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Environmental policy and technology diffusion under imperfect competition

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Chapter 7

Taxation versus subsidies

7.1 Introduction

A government has various instruments at its disposal to control pollution. This dissertation analyzes the impact of emission taxation, subsidies, tradable emission permits and tradable emission credits on the diffusion of clean technology and industrial pollution. The current chapter is devoted to the taxation and subsidy instrument, followed up by a treatment of a marketable permit and credit system in chapter 8.

In chapter 6 it has been demonstrated that when the government abstains from environmental policy, diffusion moves towards an evolutionary equilibrium where firms that produce by means of the clean technology coexist next to firms that use the dirty technology. The first question of this chapter is how the above mentioned policy instruments affect the dynamics and the equilibrium degree of diffusion. The second research question that will be dealt with is how industrial pollution –its behavior during the process of diffusion as well as the pollution level in the evolutionary equilibrium– is affected by the implementation of the specific policy instrument. This is in particular interesting because the dynamics of diffusion, with firms switching from a dirty to a clean production mode, affects the total level and composition (clean and dirty) of industrial output and accordingly pollution. In this regard it is natural to ask which instrument is better in terms of limiting pollution. That is, will environmental policy induce more firms to produce clean and, if yes, what is the long-run equilibrium penetration of clean technology users?

As stated before, the laissez faire regime did not involve any environmental policy measure and will serve as a benchmark. We start by examining emission taxation in section 7.2, followed by the subsidy regime in section 7.3. Section 7.4 contains a numerical example. The evolutionary equilibria and associated comparative statics are discussed in section 7.5. The main results and conclusions are in section 7.6.

7.2 Emission taxation

Comparative statics on total industry emissions in relation to the degree of diffusion under a laissez faire regime showed that industry emissions can increase in the first stage of diffusion and decrease in the second stage. Now assume the government wants to reduce the total level of pollution by introducing a uniform tax τ per unit of emission. To make a comparison with laissez faire possible, we use again the linear emission function as in (6.9): $e_j^{tax} = \zeta_j x_j^{tax}$ $(j = d, c)$.

In case of laissez faire, profit maximization implied maximizing revenues over total costs. Total costs under this policy regime reflect only costs involved with production. However, now for each unit of emission generated through production each individual firm $i = 1, 2, \ldots, N$ has to pay a tax τ. The tax rate is given for the firm and does not depend on diffusion s. Compared to the laissez faire case, the profit maximizing firm that chooses technology j now also has to take the emission tax into account. The profit function to be maximized then reads:

$$\max_{x_j^{tax}} \pi_j^{tax} = p_j^{tax} x_j^{tax} - c_j^{tax} - \tau e_j^{tax}. \tag{7.1}$$

Substituting (6.1), (6.7) and (6.9) in (7.1) and rewriting gives the profit functions to be maximized by the firms applying the dirty and clean technology respectively:

$$\begin{aligned} \max_{x_d^{tax}} \pi_d^{tax} &= (\theta_d - \tau\zeta_d - \beta(\widehat{X}_d^{tax} + x_d^{tax}) - \gamma X_c^{tax}) x_d^{tax} - \mu_d, \\ \max_{x_c^{tax}} \pi_c^{tax} &= (\theta_c - \tau\zeta_c - \beta(\widehat{X}_c^{tax} + x_c^{tax}) - \gamma X_d^{tax}) x_c^{tax} - \mu_c, \end{aligned} \tag{7.2}$$

with $\widehat{X}_j^{tax}$ $(j = d, c)$ as in (6.12) and X_j^{tax} $(j = d, c)$ as in (6.4). Compared to laissez faire, the constant $\tau\zeta_j$, expressing the pollution tax per unit of output, appears in the profit function. The term θ_j as expressed in (6.8) again defines the net absolute advantage for a firm endowed with technology $j = d, c$. Like under laissez faire, firms maximize short-run profits by simultaneously choosing the optimal output quantity given the current state of diffusion s, i.e., given the configuration of clean and dirty type firms. The simultaneous solution to the first-order conditions

