The Adoption of Energy Efficiency Enhancing Technologies

Market Performance and Policy Strategies in Case of Heterogeneous Firms

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Abstract

This paper analyses the adoption of energy-efficiency enhancing technologies by heterogeneous firms. The fact that energy use does not only cause external environmental costs through pollution, but also directly affects the profitability of the firm and hence its behaviour on input and output markets is taken for granted. It is demonstrated that the consideration of such market processes may have important implications for the efficiency of environmental policies concerned with energy use. The analysis focuses in particular on the efficiency of the market-led adoption and diffusion process under various policy regimes. It is shown that the promotion of energy-efficiency enhancing technologies might have unexpected effects in that it could lead to an increase in energy use, while the use of energy taxes might actually reduce the attractiveness of energy-saving technologies.

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1. Introduction

Environmental pollution by firms and the regulation of the resulting externalities have been studied extensively in environmental economics. In the most elementary economic model of environmental regulation, firms' technologies are held fixed, and emissions can only be reduced by limiting production levels through, for instance, Pigouvian taxation. It has for long been recognized, however, that apart from such a limitation of production and consumption, the adoption of environmentally friendly technologies in production processes may offer an important alternative means of achieving environmental targets (Orr, 1976). This notion has given rise to a relatively large body of literature addressing the efficiency of environmental regulation in terms of incentives given to firms to adopt cleaner technologies (Orr, 1976; Magat, 1978; Downing and White, 1986; Baumol and Oates, 1988; Malueg, 1989; Milliman and Prince, 1989; Jung, Krutilla and Boyd, 1996). The general conclusion emerging from such studies is that 'economic' instruments (taxes, tradeable permits) usually provide larger incentives for environmental innovations than 'non-economic' instruments, such as standards.

Most of these studies consider the case of pollution abatement technologies where the pollution is a purely external cost, in the sense that there are no benefits from the adoption of cleaner technologies for the firm itself, other than reduced environmental taxes or the compliance with compulsory environmental standards. However, in particular when emissions are a direct result of energy use – like in case of CO_2-emissions – this may be an overly simplifying assumption. In such cases, energy-efficiency enhancing technologies may be available, for which the reduction in emissions goes hand in hand with a more efficient use of one of the inputs in the production process, namely energy. This implies that internal and external cost reductions are intertwined, which may seem attractive at first sight in that it offers the possibility of 'win-win situations'. Although this may certainly be the case, we will show in this paper that there may also be some particular complications arising from this property of energy-efficiency enhancing technologies, which can give rise to counter-intuitive and sometimes counter-productive impacts of environmental policies. This is in particular so because the adoption of the technology will generally directly affect the firm's production cost structure, and hence its behaviour on input as well as output markets. The paper therewith provides an economic analysis of the situation where firms can choose between – or, indeed, combine – output restriction and technology adoption in response to environmental policies.

Apart from the above mentioned property of energy-efficiency enhancing technologies, there are two other features of the model presented in this paper that are worth mentioning, and distinguish the analysis from those in most of the literature. The first is that not only firms in isolation will be considered. Instead, also the effects of competition between firms – in the same market – are taken into consideration when studying the adoption of energy-efficiency enhancing technologies, and the impacts of policies thereupon. The second feature is that competing firms need not necessarily be identical, as is usually assumed in standard models of perfect competition. The effects of heterogeneity among firms on the efficiency of environmental regulation may certainly be non-trivial (Baumol and Oates, 1988), and have recently received growing interest in studies considering multiple firms (Helfand, 1991, 1993; Jung, Krutilla and Boyd, 1996; Verhoef and Nijkamp, 1997).

The paper is organized as follows. The next section presents the basic model of the firms, the market, and the energy-efficiency enhancing technology to be considered in the remainder of the paper. Section 3 proceeds by deriving some general results for the case where energy would be efficiently priced. Section 4 considers the implications of the existence of external costs of energy use for the efficiency of the adoption and diffusion process, and discusses the most important policy implications. Section 5 offers some concluding reflections. Finally, some numerical examples are presented in the Appendix.

2. The model of the firms, the market, and the innovation

It is clear that, when one aims to study a topic as broad as the adoption of energy-efficiency enhancing technologies by heterogeneous, competing firms, a large variety of modelling approaches is possible. A trade-off, for instance, exists between the level of generality of the model, and the extent to which it is capable of producing analytical and tractable results. Our aim is to keep the model as general as possible, but to economize on complexity – in particular through linearization of relations and fixation of certain parameters and ratios – wherever this does not seem overly restrictive. Furthermore, because of the relative complexity of the issue at hand itself, any other market failures apart from those resulting from energy use are assumed away, which secures that second-best elements resulting, for instance, from market power, inefficiently operating labour markets, or imperfect information will not affect the subsequent analysis. Although we recognize that such other market failures may undoubtedly play an important role in reality, we leave their treatment in the current context to future research, and wish to concentrate solely on the economic principles underlying the adoption of energy efficiency enhancing technologies by heterogeneous firms, and associated policies, in an otherwise 'first-best' world. Finally, as many 'other things' as possible are held constant, for the same reason. For instance, firms do not expand their capital stock exogenously. Despite these self-imposed limitations, however, we will try to generalize the results whenever this seems possible. In particular, the model presented below allows us to derive results that also carry over to more general, but analytically more complex configurations. These considerations have led us to the following model design.

Before the new energy-efficiency enhancing technology (referred to as the 'new technology' or the 'innovation' in the sequel) becomes available, it is assumed that each firm takes its technology and capital stock as given in the short run, and competes on the output market on basis of its short-run variable costs. The level of these are dependent on prices on the input markets, the firm's technology and capital stock, and the output level the firm chooses. Firms are assumed to be profit maximizing price-takers on both the output and the input markets, and therefore to choose per-unit-of-time output levels for which the marginal variable costs are equal to the market price on the output market. This behaviour maximizes a price-taker's short-run profits under the assumption that the short-run marginal costs are increasing with the production level. Apart from possibly adopting the new technology, a firm does not consider to expand its capital. Since capital is fixed, the short-run profit from production – more correctly referred to as the producer's surplus, since it is net of any costs of capital – should be positive in order to cover the fixed capital costs, such as interest payments.

In contrast to the standard model of perfect competition, in which all firms are assumed to be identical, the present model allows for heterogeneity among firms – which is, of course, what is usually witnessed in practice. The situation where all firms are identical is therewith a limiting case of the present model. Also, it is not imposed beforehand that all firms balance on the edge of bankruptcy, as they do in models of perfect competition due to free entry and exit. Instead, the producer's surplus may more than compensate for the costs of capital, and firms do not immediately leave the market as soon as there is a marginal change in their profitability. In principle, we will assume that no entry and exit takes place; however, track can be kept of the impact of environmental regulation and of the adoption and diffusion of the new technology on the profitability of specific firms, which allows a qualitative assessment of which firms are more likely to leave the market.

The availability of the new technology gives the firm the opportunity to change its variable cost structure, by allowing it to make a more efficient use of the energy input after adoption of the technology. The innovation, once adopted, adds to the capital stock. In contrast to 'ordinary' environmental technologies, which only affect the external costs caused by a firm, energy-efficiency enhancing technologies therefore also have an effect on the internal costs of the firm, because energy as such is usually not obtained for free. In order to be able to investigate the adoption of such a technology by a certain firm, it is therefore necessary to specify how energy use affects the production costs, or more precisely, the profits of that firm. This requires, *inter alia*, a specification of the firm's production function.

For this purpose, it is assumed that the firm uses three inputs in its production process: capital, which is quasi-fixed in the sense that the firm only considers the binary choice of whether to adopt the innovation; energy; and a third production factor that is variable in the short run. This third factor will conveniently be referred to as 'labour' for the sake of terminology, but it might be any variable input, or even a bundle of different variable inputs, used in fixed proportions. In the formal model the simplifying assumption is made that for a given capital stock, energy and labour are used in fixed proportions, regardless the level of output. Input substitution is therefore not possible for a given capital stock with given characteristics: the firm can only select a per-unit-of-time output level, but cannot influence the absolute nor the relative quantities of labour and energy necessary to produce that output level. Moreover, these relative quantities are independent of the production level chosen. Nevertheless, a binary form of input substitution is possible because the firm may adopt the new technology.

