

Four scenarios are distinguished on the basis of cost asymmetry and the relative pollution intensiveness of the clean and dirty technology. More precisely, in the class of scenarios called 'A', we follow a relatively small difference between the emission/output ratios of the dirty and clean technology. Scenario class 'B' relaxes this assumption and considers the situation of a relatively large difference between the emission/output ratios. To put it differently, by assuming a large difference in the pollution intensiveness, the clean technology can be interpreted as extremely clean, generating only a fraction of pollution per unit of output compared to the dirty technology. The other two scenario classes, tagged I and II, are based on the difference in the cost structure. Scenario type I refers to the situation of asymmetric costs, whereas scenario type II follows the symmetric cost route. Combining these different classes a total number of four scenarios can be distinguished:

- **Scenario A-I:** cost *asymmetry* and a relatively *small* difference in the pollution intensiveness of the technologies;
- **Scenario A-II:** cost *symmetry* and a relatively *small* difference in the pollution intensiveness of the technologies;
- **Scenario B-I:** cost *asymmetry* and a relatively *large* difference in the pollution intensiveness of the technologies;
- **Scenario B-II:** cost *symmetry* and a relatively *large* difference in the pollution intensiveness of the technologies.

The numerical values assigned to the different parameters as well as a complete overview of the numerical results under the four scenarios can be found in appendix 9A. Note that the values of τ, υ and δ are determined on the basis of the values of all the other parameters in order to meet $\bar{E}$ in the evolutionary equilibrium. The industry emission targets under taxation, subsidies and credits thus coincide with the emission ceiling L in the corresponding tradable permit regime.

We shall use the four scenarios to assess the consequences of each instrument for the diffusion of clean technology and for the attained level of welfare. Regarding the welfare assessment it is useful to have a benchmark. We therefore calculate in subsection 9.3.2 the maximum welfare that could be realized by a benevolent and fully informed government, which would replace the imperfect and heterogeneous market. Next, in subsection 9.3.3, the performance of the environmental policy instruments applied in an imperfect output market setting is confronted with the benchmark of welfare maximization.

9.3.2 Welfare maximization

Suppose the government aims at maximizing welfare under the constraint that aggregate emissions meet the emission ceiling $\bar{E}$. Substituting the expressions for consumer surplus (6.20) and producer surplus (6.21) into the welfare function (6.22), this optimization problem reads:

$$\max W = \frac{1}{2}\beta(X_d^2 + X_c^2) + \gamma X_d X_c + \beta(X_d x_d + X_c x_c), \tag{9.1}$$

subject to:

$$\zeta_d X_d + \zeta_c X_c = \bar{E},$$

again with $X_d = (1-s)Nx_d$ and $X_c = sNx_c$. The Lagrangian $\mathcal{L}$ of this constrained optimization problem is:

$$\mathcal{L} = W + \lambda(\bar{E} - \zeta_d X_d - \zeta_c X_c). \tag{9.2}$$

The unknowns are λ, x_d, x_c and s. The Lagrange multiplier λ can be interpreted as the shadow price for emissions.

The first derivatives of (9.2) with respect to λ, x_d, x_c and s are respectively:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial \lambda} &= \bar{E} - N(s\zeta_c x_c - (1-s)\zeta_d x_d), \qquad (9.3)\\
\frac{\partial \mathcal{L}}{\partial x_d} &= (1-s)N(2\beta x_d - \lambda\zeta_d) + (1-s)N^2(s\gamma x_c + (1-s)\beta x_d),\\
\frac{\partial \mathcal{L}}{\partial x_c} &= sN(2\beta x_c - \lambda\zeta_c) + sN^2(s\beta x_c + (1-s)\gamma x_d),\\
\frac{\partial \mathcal{L}}{\partial s} &= \gamma N^2 x_d x_c + \beta[N x_c^2(sN+1) - N x_d^2((1-s)N+1)]\\
&\qquad +\lambda N(\zeta_d x_d + \zeta_c x_c)
\end{aligned}$$

By simultaneously solving $\partial\mathcal{L}/\partial\lambda = 0, \partial\mathcal{L}/\partial x_d = 0, \partial\mathcal{L}/\partial x_c = 0$ and $\partial\mathcal{L}/\partial s = 0$, we obtain for each scenario the results as summarized in table 9.4.