$$\begin{aligned}\frac{\partial \pi_d^{tax}}{\partial x_d^{tax}} &= \theta_d - \tau\zeta_d - \beta(\widehat{X}_d^{tax} + x_d^{tax}) - \gamma X_c^{tax} - \beta x_d^{tax} = 0, \\ \frac{\partial \pi_c^{tax}}{\partial x_c^{tax}} &= \theta_c - \tau\zeta_c - \beta(\widehat{X}_c^{tax} + x_c^{tax}) - \gamma X_d^{tax} - \beta x_c^{tax} = 0,\end{aligned} \qquad (7.3)$$

yields the Cournot-Nash quantities for each state of diffusion $s \in [0,1]$:

$$\begin{aligned}x_d^{tax} &= \frac{\beta(sN+1)(\theta_d - \tau\zeta_d) - \gamma sN(\theta_c - \tau\zeta_c)}{\Theta}, \\ x_c^{tax} &= \frac{\gamma(s-1)N(\theta_d - \tau\zeta_d) - \beta((s-1)N-1)(\theta_c - \tau\zeta_c)}{\Theta},\end{aligned} \qquad (7.4)$$

with Θ as expressed by (6.16).

Diffusion is defined as the increase in the fraction s of clean type firms in the industry. As under laissez faire, we assume that $dx_c^{tax}/ds < 0$ and $dx_d^{tax}/ds > 0$. The former implies that the quantity supplied by the clean firm decreases as more firms enter the clean submarket. The latter condition reflects the reverse case: as more firms adopt the clean technology, the quantity produced by the dirty firm increases since the size of the dirty product market shrinks. From (7.4) it follows that an increase in the emission tax τ results in less supply by both the clean and dirty firm:

$$\begin{aligned}\frac{\partial x_d^{tax}}{\partial \tau} &= \frac{\gamma sN\zeta_c - \beta(sN+1)\zeta_d}{\Theta} < 0, \\ \frac{\partial x_c^{tax}}{\partial \tau} &= \frac{\beta((s-1)N-1)\zeta_c - \gamma(s-1)N\zeta_d}{\Theta} < 0.\end{aligned}$$

Furthermore, $\partial x_d^{tax}/\partial\tau > \partial x_c^{tax}/\partial\tau$; an additional euro of emission taxation reduces dirty output more than the clean output. The intuition is that the introduction of a uniform emission tax raises the prices for both the clean and dirty good (but more for the dirty good than for the clean good), which in turn results in lower sales (output) levels (and most so for the dirty product variant).

7.3 Subsidy

Whereas an emission tax affects firm-level profits adversely, the government can also influence firm profits in a positive way by means of a subsidy for each unit of emission reduction or for installing technology that has the capacity to reduce emissions. Although subsidies increase profits, one should ask whether this instrument also has a positive incentive on reducing emissions. Theory learns us though that when subsidies are directed towards stimulating technology itself[1], a faire chance exists that emissions tend to increase (e.g. Baumol and Oates, 1988). The rationale behind Baumol and Oates' explanation basically comes down to their free entry assumption. They argue that subsidies might attract new firms hence inducing an expansion in competitive outputs (*cf.* Baumol and Oates, 1988, p.212) given the assumption that emissions increase monotonically with industry output. Obviously, their result only applies to the industry level and not the firm level. Our model does not include any entry mechanism. Another main difference between Baumol and Oates (1988) and the current model is that in the former model the industry has a perfect competitive market structure, while our scope is that of imperfect competition. The interesting question is now whether also under these circumstances subsidies for clean technology could stimulate pollution and thus affect the environmental quality adversely.

We consider a form of subsidy that is directed towards the potential level of emissions. Assume the government introduces a subsidy v per unit of emission reduction r. If a firm currently employs the dirty technology and wants to switch to the clean production process by adopting the clean technology, it reduces the amount of emissions caused by the production of clean output x_c. In turn, emission reduction r can be expressed as:

$$r = (\zeta_d - \zeta_c)x_c. \tag{7.5}$$

The marginal rate of emission reduction is constant and equals the difference between the emission coefficients of the dirty and clean technology, i.e., $dr/dx_c = \zeta_d - \zeta_c > 0$. The total amount of subsidies h that will be received by the clean firm is then simply:

$$h = vr. \tag{7.6}$$

The profit function of firms using the dirty technology remains the same as under laissez faire according to (6.10). The maximization problem of the clean firm changes to:

$$\max_{x_c^{sub}} \pi_c^{sub} = p_c^{sub} x_c^{sub} - c_c^{sub} + h. \tag{7.7}$$

From (7.7) we see that the clean firm gains an amount of subsidy h equal to the amount of emission it reduces according to the emission reduction function

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[1] This could be interpreted as lump-sum subsidies.