The firm thus faces a Leontief-type of technology in the short run. In contrast to the standard Leontief production function, however, we impose diminishing factor productivity for the variable inputs in order to obtain rising marginal variable production costs, which in turn is necessary to obtain a positive producer's surplus. For reasons of analytical simplicity, it is assumed that the marginal energy and labour inputs rise linearly with production. This can be accomplished by specifying the short run production function as follows (later on, subscripts i will be used to distinguish different firms, but these are omitted here for reasons of clarity):

$$q + \tfrac{1}{2} \cdot \beta \cdot q^2 = MIN\left\{ \alpha_E \cdot E\,,\ \alpha_L \cdot L \right\} \tag{1}$$

where q is the (per-unit-of-time) production level, E is the energy input, L is the labour input, and α_E, α_L and β are technology parameters. The parameters α_E and α_L reflect the efficiency with which energy and labour are used: the higher α_E (α_L), the less energy (labour) is needed for a certain production level. The parameter β determines the extent to which the marginal productivity of energy and labour decreases with an increasing production. Equation (1) implies that at a production level q, the firm will use the following amounts of the variable inputs energy and labour:

$$E = \frac{1}{\alpha_E} \cdot (q + \tfrac{1}{2} \cdot \beta \cdot q^2) \tag{2a}$$

$$L = \frac{1}{\alpha_L} \cdot (q + \tfrac{1}{2} \cdot \beta \cdot q^2) \tag{2b}$$

so that the firm's total cost function can be written as:

$$TC(q) = (q + \tfrac{1}{2} \cdot \beta \cdot q^2) \cdot \left(\frac{w_E}{\alpha_E} + \frac{w_L}{\alpha_L} \right) + F \tag{3}$$

where w_E and w_L give the factor prices for energy and labour, respectively; and F is the per-unit-of-time fixed costs of capital. It is assumed throughout the paper that labour and capital are efficiently priced. Equation (3) implies the following linear marginal cost function, which is identical to the supply function in the present case:

$$s(q) = (1 + \beta \cdot q) \cdot \left(\frac{w_E}{\alpha_E} + \frac{w_L}{\alpha_L} \right) = k + b \cdot q \tag{4}$$

with:

$$k = \left(\frac{w_E}{\alpha_E} + \frac{w_L}{\alpha_L} \right) \quad and \quad b = \beta \cdot k$$

Now before the innovation is available, the firm will select an output level q for which the marginal production costs s(q) are equal to the market price on the output market, P:

$$q(P) = \frac{P-k}{b} \tag{5}$$

The producer's surplus π is then equal to total revenues (P·q) minus total variable costs ($k \cdot q + \frac{1}{2} \cdot b \cdot q^2$); or, after substitution of (5):

$$= \tfrac{1}{2} \cdot \frac{(P-k)^2}{b} \tag{6}$$

The per-unit-of-time short run profits can then be determined as Π=π–F.

Next, the adoption of the new technology is assumed to increase the efficiency in energy use, which implies in the present model that α_E is raised. The factor with which α_E is increased is denoted ρ, where 1≤ρ≤∞; ρ=1 implies no improvement at all, and ρ=∞ implies that after adoption of the new technology, energy is no longer needed in the production process. Adoption of the innovation therefore changes the firm's parameters as follows:

$$k^* = \left(\frac{w_E}{\cdot \quad _E} + \frac{w_L}{\quad _L} \right) = f \cdot k \quad with \quad f = \frac{\frac{w_E}{\cdot \quad _E} + \frac{w_L}{\quad _L}}{\frac{w_E}{\quad _E} + \frac{w_L}{\quad _L}}; \tag{7a}$$

$$b^* = \quad \cdot k^* = f \cdot b \tag{7b}$$

where asterisks denote values after the adoption of the innovation by the firm considered. Note that 0<f≤1; observe also that ρ=1 implies f=1 and that ρ=∞ implies $f=(w_L/\alpha_L)/(w_E/\alpha_E + w_L/\alpha_L)$. Equations (7a) and (7b) show that, owing to the adoption of the innovation, the energy use for all levels of production reduces with the same factor: $E^*(q)=1/\rho \cdot E(q)$ for all q; and that – although both k and b are reduced – it is assumed that the parameter β remains unaffected, so that the ratio between b and k remains the same. The per-unit-of-time capital costs for adopting the innovation are denoted by I, and we assume that the innovation is efficiently priced. The technology is available in only one single variant, and a firm can use the technology only once: after the additional equipment is installed, there is no possibility to use the technology for a second time and to obtain $b^{**}=f^2 \cdot b$ and $k^{**}=f^2 \cdot k$. The adoption is assumed to be irreversible. Since firms may be different from each other, also the profitability of the innovation may differ across firms. One would expect an energy-efficiency enhancing technology to be particularly profitable for firms using relatively much energy in their production process. In what follows, this is accomplished by assuming that the factor ρ is equal across firms. Hence, the new technology allows all firms to reduce the energy input necessary for any of their production levels by the same factor.

A profit maximizing firm will adopt the innovation if the gain in the per-unit-of-time producer's surplus exceeds I.[1] Hence, the assumption of profit maximizing behaviour is extended to the adoption of the innovation, and information is assumed to be perfect; that is, all firms are aware of the new technology. Denoting the gain in the producer's surplus as $\Delta\pi=\pi^*-\pi$, we can in the first instance write:

$$\Delta \quad = \tfrac{1}{2}\cdot\frac{\left(P^* - k^*\right)^2}{b^*} - \tfrac{1}{2}\cdot\frac{\left(P-k\right)^2}{b} \tag{8a}$$

Whereas it is evident that the firm will indeed consider the new values k^* and b^* when evaluating the new technology's profitability, some caution is needed with P^*. Although it will be shown below that the adoption by one single firm will in general have a depressing effect on the output market price, it would be inconsistent with the assumption of price-taking behaviour on the output market if this effect of an individual firm's investment decision on the market price would be dominant in (8a). When the number of firms is sufficiently large and an individual firm's impact on the market price becomes negligible, P^* approaches P, and (8a) can be written as:

$$\Delta \quad = \tfrac{1}{2}\cdot\frac{\left(P - k^*\right)^2}{b^*} - \tfrac{1}{2}\cdot\frac{\left(P-k\right)^2}{b} \tag{8b}$$

In general, a profit maximizing firm adopts the innovation if the expression in (8a) is greater than I. Clearly, the more negligible the firm's own impact on the market price becomes, the more closely this expression approaches (8b). We will get back to this issue of the impact of the adoption on the price on the output market below; before doing so, however, we first have to define the market equilibrium itself.

In order to determine the equilibrium on the output market, one has to define the demand relation and the industry supply relation. As far as the former is concerned, elasticity of demand will be considered, and can be included in its most simple analytical form by postulating a linear inverse demand or marginal benefit function:

$$D(Y) = d - a\cdot Y \tag{9}$$

where Y is the quantity consumed; hence, at a given market price the quantity demanded is:

$$Y(P) = \frac{d-P}{a} \tag{10}$$

[1] Although this assumption seems reasonable in the context of the present model, it ought to be mentioned that in the energy economics literature there is a persistent discussion on the so-called energy efficiency gap, the seemingly unexplained gap between the technical possibilities for energy efficiency improvements that seem profitable even from a private profit maximizing point of view, and those that are indeed adopted by firms in reality. See, among many others, DeCanio (1993), Howarth and Andersson (1993), Jaffe and Stavins (1994), Metcalf (1994), Sanstad and Howarth (1994), and Sutherland (1994).

and the consumers' surplus CS at price P can be found as the total benefits (the integral of the marginal benefits) of consuming Y(P), minus the expenses P·Y (compare (5) and (6)):

$$CS = \tfrac{1}{2}\frac{(d-P)^2}{a} \qquad (11)$$

The industry supply relation can be found by a horizontal summation of the individual firms' supply functions. If all firms were identical and had a supply function as given in (4), the industry supply function could simply be found by an outward rotation of (4) with a factor representing the number of firms. However, once it is acknowledged that firms may actually be different, and that k_i and b_i may differ among firms, a simple linear industry supply function is unlikely to apply, since it will generally be piecewise linear as soon as k_i differs among firms. In general, total industry supply at a market price P can be written as:

$$Q(P) = \sum_i q_i(P) = \sum_i \frac{P-k_i}{b_i} \qquad (12)$$

The market equilibrium before the innovation becomes available can be found by setting Y=Q, and this results in the following equilibrium market price:

$$P = \frac{\frac{d}{a} + \sum_i \frac{k_i}{b_i}}{\frac{1}{a} + \sum_i \frac{1}{b_i}} \qquad (13)$$