Table 9.4: *Welfare maximization results.*

	Scenario			
Variable	A-I	A-II	B-I	B-II
s	1	1	1	1
λ	684.4	684.4	5812.5	5812.5
x_d	0	0	0	0
x_c	18.3	18.3	38.8	38.8
X_c	146.4	146.4	310.4	310.4
W	20093.4	20093.4	90326.4	90326.4

The idea behind welfare maximization is that production is expanded as long as it generates additional positive welfare. Welfare maximization in our case implies stimulating production, but at the same time with a limit on the total allowed emissions. As is well known, the maximum welfare result can be realized by either a fully informed perfect planner or by a market system characterized by perfect competition. It turns out that the welfare maximum coincides with the corner state where the industry comprises clean firms only ($s = 1$). As a result, dirty firm-level output $x_d = 0$. Compared to scenario A, the welfare maximizing clean output x_c is higher in the B-scenario because the emission constraint is less stringent relative to the technical feasible clean production[3]. Due to the smaller emission space under the B-scenario, the shadow price for emissions λ is also higher under the B scenario. The intuition of the welfare maximizing outcome is that the clean product has a net absolute advantage over the dirty product and therefore generates a larger surplus at the margin at any level $X_d = X_c$.

Knowing the diffusion states which maximize welfare, we can compare them with the CEE and see which instrument is better from a welfare perspective. We therefore first determine the diffusion incentives under the four scenarios, i.e., calculate the CEE, and project them onto the welfare maximum states.

9.3.3 Diffusion incentives and welfare projection

Given the industry settings under the four scenarios as contained in appendix 9A, one can calculate the CEE as explained in section 9.2. Table 9.5 contains these values[4]. The relative ranking based on the equilibrium level of diffusion from high to low is between brackets and we see that all four policy regimes represent the case where $h_1\theta_c - h_2\theta_d > a$, as derived in the previous section. The ranking in table 9.5 shows the extent to which each instrument approaches the welfare maximum $s = 1$. The more an instrument is diffusion enhancing, the better the instrument since it's closer to the welfare maximum.

Table 9.5: *Constrained evolutionary equilibria under the four scenarios.*

	Scenario			
Policy regime	A-I	A-II	B-I	B-II
Subsidy	0.719 (1)	0.719 (1)	0.715 (1)	0.715 (1)
Credits	0.653 (2)	0.599 (2)	0.698 (2)	0.684 (2)
Taxation	0.647 (3)	0.586 (3)	0.691 (3)	0.670 (3)
Permits	0.647 (3)	0.586 (3)	0.691 (3)	0.670 (3)

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[3] In the A-scenario $\bar{E} = 58.4$ while under the B-scenario $\bar{E} = 31$, but ζ_c is 0.4, respectively 0.1.

[4] Before we continue keep in mind that, in itself, it does not matter how far the penetration of clean technology proceeds since the overall emission target is always met in the interior evolutionary stable diffusion state. But we can, however, compare the technological configuration of clean and dirty type firms in the industry under the four scenarios and a few things appear from these equilibrium configurations as shown in table 9.5.

Table 9.5 reveals that emission taxation and tradable permits provide equivalent diffusion incentives. This is not so strange. A comparison of the optimal output levels under taxation [equation (7.4)] and permits [equation (8.4)] learns that the expressions are equivalent when the emission tax rate τ and the permit price σ are equal. However, as stated before, the emission tax is exogenous whereas the permit price is determined endogenously. Substituting the CEE under permits into the permit price function (8.6) yields an equilibrium permit price $\tilde{\sigma}$, which exactly coincides with the emission tax τ. We also checked this numerically for the distinguished scenarios and indeed find that this holds. The levels of τ (and thus equilibrium permit price $\tilde{\sigma}$) can be found in appendix 9A. When the emission goal is the same for both taxation and permits, the permit and output market coordinate behavior such that this goal is met. Subsequently, both the taxation and permit policy generate the same behavior on the output market and are thus equivalent to each other in all aspects, i.e., all four scenarios show the same values for the considered variables under taxation and permits in the evolutionary equilibrium.