(7.5) multiplied by the subsidy υ. In the same line as in the taxation exercise, the profit function of the clean firm (7.7) can be rewritten in terms of the net absolute advantage $\theta_c = \alpha_c - \vartheta_c$:

$$\max_{x_c^{sub}} \pi_c^{sub} = (\theta_c + \upsilon(\zeta_d - \zeta_c) - \beta(\widehat{X}_c^{sub} + x_c^{sub}) - \gamma X_d^{sub})x_c^{sub} - \mu_c, \qquad (7.8)$$

with $\widehat{X}_j^{sub}$ ($j = d, c$) as defined in (6.12). Again, the aggregate output levels X_j^{sub} ($j = d, c$) can be written as in (6.4). Equation (7.8) indicates that profits increase proportionally with production x_c^{sub} with $\upsilon(\zeta_d - \zeta_c)$. The higher the volume of clean production the higher the monetary value from subsidies. Like before, one obtains the Cournot-Nash quantities by solving the first-order conditions simultaneously. The first-order condition $\partial\pi_d^{sub}/\partial x_d^{sub} = 0$ is the same as under laissez faire [see equation (6.14)]. The first-order condition for the clean firm reads:

$$\frac{\partial \pi_c^{sub}}{\partial x_c^{sub}} = \theta_c + \upsilon(\zeta_d - \zeta_c) - \beta(\widehat{X}_c^{sub} + x_c^{sub}) - \gamma X_d^{sub} - \beta x_c^{sub} = 0. \qquad (7.9)$$

The corresponding Cournot-Nash equilibria are then:

$$\begin{aligned} x_d^{sub} &= \frac{\beta(sN+1)\theta_d - \gamma sN(\upsilon(\zeta_d - \zeta_c) + \theta_c)}{\Theta}, \qquad (7.10) \\ x_c^{sub} &= \frac{\gamma(s-1)N\theta_d - \beta((s-1)N-1)(\upsilon(\zeta_d - \zeta_c) + \theta_c)}{\Theta}, \end{aligned}$$

with Θ as in (6.16). A subsidy υ stimulates the decision to adopt the clean technology and results in a higher firm-level output of the clean good:

$$\frac{\partial x_c^{sub}}{\partial \upsilon} = \frac{\beta(\zeta_c - \zeta_d)((s-1)N-1)}{\Theta} > 0.$$

The change in the output supply of the dirty firm for $s > 0$ equals:

$$\frac{\partial x_d^{sub}}{\partial \upsilon} = \frac{\gamma sN(\zeta_c - \zeta_d)}{\Theta} < 0.$$

The intuition is that a subsidy for emission reduction lowers the price of the clean product, hence attracting consumers from the dirty to the clean product variant. Evidently, when the industry only comprises dirty firms ($s = 0$), $\partial x_d^{sub}/\partial\upsilon = 0$.

7.4 A numerical example

We project the illustration of the taxation and subsidy policy on the laissez faire benchmark case and adopt the assumptions made earlier. In a nutshell, these included a price premium on the clean good ($\alpha_d < \alpha_c$), linear demand but with a higher direct price effect relative to the cross price effect ($\beta > \gamma$). The products manufactured by the two technologies are imperfect substitutes, reflected by $\gamma > 0$. Adoption of the clean technology results in lower variable costs of production compared to operating with the dirty technology ($\vartheta_d > \vartheta_c$). Finally, firm-level emissions are proportional to output, but with a lower emission/output ratio for the clean technology ($\zeta_d > \zeta_c$). As before, we assume: $N = 8, \alpha_d = 190, \alpha_c = 200, \beta = 1.5, \gamma = 1.0, \vartheta_d = 20, \vartheta_c = 12, \zeta_d = 0.6, \zeta_c = 0.4$. Contrary to laissez faire, we have to put a value for the emission tax τ and subsidy υ. We set the tax and subsidy at $\tau = 25$ and $\upsilon = 25$.[2] An emission tax rate of 25 boils down to a tax of 10 ($\zeta_c\tau = 0.4 \times 25$) per unit of x_c and 15 ($\zeta_d\tau = 0.6 \times 25$) per unit of x_d. Therefore, a tax results in an increase of the price of the dirty product, relative to the clean product by 5. The subsidy of 25 for lower emissions decreases the price of the clean product, relative to the dirty product by $(0.6 - 0.4)25 = 5$.