The equilibrium quantities demanded and supplied at that price can then be written as:

$$Y = \frac{\sum_i \frac{d-k_i}{a\cdot b_i}}{\frac{1}{a} + \sum_i \frac{1}{b_i}} \qquad (14)$$

$$q_i = \frac{\frac{d-k_i}{a\cdot b_i} + \sum_j \frac{k_j - k_i}{b_i \cdot b_j}}{\frac{1}{a} + \sum_j \frac{1}{b_j}} \qquad (15)$$

If there were no environmental externalities involved, or if energy were efficiently priced, and before the new technology becomes available, this market would be perfect in the sense that the equilibrium price and quantity will correspond to the social welfare maximizing levels. Defining social welfare as the sum of consumers' surplus and producers' profits, the social welfare maximization problem can, in general, namely be written as:

$$MAX\ W = CS + \sum_i \Pi_i = \int_0^Y D(Y)\,dy - P \cdot Y + P \cdot \sum_i q_i - \sum_i \int_0^{q_i} s(q_i)\,dx - \sum_i F_i$$
$$s.t.\ Y = Q = \sum_i q_i \qquad (16)$$

The first-order condition for each firm's production level involves $D(Y)=s(q_i)$, which is satisfied because both are equal to the market price P; compare (4) and (5), and (9) and (10).

Next, after the innovation has been adopted by a certain number of firms, the new equilibrium can be found by substituting the adopters' new values of b_i^* and k_i^* into (13), (14) and (15). The new level of social welfare can then be found by inserting these new equilibrium values in (16) and adding a term $-\Sigma_i\delta_i\cdot I$, where δ_i takes on the value of 1 if firm i has adopted the innovation and 0 otherwise. Before investigating the welfare implications of such an adoption process in the next section, we conclude the present section with a brief reflection on the model discussed so far.

The model has in common with standard perfect competition models that all actors are assumed to be price-takers, and maximize their utility (or profit) under complete information. Some stringent assumptions underlying the standard model of perfect competition, however, are relaxed: firms are allowed to make positive profits, and do not enter or exit the market due to marginal price changes. In other words, not only individual firms' supply, but also the industry supply is upward sloping. Firms are assumed to exhibit price-taking behaviour in the output market, which is consistent with the situation where the individual firm's market power is negligible. This, however, does not imply that firms should be fully myopic in the sense that they would ignore the price change P^*–P due to their own adoption; compare (8a) and (8b). To draw a parallel with the equilibrium on the output market: each firm expects the intersection of the industry supply curve and the market demand curve to be the market equilibrium. Since their own supply is part of the industry supply, they do not ignore their own impact; however, this impact is simply too small to be profitably exploited. A firm cannot gain from producing more than the volume of q implied by (5) and charging a price equal to the higher marginal cost and higher than the prevailing market price, since its sales would then drop to zero; nor can it gain from producing less and charging the market price, because it then foregoes potential profits since its marginal costs then fall short of the market price. Hence, also for price-taking firms without market power in the output market, (8a) is in fact the correct expression to evaluate the profitability of adopting the innovation at hand, while (8b) only represents a limiting case of (8a) when P^*–P becomes negligible. Where this distinction is important, we will refer to 'sufficiently small firms' when (8b) approaches (8a) 'sufficiently close' (where the interpretation of sufficiency will be dependent on the particular circumstances).

It is assumed that information is perfect; hence, self-reinforcing diffusion of the innovation according to, for instance, the 'epidemic learning' model (see, for instance, Stoneman, 1987) is not considered here. Such a dynamic process could, however, be super-imposed on the present model. The model now only describes the impacts of policies and other firms' behaviour on the profitability of adopting the technology, which would of course also be relevant in settings where firms for which the adoption is profitable only adopt with limited probability due to imperfect information or uncertainty. In the present model, this probability is implicitly set at unity, and a fully deterministic situation is assumed to apply.

Finally, it should be noted that some assumptions may seem overly restrictive; for instance, those concerning the linearity of supply and demand functions, and the constancy of relative energy and labour inputs for all production levels. However, these assumptions, while rendering the model analytically more tractable, do not fundamentally affect its comparative static properties. These assumptions only allow us to neglect third-order effects that could complicate the analysis enormously, while not affecting the main conclusions of the model. Furthermore, the assumption that ρ be equal for all firms is merely a convenient way of incorporating the fact that an innovation will usually have different effects for different firms; here, it reflects the idea that an energy saving technology will have larger impacts, *ceteris paribus*, for firms that have a relatively energy-intensive production process.

3. Welfare implications of technology adoption with efficient energy pricing

In this section, the process of technology adoption implied by the model presented above will be studied under the assumption that energy is efficiently priced. The conclusions will be helpful in the next section where we study the case we are eventually interested in, namely where energy is not efficiently priced due to the presence of an unpriced environmental externality. This section starts with a graphical exposition of the basic impacts of a technology adoption of the kind described above, and proceeds with translating the insights obtained to the more general model presented in the previous section.

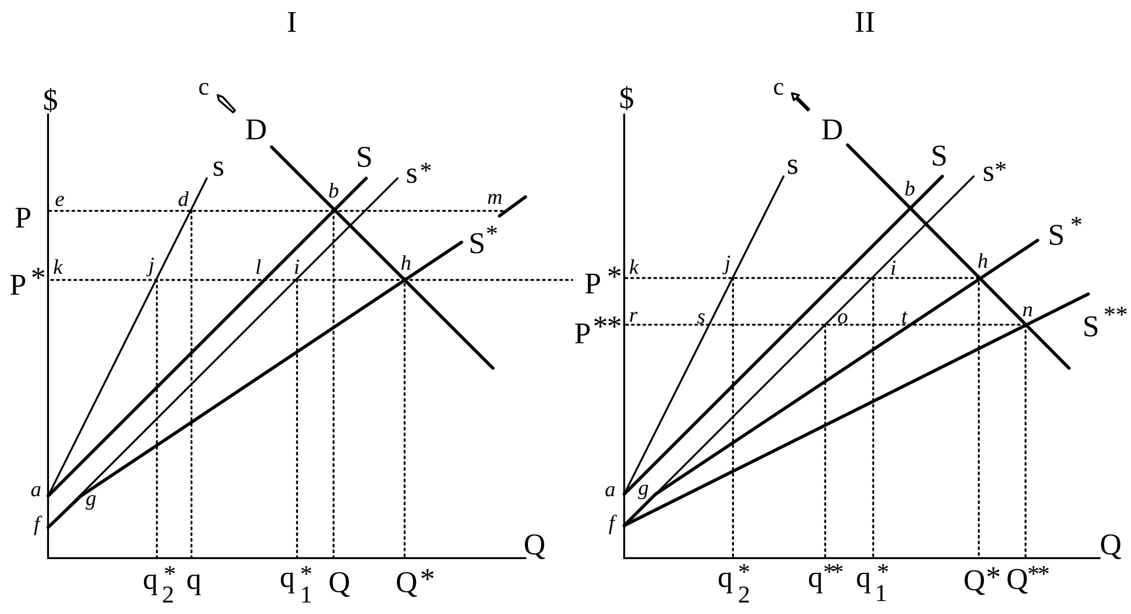

Figure 1. Welfare effects of adoption by the first (I) and the second (II) firm

First of all, we re-address the issue briefly touched upon above, involving the question towards the effect of output price changes on the profitability of the innovation; see equations (8ab). This matter may be of importance for the efficiency of the adoption process. This is illustrated in Figure 1, which shows the behaviour of firms on a market as described in the previous section. For graphical reasons, this figure shows the case where there are only two such firms, which is of course at odds with the assumption of price-taking behaviour on the output market. Nevertheless, we assume that these two firms are price-takers, which would become more plausible with increasing numbers of firms considered. The inclusion of only two firms in the figure is made solely for the purpose of diagrammatic exposition, as it magnifies the various areas indicating the welfare effects that are relevant also for the multi-firm case.