Second, given the specified market conditions, it appears that taxation and permits yield the lowest penetration of clean technology as well as lowest welfare. Subsidies perform best on the two criteria and credits are in between. The major force in explaining the differences is the impact of the instrument on total output and its composition. Subsidies for emission reduction stimulate clean production without directly discouraging dirty production. Consequently, higher total output, which tends to drive up emissions, requires a deep penetration of clean technology and a higher share of clean production in total output. This is shown in table 9.6. The table provides the shares of *clean* industry output and *clean* industry emissions in total output and total emissions respectively in the evolutionary stable diffusion states presented in table 9.5.

The story for emission taxation and permits goes the other way around. By putting a price on emissions firm-level output is negatively affected and will therefore generate lower industrial output hence yielding lower emissions. This implies that the industry under a permit and taxation policy does not have to be as 'clean' (represented by the fraction of clean type firms) as would be under subsidies. This can be seen in tables 9.5 and 9.6.

Like taxation and permits, a credit scheme attaches a price to emissions too, but only to the emissions of dirty firms that exceed the emission standard. If costs of credits depress output less than the taxation and permit scheme do, it requires a somewhat deeper penetration of clean technology (see table 9.5) and a bit larger share of clean output (see table 9.6).

Table 9.6: *Shares of clean industry output and clean industry emissions in the constrained evolutionary equilibria.*

Policy	Scenario							
	A-I		A-II		B-I		B-II	
	% X_c	% E_c	% X_c	% E_c	% X_c	% E_c	% X_c	% E_c
Taxation	64.7	55.0	58.6	48.6	69.2	27.1	67.0	25.2
Subsidy	71.9	63.0	71.9	63.0	71.5	29.4	71.5	29.4
Permits	64.7	55.0	58.6	48.6	69.2	27.1	67.0	25.2
Credits	65.2	55.7	59.9	49.8	69.8	27.7	68.4	26.5
Welf. max.	100	100	100	100	100	100	100	100

In essence, from an overall point of view the underlying evolutionary stable configurations of which type of firms contributes most to pollution is not so important since the emission target is fixed and equal across the different scenarios. With this we mean that from an industry's perspective it does not matter how the emission target is reached. Focusing on the shares of clean output and 'clean' emissions we find (not surprisingly) a complete parallel between the outcomes under taxation and permits due to the equivalence of the equilibria.

As table 9.6 indicates, in all cases clean industry output has the biggest share in total output. In this respect subsidies are best and face shares exceeding 70%. Credits are second-best, followed by taxation and permits. The differences are not so big across scenarios in the percentage levels of X_c. This is different when we take a look at the share of industry emissions that is attributed to the clean firms in the total volume of emissions. Under scenarios B-I and B-II the percentage of clean industry emissions in total emissions is much lower than under scenarios A-I and A-II. This is due to the large difference in the emission coefficients between the two technologies under scenario type B, i.e., the abatement technology is extremely clean relative to the dirty technology. Consequently, the relative share of clean emissions under B-I and B-II will then also be lower compared to A-I and A-II.

The welfare interpretation of table 9.6 is straightforward. In general, it is well known that oligopolistic markets generate an output level that is too low compared to the welfare maximum. As stated before, the introduction of emission taxes and permits tend to restrict clean and dirty output even further. If the market structure would have been perfectly competitive, the negative impact on output would have been optimal because it prevents output from being too high given the shadow price of emissions. But in our case where output is already too low due to Cournot oligopoly, permits and taxes work in the wrong direction. On the other hand,emission reduction subsidies (which tend to increase output) is the most appropriate instrument here to raise welfare. Tradable credits, which lowers the price of clean products but increases the price of dirty products, is just in between in its impact on output and welfare.