Figure 7.1 depicts the total amount of industry output under laissez faire, taxation and subsidies. For $k = lf, tax, sub$ aggregate output is increasing in the first stage of diffusion, i.e., for $s = 0$ till $s \approx 0.6$. As already explained in section 6.5, enhanced price competition lowers equilibrium prices as diffusion increases hence inducing more consumption, i.e., production.

We already explained in chapter 6 why emissions tend to increase under laissez faire in the first stage of diffusion. This is because the production effect exceeds the substitution effect of the technology switch from a dirty to a clean production mode. That is, production is intensified by the lower equilibrium prices as a result of competition as diffusion increases, i.e., as more firms enter the clean product market. The same analogy applies to the taxation and subsidy policy. The only difference is that these two policies introduce a cost-price differential. A subsidy υ reduces the average and marginal costs of clean output x_c, which induces aggregate output X_c^{sub} to grow. The emission tax τ has a reverse effect; the average and marginal costs of both x_d and x_c increase, but to a larger extent for dirty output x_d. Consequently, the aggregate output levels X_d^{tax} and X_c^{tax} decrease and result in an overall level

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[2] The values of the emission tax τ and subsidy υ are set quite arbitrarily because we do not worry about which incentive induces most firms to adopt the clean technology in the long-run. This issue will be examined more extensively in section 7.5. To illustrate the effect of the emission taxation and the subsidy on the diffusion incentive (which is likely to be positive), they simply have to be greater than zero. Note, however, that the level of the subsidy υ should insure positive marginal costs of clean production. Defining total costs under subsidies as $c_c - h$, the marginal costs are positive if and only if $\partial c_c/\partial x_c > \partial h/\partial x_c$. This holds if and only if $\vartheta_c > \upsilon(\zeta_d - \zeta_c)$.

of industrial production which is below the corresponding level under laissez faire ($X^{tax} < X^{lf}$) for all $s \in [0, 1]$.

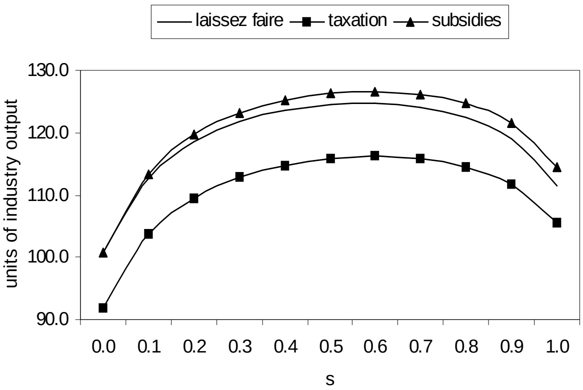

Figure 7.1: *Industry output under laissez faire, taxation and subsidies.*

Since emissions are proportional to production, the translation to a pollution measure is straightforward. We see in figure 7.2 that emissions (slightly) increase for low values of s. However, the figure shows that the increase is not completely parallel with the increase in aggregate output as indicated in figure 7.1. Apparently, the substitution effect does not completely outweigh the production effect of switching from the dirty to the clean technology. As can be seen in figure 7.2, the substitution effect dominates after $s \approx 0.3$. This result coincides with the result obtained by Moraga-González and Padrón-Fumero (2002) who also find that total emissions increase under emission standards and product charges, also as a result of a tougher price competition that soar sales and so production. Furthermore, figure 7.2 also indicates that subsidies on emission reduction result in a higher level of industry emissions compared to laissez faire for all diffusion states $s \in [0, 1]$. So, this type of subsidy turns out not to be so environmentally friendly as one would expect. The reason for this is that subsidies, reducing the average costs of production, lead to a lower price of x_c and stimulate production more intensively than under the laissez faire and taxation policy.