The demand is given by curve D, and an individual firm's supply curve before the innovation is available is given by s. We start, in Figure 1.I, with the case where both firms are identical, so that industry supply is given by S, the equilibrium market price by P, total production and consumption by Q, and the production by each firm by q_i. Total welfare is maximized and is given by the sum of the consumers' surplus *ebc* (*c* is the intersection of the demand curve with the vertical axis), and the producers surpluses *ajk*+*alj* (note that *ajk*=*alj*); hence, the triangle *abc* reflects total welfare. The adoption of the innovation gives the firm the opportunity to obtain the lower marginal cost function s^*, with lower levels of k (the intersection with the vertical axis) and b (the slope); compare (7ab). The adoption by the first firm therefore causes the industry supply curve to change to S^*. Figure 1.I shows the welfare effects of this adoption by, say, firm 1.

First consider the case where firm 1, in spite of its assumed price-taking behaviour on the output market, does consider the impact of its adoption on the market price. This firm will then realize that the new equilibrium will be P^*Q^*, with $q_1^*>q_2^*$, and will consider $\Delta\pi_1$=*fik–ade=fija-kjde=fghla-kjde*. Suppose that this indeed exceeds I, so that the adoption is made. In that case, firm 2 suffers from this adoption because the market price falls, and it can only profitably produce up to q_2^*. The loss in producer's surplus for firm 2 is equal to *kjde*, which is equal to the negative element in firm 1's welfare change (note that *kjde=jlbd*). The consumers benefit due to the lower market price, inducing higher consumption, and the increase in the consumers' surplus is given by *khbe*. Note that the loss for firm 2 and the negative element in the welfare change for firm 1 are not lost for society: these reductions in producer surpluses due to lower market prices are 'transferred' to consumers and become part of the consumer surplus in the new equilibrium. The loss by firm 2 is more than compensated by the gain for the consumers (*khbe* necessarily exceeds *kjde*), and also the sum of the loss by firm 2 and the equivalent negative element in the welfare change for firm 1 are more than compensated by the gain for the consumers (*khbe* necessarily exceeds *klbe*). Finally, the effect on social welfare, ΔW, is given by the polygon *fghba*. Hence: firm 1 benefits from its adoption, firm 2 loses, and the consumers gain.

It is easy to see that firm 1 faces an insufficiently high incentive to adopt the innovation when it considers the effect of its own adoption on the market price. The incentive misses out on a factor $\Delta W–\Delta\pi_1$=*jhbd*. If the cost of the innovation I has a value for which $\Delta\pi_1<I<\Delta W$, the firm will not adopt the innovation, whereas an adoption would be socially beneficial. Only if the demand were perfectly elastic (a 'flat' demand curve) would the private and social incentives exactly coincide, because $P=P^*$ in that case, and the welfare effects for firm 2 and the consumers vanish, so that the private incentive for firm 1 corresponds to the socially optimal incentive. On the other hand, if the firm ignores the effect of its own adoption on the market price and is 'myopic', it will expect an increase in its producer's surplus *fgmba*$>\Delta W>\Delta\pi_1$; implying a, from the social point of view, excessively large incentive to adopt. Then, the situation where *fgmba*$>I>\Delta\pi_1$ is conceivable, in which case the firm finds, 'to its surprise', that the adoption was not beneficial after all.

Before discussing the case where the number of firms is much larger than 2, we briefly consider the welfare implications of a subsequent adoption by firm 2, depicted in Figure 1-II. These effects are in a qualitative sense comparable to those shown in Figure 1-I. After firm 2's adoption, both firms then have the supply relation denoted s^*, so that S^{**} gives the new industry supply and the new market equilibrium involves P^{**}, Q^{**}, and q^{**} for both firms. Firm 2 enjoys an increase in its producer's surplus $\Delta\pi_2$=*fntg–othi* (note that *othi=rsjk*); firm 1 is negatively affected: $\Delta\pi_1$=–*roik*; and the consumers benefit with *rnhk*. Again, the social welfare gain is larger than the incentive faced by firm 2. Note that the firms are again identical after firm 2's adoption. Furthermore, the profitability of adoption for firm 2 is, in the sketched case, smaller than that it was for firm 1, and so is the absolute price reduction. More general conclusions, based on the model presented in the previous section, will be given below.

The extent to which the private incentive for adoption falls short of the socially optimal incentive is directly dependent on the equilibrium price change induced by a single firm's adoption. If the number of firms increases – which also implies that the assumption of price-taking behaviour on the output market becomes more plausible – the potential problem of insufficient incentives to adopt therefore becomes smaller. In the limit with infinitesimal firms, where the adoption by a single firm has a negligible impact on the market price, the 'missed incentive' becomes negligible as well, and the adoption process is in principle efficient. The reader may verify this by re-drawing Figure 1 under the assumption that S is composed of a large number of identical s curves, and – for the sake of the thought experiment – that I is reduced by the same factor as by which the number of firms is increased.

It should be noted that the negative effects of the adoption by a single firm on the other firms' profits, and the positive effect on consumers' surplus, are not dependent on the question of whether the adopting firm behaves myopically. Furthermore, if, in a market with many small firms, each ignoring the impact of their own investment decision on the market price because this impact is very small, a sufficiently large share of these firms have adopted the innovation, the new equilibrium will still involve a lower market price and a higher consumers' surplus – even though an individual firm's impact on the market price may be negligible. Also with many (identical) small firms, an industry supply curve such as S in Figure 1 would shift outwards, for instance, from S to S^* after half of the firms have adopted, and from S^* to S^{**} after they have all adopted. The aggregate welfare impacts of adoption by a given number of small firms are therefore comparable to those outlined above.

The implications of the above analysis can be traced in the formal model presented in Section 2, and can be summarized in the following set of propositions, which are valid provided no firms' supply, nor the market demand, is perfectly elastic or perfectly inelastic, provided that all firms are price-takers in the output market, and provided the innovation is non-trivial ($\rho>1$):

Proposition 1 The voluntary adoption of the innovation by any of the firms leads to a decrease in the equilibrium market price; a decrease in all other firms' equilibrium outputs, producer's surpluses and profits; an increase in total equilibrium production, consumption and consumers' surplus; an increase in the adopter's equilibrium output; and an increase in the adopter's producer's surplus and profits provided the adopter is not myopic.

Proof The adoption by firm i implies $b_i^*<b_i$, $k_i^*<k_i$ with $k_i^*/b_i^*=k_i/b_i$ by (7ab). By (13), this implies that $P^*<P$. For all firms $j\neq i$, q_j and π_j must therefore have gone down by (5) and (6), and Y=Q and CS must have gone up by (10) and (11). Since F_j remains unaffected by firm

i's adoption, also Π_j must have gone down for all firms $j \neq i$. Hence: $q_j^* < q_j$, $\pi_j^* < \pi_j$, and $\Pi_j^* < \Pi_j$ for all $j \neq i$; $Q^* = Y^* > Q = Y$; and $CS^* > CS$. Since $Q^* > Q$ and $q_j^* < q_j$ for all $j \neq i$, $q_i^* > q_i$ by (12). Finally, $\pi_i^* > \pi_i$ and $\Pi_i^* > \Pi_i$ because voluntary adoption by a non-myopic firm occurs only if $\pi_i^* - \pi_i - I = \Pi_i^* - \Pi_i \geq 0$.■

Generalization Proposition 1 carries over to any configuration where the market demand is downward sloping, and individual firms' supply and hence industry supply functions are upward sloping, and where the adoption leads to a lower marginal cost for all adopter's production levels. The crucial mechanism is that the adopter's supply function and hence the industry supply function shifts downwards owing to the adoption.

Note that Proposition 1 implies that it is conceivable that, although each individual firm benefits from its own adoption, all firms may be worse off due to the availability of the innovation: the negative effect on profits caused by other firms' adoptions may exceed the benefits of the firm's own adoption. The firms could therefore end up in a prisoners' dilemma, where they would all be better off if no firm would adopt, but all individually have an incentive to adopt themselves.

Proposition 2a The voluntary adoption of the innovation by any of the firms leads to an increase in social welfare, provided all input and output markets operate efficiently and firms are not myopic.