We also calculated the situation under the four scenarios in case the products are perfect substitutes in the sense that $\beta = \gamma$ (but $\alpha_c > \alpha_d$). Then under all four scenarios the clean firm still has a net absolute advantage over the dirty firm ($\theta_d < \theta_c$). In this case, competition between clean and dirty firms is enhanced and the distance between the oligopolistic level of output and the welfare maximizing output (equal to the output level under perfect competition) is smaller. In this type of market, a subsidy for emission reduction would stimulate output too much thus reducing welfare. Here tradable permits and emission taxes are the most appropriate instruments (as they would have been in a perfectly competitive output market) to keep output in check and thus raise welfare. The tradable credit policy is second-best.

Finally, let's take a closer look at the welfare components consumer and producer surplus. Table 9.7 gives an overview of the shares of these components in the CEE. Table 9.7 shows that across scenarios in equilibrium roughly 77% is attributed to CS, while the remaining 23% is PS. Cost asymmetry and differences in the relative pollution intensiveness doesn't seem to have a significant impact on changes of these welfare components. In the welfare maximum $s = 1$, CS is somewhat bigger (80%) and PS a little lower (20%) compared to the levels in the CEE. From this result we can also deduce that stimulating diffusion by means of environmental policy will harm producers simply because PS in the CEE is bigger that PS in the welfare maximum. The reverse holds for consumers; they gain from environmental policy in terms of enhanced diffusion relative to the welfare maximum.

Table 9.7: *Shares of consumer and producer surplus in the constrained evolutionary equilibria.*

	Scenario							
Policy regime	A-I		A-II		B-I		B-II	
	%CS	%PS	%CS	%PS	%CS	%PS	%CS	%PS
Taxation	77.2	22.8	77.0	23.0	77.4	22.6	77.3	22.7
Subsidy	77.6	22.4	77.6	22.4	77.6	22.4	77.6	22.4
Permits	77.2	22.8	77.0	23.0	77.4	22.6	77.3	22.7
Credits	77.3	22.7	77.1	22.9	77.5	22.5	77.4	22.6
Welf. max.	80.0	20.0	80.0	20.0	80.0	20.0	80.0	20.0

9.4 Concluding remarks

In this chapter we evaluated a system of emission taxation, subsidies for emission reduction, tradable emission permits and tradable credits to see how they perform in stimulating the diffusion of clean technology in the long-run and in increasing welfare. In order to avoid an arbitrary comparison, we introduced an emission target which is equal for all four pollution control policies. For each instrument we subsequently determined the so-called ‘constrained evolutionary equilibrium’ (CEE), which is the equilibrium diffusion state that satisfies the emission target. The CEE is thus a direct measure of the diffusion incentive given a fixed emission target. Emission taxation and permits provide an equivalent diffusion incentive and the emission tax coincides with the permit price in the evolutionary equilibrium under permits in such a case.

A comparison of the dynamically stable CEE reveals that no unique instrument ranking exists. Which instrument provides the highest penetration of clean technology depends on the market (demand) structure, cost structure and the relative pollution intensiveness of the clean and dirty technology. When products are perfect substitutes and the clean firm has a net absolute advantage over the dirty type firm, (1) permits and emission taxes provide the biggest incentive, followed by (2) credits and (3) subsidies. In case the dirty firm has a net absolute advantage over the clean firm, the ranking becomes (1) subsidies, (2) credits and (3) permits and taxes. So, the instrument ranking switches depending on the demand structure and cost setting.

We have investigated the welfare impacts numerically. The instrument that generates the highest degree of diffusion is also closest to the welfare maximum. So there is strict complementarity of instrument choice maximizing diffusion and maximizing welfare. For a market structure that diverges not too much from perfect competition, the welfare performance takes the ranking order: (1) permits and emission tax, (2) credits, (3) subsidies. The ranking order is reversed with product heterogeneity and a stronger distortion due to oligopoly. In case of such a strong oligopolistic market structure, the analysis suggests a second-best policy. A 'distorting' environmental policy instrument - emission reduction subsidy - is applied to redress the distortion created by an oligopolistic market structure. This redress consists of stimulating output, which is held back by profit maximizing oligopolistic firms; there is a boost from the emission reduction subsidy, which indirectly stimulates the demand for clean products.