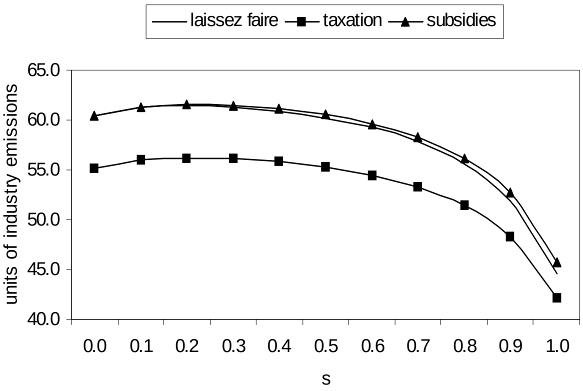

Figure 7.2: *Industry emissions under laissez faire, taxation and subsidies with emission coefficients* $\zeta_d = 0.6$ and $\zeta_c = 0.4$.

However, next to this adverse environmental effect there is also good news. As table 7.1 shows, the emission reduction subsidy causes a higher equilibrium degree of diffusion and total emissions are in equilibrium a bit lower (58.5) than without the subsidy, that is in the laissez faire equilibrium (58.7). In particular, the diffusion equilibria are: $\tilde{s}^{lf} = 0.645, \tilde{s}^{tax} = 0.699$ and $\tilde{s}^{sub} = 0.682$.

Table 7.1: *Industry emissions.*

Policy	Industry Emissions	
	$s = 0$	$s = \tilde{s}$
laissez faire	60.4	58.7 (s = 0.645)
taxation	55.1	53.3 (s = 0.699)
subsidy	60.4	58.5 (s = 0.682)

As expected, environmental policy has a positive effect on the final outcome of the diffusion process. Compared to laissez faire, eventually the dynamically stable states $\tilde{s}$ are higher under taxation and subsidies, i.e., the technology distribution changes to a situation where in the end more firms are of the clean type. A striking feature is that under the assumed market conditions the taxation instrument, which penalizes pollution, brings about a higher degree of diffusion of clean firms than the subsidy instrument, which in fact rewards production.

What happens to total emissions when the clean technology becomes even less pollution intensive relative to the dirty technology? Figure 7.3 depicts the volume of emissions as a function of diffusion for $\zeta_c = 0.2$ (whereas 0.4 in the benchmark). Then total industry emissions is strictly decreasing in s. The substitution effect is then stronger than the production effect, i.e., total output of all clean firms E_c gets lower compared to the case where it was more pollution intensive. In the benchmark case the total emissions under subsidies exceeded the corresponding level under laissez faire for all $s \in [0, 1]$ but this effect now disappeared; total emissions are slightly less than under laissez faire. The picture suggests that, relative to the dirty technology, the 'cleaner' the pollution control technology is in terms of lower emissions per unit of production, the better this is for the environmental quality measured by a lower aggregate volume of emissions. So there are two positive effects. First, pollution declines as diffusion of clean technology progresses (under all three policy regime). Second, both the tax and subsidy regime generate lower emissions than under laissez faire.

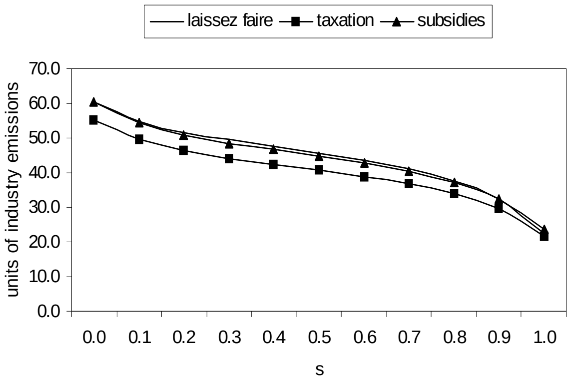

Figure 7.3: *Industry emissions under laissez faire, taxation and subsidies with emission coefficients* $\zeta_d = 0.6$ and $\zeta_c = 0.2$.