Proof First, write the change in social welfare ($\Delta W = W^* - W$) as the sum of the changes in the consumers' surplus ($\Delta CS = CS^* - CS$) and the changes in all firms' profits ($\Delta\Pi_k = \Pi_k^* - \Pi_k$ for all k). Observe that the change in the adopter's profits ($\Delta\Pi_i$) is equal to the change in its producer's surplus ($\Delta\pi_i$) minus the investment cost (I), and that the change in all other firms' profits ($\Delta\Pi_j$ for all $j \neq i$) is equal to the change in their producer's surpluses ($\Delta\pi_j$):

$$\Delta W = \Delta CS + \Delta\Pi_i + \sum_{j \neq i} \Delta\Pi_j = \Delta CS + \Delta \quad_i - I + \sum_{j \neq i} \Delta \quad_j \tag{17}$$

It will now be proven that $\Delta W \geq \Delta\pi_i - I > 0$. Voluntary adoption by a non-myopic firm occurs only if $\Delta\pi_i > I$, so the latter part is always satisfied. If $P^* = P$, $\Delta W = \Delta\pi_i$ because $\Delta CS = \Delta\pi_j = \Delta\Pi_j = 0$ for all $j \neq i$ by (6) and (11), and the proposition is proven. If $P^* < P$, $\Delta CS > 0$ and $\Delta\pi_j < 0$ for all j by Proposition 1. However, $\Delta W > \Delta\pi_i - I$ because $\Delta CS > \sum_{j \neq i} -\Delta\pi_j$. To see why this is the case, we write $\Delta CS + \sum_{j \neq i} \Delta\pi_j$ as:

$$\int_{P^*}^{P} Y(p) - \sum_{j \neq i} q_j(p)\, dp \tag{18}$$

Because $Y(P) \geq \sum_{j \neq i} q_j(P)$ by (12); $dY/dP < 0$ by (10); $dq_j/dP > 0$ for all j by (5); and $P^* < P$ is the case under consideration, the expression in (18) and hence that in (17) is always greater than or equal to zero. Note that $P^* > P$ is irrelevant by Proposition 1.■

Graphical proof See Figure 1.I. Since $\Delta W - \Delta \pi_1 = jhbd > 0$ and a non-myopic firm adopts only if $\Delta \pi_i > I$, the proposition is proven.■

Generalization Proposition 2a carries over to any configuration where Proposition 1 and its generalization hold. The crucial mechanism is that $\Delta W \geq \Delta \pi_i > 0$. Adoption by a non-myopic firm occurs only if $\Delta \pi_i > 0$, and $\Delta CS + \sum_{j \neq i} \Delta \pi_j \geq 0$ holds for the general case where the demand function is not upward sloping and the supply functions are not downward sloping.

Proposition 2b Under the conditions where Proposition 2a and its generalization hold, the firm faces an incentive to adopt the innovation which is smaller than or equal to the socially optimal incentive.

Proof $\Delta W \geq \Delta \pi_i - I$, as is demonstrated in the proof to Proposition 2a.■

Proposition 2c Under the conditions where Proposition 2a and its generalization hold, if the firms have perfect foresight (or if the ranking of the profitability of adoption across firms is not 'too much dependent on the prevailing market price'), and if the non-adopters are sufficiently small, the voluntary adoption process is Pareto efficient.

Proof All voluntary adoptions have increased social welfare by proposition (2a). If the non-adopters are sufficiently small, ΔW approaches $\Delta \pi_j - I$ for all non-adopters j, so that the fact that these adopters cannot profitably adopt implies that also society could not benefit from their adoption. Hence, social welfare cannot be increased by stimulating further adoptions. Observe that the order of individual adoptions is irrelevant for the eventual market equilibrium after the adoption process has terminated (compare (13)), and hence irrelevant for the eventual level of social welfare. The requirement that the ranking of the profitability of adoption among firms should not be 'too much dependent on the prevailing market price' therefore only serves to account for the possibility that after the adoption process has terminated, it should not be beneficial to society, or to the adopter itself, if one of the adoptions could be reversed. This requirement is not necessary if firms have perfect foresight, because firms will not adopt if they know that after the full adoption process has terminated, they will regret their adoption.■

Proposition 3 The adoption of the innovation by one of the firms reduces the profitability of this innovation for all other firms, provided the latter are 'sufficiently small' in comparison to the market.

Proof The adoption by the first firm (denoted as firm h) implies $P < P^{\#}$ by Proposition 1, where $P^{\#}$ (P) denotes the market price before (after) firm h has adopted. The profitability of the innovation for a subsequent firm i can be written as $\Delta\pi_i$–I. Since I is constant, we only have to prove that $\Delta\pi_i < \Delta\pi_i^{\#}$ due to $P < P^{\#}$. For that purpose, we first rewrite (8a) and (8b) as follows:

$$\Delta\ {}_i = \frac{1}{2 \cdot b_i} \cdot \left[\frac{1}{f_i} \cdot P^{*2} - P^2 + \left(f_i - 1\right) \cdot k_i^{\ 2} + 2 \cdot k_i \cdot \left(P - P^*\right) \right] \tag{19a}$$

$$\Delta\ {}_i = \frac{1}{2 \cdot b_i} \cdot \left[\left(\frac{1}{f_i} - 1 \right) \cdot P^2 + \left(f_i - 1\right) \cdot k_i^{\ 2} \right] \tag{19b}$$

Equation (19b) gives the profitability of the adoption for a firm that is very small and that can therefore safely assume P^*=P. It is evident that according to (19b), $\Delta\pi_i$ is decreasing in P (note that f_i<1 and P>k_i). Hence, the adoption by firm h, leading to a lower market price $P < P^{\#}$, must have reduced $\Delta\pi_i$. For the more general expression (19a), rewrite the numerator and denominator in (13) so as to obtain:

$$P = \frac{N}{B_i + X} \tag{20}$$

where $N = d/a + \sum_j k_j/b_j$; $B_i = 1/b_i$; and $X = 1/a + \sum_{j \neq i} 1/b_j$.The adoption by firm h leaves N unaffected and leads to an increase in X. We may then write:

$$\frac{\Delta\ {}_i}{X} = B \cdot \left[\left(\frac{N}{B_i + X} - k_i \right) \cdot \frac{N}{\left(B_i + X\right)^2} - \left(\frac{N}{B_i + f_i \cdot X} - k_i \right) \cdot \frac{N}{\left(B_i / f_i + X\right)^2} \right] \tag{21}$$

which is smaller than zero provided X is sufficiently much larger than B_i; in other words: if firm i is ‘sufficiently small’ in comparison to the market.■

Generalization Proposition 3 carries over to many configurations where Proposition 1 and its generalization hold for both firm h’s and firm i’s adoption. The crucial mechanism is that the lower price market price due to firm h’s adoption reduces the gain in producer’s surplus that firm i enjoys from the downward shift of its marginal cost curve after its own adoption. The conditions under which firm i is indeed ‘sufficiently small’, however, cannot be derived in this general case. These conditions depend, *inter alia*, on the curvature of the demand function. The more convex the demand, the larger the probability that the profitability for a subsequent adopter may be equal to or even exceed that of its predecessor if the firms are not ‘sufficiently small’. For instance, if in Figure 1 the demand curve were kinked at *h*, with a flat segment to the right of *h*, we would find $\Delta\pi_2 > \Delta\pi_1$.

Corollary 1 Identical firms need not remain identical after an innovation has become available: the adoption by some firms may make it unprofitable for others to adopt.

Proof Corollary 1 follows from Proposition 3.■

Note that Corollary 1 may create a problem if all identical firms would simultaneously have to decide whether to adopt. If the availability of the equipment for individual firms at each moment in time is limited, this problem would of course be dampened. Nevertheless, we may end up in the situation where some firms are better off (the adopters) than others (the non-adopters) who were formerly identical, after the adoption process has finished. This can be seen by applying Proposition 1 to the marginal adopter and the marginal non-adopter. This is of course at odds with the intuitive expectation that firms that are identical should either all behave in the same way, or should at least, in any equilibrium process, be equally well off as those who followed a different strategy. The reason that this is not necessarily the case in the present model is the absence of possible equilibrating processes, such as changes in the innovation's cost or (expected) profitability over time, and a general lack of a time dimension (see, for instance, Fudenberg and Tirole, 1985; and Reinganum, 1989).

Proposition 4 The profitability of the innovation for a firm i is, for a given initial market price P, given factor prices w_E and w_L, and a given ρ, decreasing in k_i (keeping b_i and f_i fixed), decreasing in b_i (keeping k_i and f_i fixed), decreasing in f_i (keeping b_i and k_i fixed); and decreasing in the ratio $\alpha_{E,i}/\alpha_{L,I}$ (keeping b_i and k_i fixed), provided the firm is 'sufficiently small'.