As a consequence, the instrument choice entails an awkward complication for the policy maker. To be able to impose the most suitable instrument for stimulating diffusion (and by that welfare) as much as possible, the policy maker needs to have adequate information about the market structure, the pollution intensiveness of the technologies and even information on private costs. A lack of information about this implies a weakening of the policy basis to initiate the right incentive. To make policy decisions even more complicated, the policy maker should not only look at the ultimate equilibrium position, but also at the economic adjustment pains it may cause and the pattern of emissions during diffusion.

In the welfare maximizing case, dirty output is crowded out completely, leaving no room for the dirty technology. Knowing that welfare maximization reflects solely the supply of clean products, we can say that under imperfect competition there is not only too little production (as is commonly known), but that there is also too much supply of dirty output. Considering the lack of up-to-date information on the specific features of the market, that is, the level of product differentiation and the firm's relative absolute advantages, the most sensible way to proceed is a general competition policy, which eliminates barriers to entry for new firms, aiming at workable competition and applies first-best instruments in its environmental policy. That is, environmental taxes or the politically more feasible instrument of grandfathered permits to stimulate the adoption and diffusion of clean technology.

9.5 Appendix 9A

Scenario A-I

$N = 8$; $\zeta_d = 0.6$, $\zeta_c = 0.4$; $\alpha_d = 190$, $\alpha_c = 200$, $\beta = 1.5$, $\gamma = 1.0$; $\mu_d = 0$, $\mu_d = 0$, $\vartheta_d = 20$, $\vartheta_c = 12$; $\bar{E} = 58.4$; $\tau = 1.220$; $\upsilon = 50.0$; $\delta = 0.469$

	Instrument				
Variable	laissez faire	taxation	subsidy	permits	credits
$\tilde{s}$	0.644	0.647	0.719	0.647	0.653
p_d	43.3	44.0	44.0	44.0	44.0
p_c	35.3	35.8	26.0	35.8	35.0
c_d	311.3	310.2	320.0	310.2	311.0
c_c	186.8	186.1	192.0	186.1	186.6
x_d	15.6	15.5	16.0	15.5	15.6
x_c	15.6	15.5	16.0	15.5	15.6
π_d	363.4	360.9	384.0	360.9	362.8
π_c	363.4	360.9	384.0	360.9	362.8
X_d	44.3	43.8	36.0	43.8	43.2
X_c	80.3	80.3	92.0	80.3	81.1
X	124.6	124.1	128.0	124.1	124.4
E_d	26.6	26.3	21.6	26.3	25.9
E_c	32.1	32.1	36.8	32.1	32.5
E	58.7	58.4	58.4	58.4	58.4
CS	9853.0	9791.6	10632.0	9791.6	9855.1
PS	2907.3	2887.5	3072.0	2887.5	2902.2
W	12760.3	12679.1	13704.0	12679.1	12757.3

Scenario A-II

$N = 8$; $\zeta_d = 0.6$, $\zeta_c = 0.4$; $\alpha_d = 190$, $\alpha_c = 200$, $\beta = 1.5$, $\gamma = 1.0$; $\mu_d = 0$, $\mu_d = 0$, $\vartheta_d = 20$, $\vartheta_c = 20$; $\bar{E} = 58.4$; $\tau = 2.195$; $\upsilon = 90.0$; $\delta = 0.480$