If environmental policy can promote the use of a less polluting technology and simultaneously decrease costs, its impact will also (at least partly) be to stimulate output as can be seen in figure 7.1. Subsequently, this output effect on emissions could overrule the beneficial technology impact. How does the production side of the model affect profits and hence diffusion, represented by the short-run profit differential? The laissez faire policy (examined in the previous chapter) showed that the profit differential is a decreasing function of diffusion. In addition to $k = lf$, the profit differential is also calculated for the regimes $k = tax, sub$. The differentials are depicted in figure 7.4 for the benchmark value $\zeta_c = 0.4$. We see that under taxation and subsidies too the profit differential declines as diffusion increases. By definition [see equation (6.23)], this means that for $s^k < (>) \tilde{s}^k$ the clean firm profits $\pi_c^k > (<) \pi_d^k$. At $s^k = \tilde{s}^k$ the incentive to switch is absent since $\pi_c^k = \pi_d^k$.

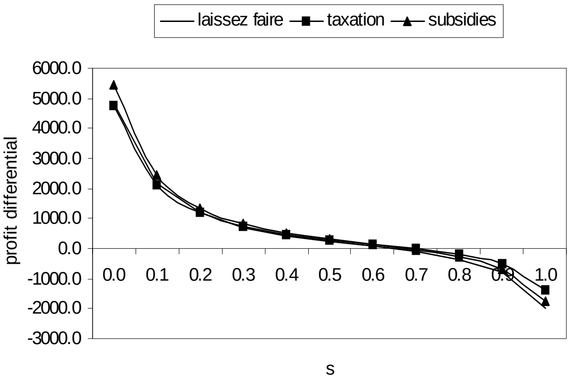

Figure 7.4: *Profit differential under laissez faire, taxation and subsidies.*

7.5 Policy equilibria and comparative statics

In the easiest case there is only one single interior diffusion equilibrium. In chapter 6 it has been shown that when the profit differential decreases with diffusion this holds. Alternatively, two corner equilibria could be established; either there will be complete specialization in the clean good ($s = 1$) or complete specialization in the dirty good ($s = 0$). As we have shown in the previous chapter, for the existence of these corner equilibria the profit differential should be increasing in diffusion. In order to rank the instruments on their diffusion incentives, we focus on the corresponding *interior* Nash equilibria. Due to its uniqueness, this interior Nash equilibrium is automatically an evolutionary equilibrium. We thus focus on the long-run diffusion outcomes under taxation and subsidies, represented by the state where firms are indifferent between the two technologies, i.e., the interior evolutionary equilibria. In determining which instrument promotes the penetration of clean technology most, we need to compare the evolutionary equilibria with each other. Table 7.2 contains the analytical expressions of the evolutionary equilibria under laissez faire, taxation and emission reduction subsidies. Again, they are the states of diffusion where profits of the clean and dirty firm are equal to each other. Note that these values are the equilibria assuming zero fixed costs.

Table 7.2: *Evolutionary equilibria.*

Policy	$\tilde{s}$
laissez faire	$\frac{\beta(N+1)\theta_c-(\gamma N+\beta)\theta_d}{(\beta-\gamma)N(\theta_d+\theta_c)}$
taxation	$\frac{\beta(N+1)(\theta_c-\tau\zeta_c)-(\gamma N+\beta)(\theta_d-\tau\zeta_d)}{(\beta-\gamma)N(\theta_d+\theta_c-\tau(\zeta_d+\zeta_c))}$
subsidy	$\frac{\beta(N+1)(\theta_c+\upsilon(\zeta_d-\zeta_c))-(\gamma N+\beta)\theta_d}{(\beta-\gamma)N(\theta_d+\theta_c-\upsilon(\zeta_c-\zeta_d))}$

We already did some comparative statics for the laissez faire regime in subsection 6.4.3 and so here we will focus on the comparative static results of taxation and subsidies. Obviously, the evolutionary equilibria of laissez faire, taxation and subsidies coincide ($\tilde{s}^{lf} = \tilde{s}^{tax} = \tilde{s}^{sub}$) in case the emission tax $\tau = 0$ and subsidy $\upsilon = 0$. So, from now on we assume $\tau, \upsilon > 0$. We would expect a positive diffusion incentive for positive values of τ and υ. Indeed we find:

$$\begin{aligned}\frac{\partial \tilde{s}^{tax}}{\partial \tau} &= \frac{(\beta(N+2)+\gamma N)(\zeta_d\theta_c-\zeta_c\theta_d)}{(\beta-\gamma)N(\theta_d+\theta_c-\tau(\zeta_d+\zeta_c))^2} > 0, \qquad (7.11)\\ \frac{\partial \tilde{s}^{sub}}{\partial \upsilon} &= \frac{(\beta(N+2)+\gamma N)(\zeta_d-\zeta_c)\theta_d}{(\beta-\gamma)N(\theta_d+\theta_c-\upsilon(\zeta_c-\zeta_d))^2} > 0.\end{aligned}$$