Proof Proposition 4 follows from taking the following partial derivatives to (19a), where impacts on P are ignored because P is kept fixed, and where ϕ represents all terms resulting from second-order changes in P (therefore, ϕ captures all effects resulting from changes in P^* with P kept fixed; note that ϕ will be different in (22)–(24)):

$$\frac{\Delta_i}{k_i} = \frac{1}{b_i} \cdot \left[(f_i - 1) \cdot k_i + \left(P - P^* \right) \right] + \tag{22}$$

$$\frac{\Delta_i}{b_i} = -\frac{1}{4 \cdot b_i^2} \cdot \left[\frac{1}{f_i} \cdot P^{*2} - P^2 + (f_i - 1) \cdot k_i^2 + 2 \cdot k_i \cdot \left(P - P^* \right) \right] + \tag{23}$$

$$\frac{\Delta_i}{f_i} = \frac{1}{2 \cdot b_i} \cdot \left[-\frac{1}{f_i^2} \cdot P^{*2} + k_i^2 \right] + \tag{24}$$

If the firm is sufficiently small, $P–P^*$ and hence ϕ approaches zero, and (22), (23), and (24) are smaller than zero because $f_i<1$ and $P \geq k_i$. By (7a), $\partial f_i/\partial \alpha_{E,i}>0$ and $\partial f_i/\partial \alpha_{L,i}<0$, which completes the proof.[2]■

[2]Note that a marginal change in k_i with b_i held fixed requires a marginal change in β_i, and that a marginal change in k_i with f_i, w_E and w_L held fixed imposes a restriction on the proportional changes in $\alpha_{E,i}$ and $\alpha_{L,i}$ (see 7a); that a marginal change in b_i with k_i and f_i held fixed requires a marginal change in β_i by (7ab); and

Generalization Because Proposition 4 deals with parameters in the specific model presented in Section 2, it is hard to generalize the results one by one. However, for any sufficiently small firm, whose adoption has a negligible effect on the market price, one would normally expect the profitability of adopting an energy-efficiency enhancing innovation to increase when (1) the firm's supply curve has a lower position (compare k_i) and (2) is flatter (compare b_i), keeping all other things constant. Furthermore, one would also expect the innovation to be more profitable overall, (3) the stronger its relative impact on cost levels for all production levels (compare f_i), and the (4) larger the relative share of energy in the total inputs used in the firm's production process in the initial situation (compare $\alpha_{E,i}$ and $\alpha_{L,i}$).

Propositions 1–4 paint a rather optimistic picture of the market diffusion process of the innovation. This process is quite efficient by Propositions 2a and 2c: a voluntary adoption will always increase social welfare, although the incentive to adopt may be insufficient for the last adopter(s) by Proposition 2b. Consumers will always benefit (Proposition 1), but during the process, firms may impose negative *pecuniary* externalities on each other (Propositions 1 and 3). Finally, as one would expect with heterogeneous firms, the innovation's profitability may vary over firms according to their present cost structure: especially relatively large and energy-intensive firms may find the adoption attractive (Proposition 4). Such heterogeneity of firms is certainly conceivable, as it may even have resulted from the adoption and diffusion of a previous innovation by Corollary 1. In the next section, we will investigate the implications of the above conclusions for the case where the energy input is not efficiently priced, as was assumed above.

4. Inefficiently priced energy and environmental policies

We now turn to the case of actual relevance, namely where the use of energy causes a negative environmental externality. It is postulated that the use of one unit of energy causes environmental damage which has a social value denoted by ε, where ε captures, for instance, the social (and the regulator's) valuation of external costs of global warming through CO_2-emissions, or the unpriced social value of excessively rapid depletion of fossil energy resources. In the context of the present paper, the exact interpretation of ε does not really matter; all that matters is that energy use is undervalued from a social point of view due to a given market failure. We will refer to this environmental externality as 'emissions'. The value of ε is assumed to be constant; that is, independent of the total level of energy use in the industry considered, and is equal for all firms. For the example of emissions, one unit of energy (e.g., a litre of fuel) produces the same amount of CO_2, with

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that a marginal change in f_i with k_i and b_i held fixed requires a marginal changes in the composition of k_i in terms of relative shares of labour and energy costs by (7a), and hence opposing changes in $\alpha_{E,i}$ and $\alpha_{L,i}$ because w_E and w_L are kept fixed by assumption.

the same social costs, no matter by which firm it is used. The social value of energy use is therewith equal to w_E+ε.

In this case, social welfare before the innovation has become available (25a) and after the adoption process is completed (25b) can be written as:

$$W = CS + \sum_i \left(\Pi_i - \quad \cdot E_i\right) = CS + \sum_i \left(\quad _i - \quad \cdot E_i - F_i\right) \tag{25a}$$

$$W^{**} = CS^{**} + \sum_i \left(\Pi_i^{**} - \quad \cdot E_i^{**}\right) = CS^{**} + \sum_{i=1}^{n} \left(\quad _i^{**} - \quad \cdot E_i^{**} - F_i - I\right) + \sum_{i=n+1}^{N} \left(\quad _i^{**} - \quad \cdot E_i^{**} - F_i\right) \tag{25b}$$

where double asterisks denote the situation after the adoption process has finished, the total number of firms is denoted by N, and, in the after-adoption situation, firms are ordered such that the first n firms are the adopters, and the last N–n firms are the non-adopters.

It is intuitively clear that, because of the presence of the unpriced externality, the free market does in general not generate the Pareto efficient production and consumption levels; that is, the maximization of (25a) before the innovation has become available, or (25b) after the adoption process is completed. Focusing on the pre-innovation market, this can easily be seen by observing that the social cost of energy use is now w_E+ε, and by allowing the regulator to set an energy tax τ_E. Reworking equations (2)–(6) and (9)–(16), the intuitive optimal energy tax τ_E=ε can be derived by observing that each firm's marginal social cost can be found by replacing w_E by w_E+ε in (4), and its supply function – which now possibly diverges from the marginal social cost – by replacing w_E by $w_E+\tau_E$ in (4). Hence, a free market, with τ_E=0, generally fails to achieve the optimal welfare.

It is, however, not this energy tax in the static pre- or post-innovation market that we are primarily interested in, but it is especially the interaction between the market failure and the adoption *process* that is of concern. For that purpose, the following two propositions are relevant:

Proposition 5 The impact of an energy tax on the profitability of the adoption is ambiguous in sign, and is decreasing in the share of energy costs in the firm's total production costs, and decreasing in the elasticity of the market demand over the relevant range.

Proof To avoid too much analytical clutter, consider the case where the firm is sufficiently small and P^*=P can be assumed. Next, use (4) and (7ab) to rewrite (19b) as follows:

$$\Delta \quad _i = \frac{1}{2 \cdot \quad _i} \cdot \left[\left(\frac{1}{k_i^*} - \frac{1}{k_i} \right) \cdot P^2 + \left(k_i^* - k_i \right) \right] \tag{26}$$

While observing that the equilibrium market price P may change due to a (generic) energy tax, the partial derivative of (26) w.r.t. a marginal change in the energy tax τ_E is the same as the derivative w.r.t. a marginal change in w_E, and can be written as:

$$\frac{\Delta\ _i}{w_E}=\frac{1}{2\cdot\ _i}\cdot\left[\left(\frac{1}{k_i^{\,2}}\cdot\frac{k_i}{w_E}-\frac{1}{k_i^{*2}}\cdot\frac{k_i^{*}}{w_E}\right)\cdot P^2+\left(\frac{k_i^{*}}{w_E}-\frac{k_i}{w_E}\right)+2\cdot\left(\frac{1}{k_i^{*}}-\frac{1}{k_i}\right)\cdot P\cdot\frac{P}{w_E}\right]$$

or:

$$\frac{\Delta\ _i}{w_E}=\frac{1}{2\cdot\ _i}\cdot\left[\left(\frac{P^2}{k_i^{\,2}}-1\right)\cdot\frac{1}{\ _E}-\left(\frac{P^2}{f_i^{\,2}\cdot k_i^{\,2}}-1\right)\cdot\frac{1}{\ \cdot\ _E}+2\cdot\left(\frac{1}{k_i^{*}}-\frac{1}{k_i}\right)\cdot P\cdot\frac{P}{w_E}\right] \tag{27}$$

because $\partial k_i/\partial w_E=1/\alpha_{E,I}$, $\partial k_i^{*}/\partial w_E=1/(\rho\cdot\alpha_{E,I})$, and $1/k^{*2}=1/(f^2\cdot k^2)$. Setting the term involving $\partial P/\partial w_E$ equal to zero for the moment – which it would be if the demand were completely elastic – it is now easy to see that:

$$sign\left\{\frac{\Delta\ _i}{w_E}\right\}\Bigg|_{\frac{P}{w_E}=0}=sign\left\{-\frac{\frac{P^2}{f_i^{\,2}}-k_i^{\,2}}{P^2-k_i^{\,2}}\right\} \tag{28}$$