	Instrument				
Variable	laissez faire	taxation	subsidy	permits	credits
$\tilde{s}$	0.582	0.586	0.719	0.586	0.599
p_d	42.8	44.0	44.0	44.0	44.0
p_c	42.8	43.6	36.0	43.6	42.0
c_d	304.3	302.4	320.0	302.4	304.0
c_c	304.3	302.4	320.0	302.4	304.0
x_d	15.2	15.1	16.0	15.1	15.2
x_c	15.2	15.1	16.0	15.1	15.2
π_d	347.4	343.0	384.0	343.0	346.6
π_c	347.4	343.0	384.0	343.0	346.6
X_d	50.9	50.0	36.0	50.0	48.8
X_c	70.9	70.9	92.0	70.9	72.8
X	121.8	120.9	128.0	120.9	121.6
E_d	30.5	30.0	21.6	30.0	29.3
E_c	28.3	28.4	36.8	28.4	29.1
E	58.8	58.4	58.4	58.4	58.4
CS	9312.8	9201.4	10632.0	9201.4	9313.9
PS	2778.8	2744.1	3072.0	2744.1	2772.6
W	12091.6	11945.5	13704.0	11945.5	12086.4

Scenario B-I

$N = 8$; $\zeta_d = 0.6; \zeta_c = 0.1$; $\alpha_d = 190, \alpha_c = 200$, $\beta = 1.5$, $\gamma = 1.0$; $\mu_d = 0$, $\mu_d = 0$, $\vartheta_d = 20$, $\vartheta_c = 12$; $\bar{E} = 31$; $\tau = 10.687$; $\upsilon = 18.943$; $\delta = 0.251$

	Instrument				
Variable	laissez faire	taxation	subsidy	permits	credits
$\tilde{s}$	0.644	0.691	0.715	0.691	0.698
p_d	43.3	49.3	44.0	49.3	47.7
p_c	35.3	35.9	26.5	35.9	33.2
c_d	311.3	304.8	319.5	304.8	309.0
c_c	186.8	182.9	191.7	182.9	185.4
x_d	15.6	15.2	16.0	15.2	15.5
x_c	15.6	15.2	16.0	15.2	15.5
π_d	363.4	348.4	382.9	348.4	358.2
π_c	363.4	348.4	382.9	348.4	358.2
X_d	44.3	37.6	36.4	37.6	37.3
X_c	80.3	84.3	91.4	84.3	86.3
X	124.6	121.9	127.8	121.9	123.6
E_d	26.5	22.6	21.9	22.6	22.4
E_c	8.0	8.4	9.1	8.4	8.6
E	34.6	31.0	31.0	31.0	31.0
CS	9853.0	9562.7	10587.9	9562.7	9852.1
PS	2907.3	2787.1	3063.2	2787.1	2865.3
W	12760.4	12349.8	13651.1	12349.8	12717.4

Scenario B-II

$N = 8; \zeta_d = 0.6$; $\zeta_c = 0.1$; $\alpha_d = 190$; $\alpha_c = 200$; $\beta = 1.5$; $\gamma = 1.0$; $\mu_d = 0$; $\mu_d = 0$; $\vartheta_d = 20$; $\vartheta_c = 20$; $\bar{E} = 31$; $\tau = 19.715$; $\upsilon = 34.943$; $\delta = 0.258$

	Instrument				
Variable	laissez faire	taxation	subsidy	permits	credits
$\tilde{s}$	0.582	0.670	0.715	0.670	0.684
p_d	42.8	53.8	44.0	53.8	50.8
p_c	42.8	43.9	26.5	43.9	38.7
c_d	304.3	292.3	319.5	292.3	300.5
c_c	304.3	292.3	319.5	292.3	300.5
x_d	15.2	14.6	16.0	14.6	15.0
x_c	15.2	14.6	16.0	14.6	15.0
π_d	347.4	320.5	382.9	320.5	338.5
π_c	347.4	320.5	382.9	320.5	338.5
X_d	50.9	38.6	36.4	38.6	38.0
X_c	70.9	78.3	91.4	78.3	82.2
X	121.8	116.9	127.8	116.9	120.2
E_d	30.5	23.2	21.9	23.2	22.8
E_c	7.1	7.8	9.1	7.8	8.2
E	37.6	31.0	31.0	31.0	31.0
CS	9312.8	8743.9	10587.9	8743.9	9272.7
PS	2778.8	2564.0	3063.2	2564.0	2708.3
W	12091.6	11307.9	13651.1	11307.9	11981.0