Let's look more carefully at the effect of a tax change. Under the assumptions made earlier $\partial\tilde{s}^{tax}/\partial\tau > 0$. To analyze it on broader level, it can be shown that $\partial\tilde{s}^{tax}/\partial\tau \gtreqless 0$ iff $\zeta_d/\zeta_c \gtreqless \theta_d/\theta_c$. The denominator of (7.11) is always positive. The first term of the numerator $(\beta(N+2)+\gamma N) > 0$ and for $\partial\tilde{s}^{tax}/\partial\tau > 0$ the second term $(\zeta_d\theta_c - \zeta_c\theta_d)$ of the numerator then must be positive. This is true when $\zeta_d/\zeta_c > \theta_d/\theta_c$. By assumption the ratio $\zeta_d/\zeta_c > 1$. Based on our assumptions of a price premium on the clean good $(\alpha_c > \alpha_d)$ and higher variable costs for the dirty good $(\vartheta_c < \vartheta_d)$, the ratio $\theta_d/\theta_c < 1$. Thus the mathematical conditions for a positive numerator are met given our modelling assumptions and an increase of the tax rate always induces more firms to adopt the clean technology. Exactly the same argument explains why $\partial\tilde{s}^{sub}/\partial\upsilon > 0$.

Similar to the laissez faire case, we can analyze the situation where the difference in net absolute advantage $\theta_j = \alpha_j - \vartheta_j$ diminishes and in the limit case approaches zero. Because we assumed that $\alpha_c > \alpha_d$ and $\vartheta_c < \vartheta_d$ the clean firm has a net absolute advantage: $\theta_c > \theta_d$. The reason why in the limit case $\theta_d \to \theta_c$ might be due to either a reduction in the price premium of the clean good α_c relative to α_d, or a reduction in the variable costs ϑ_d of producing dirty relative to the variable costs ϑ_c of the clean firm. The question is how the final equilibrium outcome is affected when neither firm type faces a net absolute advantage given $\tau, \upsilon > 0$.

Recall that in the laissez faire case as the difference in net absolute advantage diminishes and eventually becomes zero, the industry is equally segregated into 50% of clean technology firms and 50% of the firms applying the dirty technology, i.e., the long-run steady state $\tilde{s}^{lf} = 0.5$ as $\theta_d \to \theta_c$, irrespective of the degree of product differentiation. Since both $\partial\tilde{s}^{tax}/\partial\tau > 0$ and $\partial\tilde{s}^{sub}/\partial\upsilon > 0$, one would expect that in the limit case where the difference in absolute advantage vanishes, the taxation and subsidy policy would generate a penetration of clean technology of more than 50%. So, $\lim_{\theta_d\to\theta_c}\tilde{s}^k > \frac{1}{2}$ $(k = tax, sub)$ for $\tau, \upsilon > 0$. In particular:

$$\begin{aligned}\lim_{\theta_d\to\theta_c}\tilde{s}^{tax} &= \frac{\tau[\beta(N+1)\zeta_c - (\beta+\gamma N)\zeta_d] + (\gamma-\beta)N\theta_c}{N(\beta-\gamma)(\tau(\zeta_c+\zeta_d) - 2\theta_c)} > \frac{1}{2}, \qquad (7.12)\\ \lim_{\theta_d\to\theta_c}\tilde{s}^{sub} &= \frac{\beta(N+1)\upsilon(\zeta_c-\zeta_d) + (\gamma-\beta)N\theta_c}{N(\beta-\gamma)(\upsilon(\zeta_c-\zeta_d) - 2\theta_c)} > \frac{1}{2}.\end{aligned}$$

Compared to laissez faire, the reason why more than 50% of the firms adopt the clean technology in the long-run also makes sense from an economic point of view. Under taxation the firm has to pay a tax per unit of emission. When the net absolute advantages for both types of firms are equal, it becomes more attractive for a dirty technology firm to switch to a clean production mode after a tax has been introduced since the clean technology will yield a lower level of emissions (given production is the same under the clean and dirty technology). After this technology switch less taxes have to be paid and diffusion of clean technology is enhanced. The same reasoning applies to the subsidy policy. In this case, a firm receives an amount of money for each unit of emission reduction. Again, if neither firm type faces a net absolute advantage firms will adopt the clean technology since this generates more emission reduction than the dirty technology (at equal output levels). In turn, diffusion of clean technology is positively affected by the introduction of a subsidy.