Observe from (7a) that if $w_E/\alpha_{E,i}$ becomes relatively small, f_i approaches 1 so that (27) is positive according to (28). On the other hand, if $w_E/\alpha_{E,I}$ becomes relatively large, f_i approaches $1/\rho$, so that (27) is negative according to (28), provided $\partial P/\partial w_E=0$. If $\partial P/\partial w_E>0$, the impact of the energy tax on the profitability of adoption is of course less negative, or more positive than implied by (28). Finally, it is evident that $\partial P/\partial w_E$ is decreasing in 1/a, and hence in the demand elasticity over the relevant range by (13). As long as the price change induced by the adoption (P^*–P) would not dominate the (adapted) expressions (26)–(28), the proven ambiguity will carry over to situations where P^*–P is small but not negligible.■

Generalization Since the ambiguity holds for the special case of the linearized model, the proposition is likely to carry over to many other configurations. The crucial mechanism is that an energy tax has two opposing impacts on the profitability of the adoption: on the one hand, there is the positive impact through the increased price of energy; on the other hand, the firms' profits are negatively affected, which in turn implies that also a more or less proportional increase in these profits through the adoption (compare (19ab)) is reduced in size. The second part of the proposition applies to any situation where individual supply functions are not completely inelastic.

Proposition 6 The impact of the adoption by a firm on the total energy use in the industry, and hence on social welfare in case the energy input is not efficiently priced, is ambiguous in sign, and the total energy use in the industry after an adoption is increasing in the elasticity of market demand over the relevant range.

Proof The change in energy use by the adopter can be written from (2a) as:

$$\Delta E_i = \frac{1}{\cdot_{E,i}} \cdot (q_i^* + \tfrac{1}{2} \cdot \;_i \cdot q_i^{*2}) - \frac{1}{_{E,i}} \cdot (q_i + \tfrac{1}{2} \cdot \;_i \cdot q_i^2) \tag{29}$$

whereas the change in energy use by all other firms can be written as:

$$\Delta E_j = \frac{1}{_{E,j}} \cdot \left((q_j^* + \tfrac{1}{2} \cdot \;_j \cdot q_j^{*2}) - (q_j + \tfrac{1}{2} \cdot \;_j \cdot q_j^2) \right) \tag{30}$$

where q_j^* denotes firm j's production level after firm i's adoption. First of all, it is easy to see that the total energy use in the industry after an adoption is increasing in the elasticity of market demand over the relevant range by writing each firm k's energy use after firm i's adoption, E_k^*, as the terms in (29) and (30) involving q_k^*, and by observing that q_k^* is increasing in P^* for all k by (5), and that P^*, for a given P, is increasing in 1/a, and hence in the elasticity of demand over the relevant range, by (13). For completely elastic demand, with a=0, $P^*=P$ and hence $\Delta E_j=0$ for all $j \neq i$; but for a>0, $P^*<P$ and $\Delta E_j<0$. For firm i, the sign of ΔE_i depends on the relative size in the changes $q_i^*–q_i$ and $\alpha_{E,i}^*(=\rho \cdot \alpha_{E,i})–\alpha_{E,i}$. We prove that this is ambiguous in sign for the case where $P^*=P$. Writing the ratio q_i^*/q_i as G_i, we first observe that $G_i=(P/f_i–k_i)/(P–k_i)>1/f_i$ if $k_i>0$. Next, we rewrite (29) as:

$$\Delta E_i = \frac{1}{_{E,i}} \cdot \left(\frac{G_i}{_i} (q_i + \tfrac{1}{2} \cdot \;_i \cdot G_i \cdot q_i^2) - (q_i + \tfrac{1}{2} \cdot \;_i \cdot q_i^2) \right) \tag{31}$$

Both $G_i>1/f_i$ and $\rho>1/f_i$, but no general statement can be made about the relative size of ρ and G_i. Therefore, ΔE_i, and therefore also the change in the total energy use in the industry, is ambiguous in sign with a completely elastic demand. However, even with completely inelastic demand, the change in the total energy use in the industry is ambiguous in sign. In that case, one can write $\Delta q_i=–\Sigma_{j\neq i}\Delta q_j$: the additional production by the adopter is offset by a reduced production by the other firms. If $\alpha_{E,i}$ is sufficiently small, it is conceivable that the total energy use in the industry increases if, even after the adoption, firm i uses relatively much energy for its production compared to the other firms.

If the energy input is not efficiently priced, the impact of the adoption on social welfare is therefore also ambiguous in sign by (25ab).■

Generalization Since the ambiguity holds for the special case of the linearized model, the proposition is likely to carry over to many other configurations. The crucial mechanism is that the adoption has two opposing impacts on the adopter's energy use: on the one hand, it makes sure that energy is used more efficiently; on the other hand, because of the increased efficiency in production, there is a positive effect on the adopter's production level. The adopter's increased production may replace some of its competitors' production, which may or may not have required a smaller energy input. The second part of the proposition carries over to any situation where individual supply functions are not completely inelastic.

From propositions 1–6, a number of conclusions can be drawn regarding the efficiency of the adoption of energy-efficiency enhancing technologies by heterogeneous firms and associated environmental policies. First of all, whereas one might expect that a Pigouvian tax would unambiguously increase the incentive to adopt the technology, this certainly need not be the case when it is taken into consideration that (1) firms may prefer to respond to an energy tax by output restriction, and (2) an energy tax may reduce equilibrium outputs and profits to such an extent that a more or less proportionate increase in the profits owing to the efficiency enhancing character of the innovation (compare (19ab)) no longer outweighs the costs of adoption (see Proposition 5). Instead, therefore, of stimulating adoption *per se*, the role of an energy tax is far more subtle, in that it stimulates efficient adoption. That is, it promotes adoption by firms that should adopt from the social point of view, and prevents adoption by firms that should not adopt from this viewpoint (see Proposition 2c).

This notion is in particular important when firms are different. In that case, a lack of energy taxes may cause the ‘wrong’ firms to adopt. By Propositions 4 and 5, especially relatively energy-intensive firms will face a disproportionally high incentive to adopt in case energy is under-priced from a social point of view. Starting from the lower level of social welfare (see (25a)), adoptions may certainly often increase social welfare also in absence of energy taxes – in particular if the total energy use decreases due to the adoption – (see Proposition 6), but this observation ignores that the social welfare gains due to adoption would have been even larger – and always positive by Proposition 2a – under optimal energy taxes.

As a result, if the adoption process under the absence of energy taxes results in a different set of firms adopting the innovation than would have been the case under optimal energy taxes, the overall Pareto efficient outcome may even be unattainable. After the adoption process has finished, the introduction of optimal energy taxes will then lead to a lower level of social welfare than could have been obtained if optimal energy taxes were applied throughout (compare Proposition 2c). Firms that have adopted, but should not have done so, cannot reverse the decision if the investment is irreversible. For firms that have not adopted, but should have done so, the adoption may remain unattractive even after the introduction of optimal energy taxes if other firms have already adopted (Proposition 3). Moreover, the more closely the market approaches the situation where firms operate on the edge of bankruptcy – as they do in perfect competition – the larger the probability that relatively energy-extensive firms that would have adopted under optimal energy taxes will have to leave the market in the situation where the technology becomes available under absence of optimal energy taxes (however, under these free-entry/free-exit conditions, re-entry is of course also easier if the market would allow this due to a late introduction of optimal energy taxes). Hence, the ‘structure’ of the industry may be negatively affected by the adoption process if energy is not efficiently priced. Although it may seem favourable at first sight that relatively energy-intensive firms face a disproportionally large incentive to adopt, the welfare gain to be obtained would be larger if the relatively energy-extensive firms would adopt, and increase their market share – often at the expense of the relatively energy-intensive firms – (see Proposition 1).