The two instruments differ, however, in their marginal effect (also under our original inequality of $\theta_d < \theta_c$). The effect on diffusion of a marginal tax increase is larger than the effect of a marginal increase of a subsidy, i.e., $\partial \tilde{s}^{tax}/\partial \tau > \partial \tilde{s}^{sub}/\partial \upsilon$. This too makes sense. The main reason is that a tax affects all firms, irrespective of whether they are dirty or clean, whereas a subsidy does not. Every firm has to pay the tax and, given output is equal across firm type, the amount to pay is higher for the dirty firm due to higher firm-level emissions relative to the clean firm. The production costs of a firm that currently employs the dirty technology and decides not to adopt the clean one after the introduction of the emission tax τ, will rise more relative to the dirty firm that makes the switch to the clean production mode.

A subsidy only influences those firms that reduce emissions. If, after the introduction of a subsidy, a dirty firm sticks to its dirty technology then nothing changes for this firm, i.e., its costs remain the same. Therefore, the incentive to switch is lower than under taxation. On the other hand, firms that do make the transition to the clean technology mode will have an advantage in terms of the amount of subsidy it receives. To summarize: the marginal positive effect of the subsidy on diffusion of clean technology will be lower than its taxation counterpart. Note that this does not only hold in the limit case as the net absolute advantages disappear, but also applies more generally.

7.6 Concluding remarks

In this chapter, the Cournot model as outlined in chapter 6 and which represented the laissez faire regime, was extended by adding two environmental policy instruments, viz. a uniform emission tax and a subsidy per unit of emission reduction. For each of these pollution control policies it was analyzed to what extent they stimulate the diffusion of clean technology in the ultimate long-run taking the laissez faire regime as a benchmark. Just as was assumed under the laissez faire case, the clean and dirty product are imperfect substitutes. For the parameter restrictions given in chapter 6, both policy regimes evolve towards a unique dynamically stable interior solution, i.e., a stable mixture of clean and dirty type firms. These are the evolutionary equilibria. Evaluating these evolutionary equilibria on the basis of the extent to which they enhance the diffusion of clean technology, we find that both the uniform effluent tax and subsidy per unit of emission reduction have a positive effect relative to laissez faire. However, which of the two instruments provides the biggest incentive is quite ambiguous and depends on the parameter values that describe the market conditions. We shall go more deeply into this question in chapter 9.

After having specified a differentiated product market with products being imperfect substitutes, it is shown numerically how aggregate output and hence total emissions evolve as a function of the diffusion process. When emission taxes are applied, total emissions tend to be lower than under laissez faire for all diffusion states. The outcomes are more sensitive to the relative pollution intensiveness of the two technologies in case of emission reduction subsidies. When the difference between the dirty and clean technology is not too large in terms emissions per unit of output, the subsidy instrument can cause emissions to be even higher than they are under laissez faire at any given state of diffusion due to the stimulus a subsidy gives to output. However, when the difference between the dirty and clean technology is sufficiently large, this result does not longer hold and the subsidy instrument generates a lower volume of emissions than under laissez faire for all states of diffusion.

The difference in emission coefficients also affects the volume of emissions as diffusion of clean technology increases. If the difference is relatively small, emissions increase in the early stage of diffusion and only in a later stage emissions start to decrease under all three policy regimes[3]. But when the difference in pollution coefficients is relatively large the volume of industry emissions is strictly decreasing in diffusion under the laissez faire, taxation, as well as the subsidy regime. The substitution effect of switching from a dirty to a clean production process then outweighs the production effect.

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[3] Note that our model finds an increase in both the firm-level and industry-level, assuming a monotonic relationship between output and emissions, *without* including any entry mechanism as in e.g. Baumol and Oates (1988).