These conclusions also have implications for the use of different environmental instruments, other than Pigouvian taxes. First, consider the use of subsidies on the adoption of the innovation. If optimal energy taxes apply, such a subsidy is in principle counter-productive, because those firms for which it is socially efficient will face the optimal incentive to adopt already (see Proposition 2c), and a subsidy will only cause a redistribution of money without affecting the behaviour of these firms. Moreover, the subsidy may encourage some other firms to adopt, although this is not efficient from a social point of view (Proposition 2c). In the absence of optimal energy taxes, however, a general conclusion cannot be drawn, since there will be a number of counteracting forces at work. A subsidy then may or may not offer a socially beneficial environmental policy instrument. Obviously, the subsidy will encourage the adoption of the technology, and therewith a relatively more energy efficient production by those firms that would not have adopted without the subsidy. However, this will generally lead to a larger production by these firms (and by the total industry), which leaves the impact on total energy use ambiguous (Proposition 6). The increased production by these firms may of course partly offset production by other firms, some of which may have taken place with a larger energy input, and some of which, however, with a smaller energy input. Besides, there are of course social costs (I per adopter) associated with the induced additional adoption due to the subsidy, which should also be taken into consideration when evaluating this instrument. Next, it may well be the case that in absence of energy taxes, the incentive to adopt is in fact already excessively large (Proposition 5), so that a subsidy would only aggravate this inefficiency. Moreover, by Propositions 4 and 5, a subsidy in the absence of optimal energy taxes will disproportionally strongly encourage the adoption by firms that are relatively energy-intensive, which will weaken the position of the relatively energy-extensive firms as argued above. These conclusions on the use of subsidies form a rather strong contrast to those presented by Carraro and Siniscalco (1992), who argue that in a completely open economy, and under the assumption of completely elastic supply, a subsidy is the preferable environmental policy instrument. This demonstrates the dependence of policy conclusions on the particular market form and demand and supply elasticities considered.

A second possible environmental policy instrument concerns standards. In the context of the present paper, two types of standards are of particular interest, namely ‘performance standards’, where the regulator sets, for instance, a maximum level of energy use and hence emissions per unit of output, and ‘technology’ or ‘design standards’, where the regulator would force the adoption of the technology upon the firm (see also Besanko, 1987). Starting with the latter, it can first be observed that Proposition 2c suggests that a technology standard is in principle counter-productive if optimal energy taxes apply, simply because it need not be optimal – from a social point of view – for all firms to adopt the technology, whereas those firms for which it is socially efficient will face the optimal incentive to adopt already. In the absence of optimal energy taxes, however, a general conclusion, again, cannot be drawn. An advantage of imposing a technology standard is then found in the effect that at least all firms adopt, which reduces the possibility of relatively energy-intensive firms to expand their market shares at the expense of other firms, as may happen under non-intervention or with a subsidy. Moreover, all firms will use energy more efficiently than they did before. On the other hand, the additional social costs of having all firms adopting need of course not outweigh this possible benefit. Moreover, the output-enhancing impact of the technology on total energy use will counteract, and may even outweigh, the energy-efficiency gain, especially if the market demand is relatively elastic, so that total energy use may actually even increase due to the standard.

Performance standards seem more attractive from the perspective of overall efficiency, because they leave the firm the possibility of deciding exactly how to meet the standard (see also Besanko, 1987). The second-best optimal level of such a standard is not easy to derive for heterogeneous firms (see also Verhoef and Nijkamp, 1997), but one would normally expect a second-best optimal level which is at least binding for some firms. For reasons of space, however, this possibility will not be considered any further here.

5. Conclusions

In this paper, we have studied the adoption of energy-efficiency enhancing technologies by heterogeneous firms. Attention was given to the fact that energy use not only causes external environmental costs through pollution, but also directly affects the profitability of the firm, and hence its behaviour on input and output markets. As a consequence, Pareto optimality may require a delicate mix of output reduction by some firms, and the adoption of a new technology by others, possibly combined with output reduction, but in some cases expansion of output instead.

It was demonstrated that the consideration of such notions may have important, and sometimes counter-intuitive implications for the efficiency of environmental policies directed to energy use. For instance, the promotion of energy-efficiency enhancing technologies by means of subsidies may be counter-productive in that it could actually lead to an increase in energy use, and the use of energy taxes may actually reduce the attractiveness of energy-saving technologies. Both possibilities become more likely if the demand for the output is more elastic. An important conclusion arising from the exercise is that the role of an optimal energy tax is far more subtle than that of stimulating adoption *per se*. Instead, an energy tax will stimulate efficient adoption; that is, it promotes adoption by firms that should adopt from a social point of view, and prevents adoption by firms that should not adopt from this viewpoint. Indeed, it was shown that a market-led diffusion process of an energy-efficiency enhancing technology in the absence of optimal energy taxes may adversely affect the industry's structure, and may prevent the overall social optimum from being attainable after this process has finished.

The model used for deriving these results could clearly be criticized for its analytical simplicity, in particular the linearization of some key relationships and the assumed fixity of some of the ratios. However, it was argued that, and why, the presented propositions do not crucially depend on these assumptions, and it can therefore safely be stated that the conclusions should generally apply to much more general settings as well. Nevertheless, there are certainly aspects of adoption and diffusion processes in reality that were ignored in the present analysis but deserve attention in future research. These include, for instance, the existence of uncertainty and imperfect information, the spatial and dynamic dimension in adoption and diffusion processes, and the international dimension in energy policies.

References

Baumol, W.J. and W.E. Oates (1988) *The Theory of Environmental Policy*, second edition. Cambridge University Press, Cambridge.

Besanko, D. (1987) "Performance versus design standards in the regulation of pollution" *Journal of Public Economics* **34** 19-44.

Carraro, C. and D. Siniscalco (1992) "Environmental innovation policy and international competition" *Environmental and Resource Economics* **2** 183-200.

DeCanio, S.J. (1993) "Barriers within firms to energy-efficient investments" *Energy Policy* **21** 906-914.

Downing, P.B. and L.J. White (1986) "Innovation in pollution control" *Journal of Environmental Economics and Management* **13** 18-29.

Fudenberg, D. and J. Tirole (1985) "Preemption and rent equalization in the adoption of new technology" *Review of Economic Studies* **52** 383-401.

Helfand, G.E. (1991) "Standards versus standards: the effects of different pollution restrictions" *American Economic Review* **81** 622-634.

Helfand, G.E. (1993) "The relative efficiency of different standards when firms vary" *Natural Resource Modeling* **7** 203-217.

Howarth, R.B. and B. Andersson (1993) "Market barriers to energy efficiency" *Energy Economics* **15** 262-272.

Jaffe, A.B. and R.N. Stavins (1994) "The energy paradox and the diffusion of conservation technology" *Resource and Energy Economics* **16** 91-122.

Jung, C., K. Krutilla and R. Boyd (1996) "Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives" *Journal of Environmental Economics and Management* **30** 95-111.

Magat, W.A. (1978) "Pollution control and technological advance" *Journal of Environmental Economics and Management* **5** 1-25.

Malueg, D.A. (1989) "Emission credit trading and the incentive to adopt new pollution abatement technology" *Journal of Environmental Economics and Management* **16** 52-57.

Marin, A. (1978) "The choice of efficient pollution policies: technology and economics in the control of sulphur dioxide" *Journal of Environmental Economics and Management* **5** 44-62.

Metcalf, G.E. (1994) "Economics and rational conservation policy" *Energy Policy* **22** 819-825.

Milliman, S.R. and R. Prince (1989) "Firm incentives to promote technological change in pollution control" *Journal of Environmental Economics and Management* **17** 247-265.

Orr, L. (1976) "Incentive for innovation as the basis for effluent charge strategy" *American Economic Review* **56** 441-447.

Reinganum, J.F. (1989) "The timing of innovation: research, development, and diffusion". In: R. Schmalensee and R.D. Willig (1989) *Handbook of Industrial Organization* **1**. North-Holland, Amsterdam, 849-908.

Sanstad, A.H. and R.B. Howarth (1994) "'Normal' markets, market imperfections and energy efficiency" *Energy Policy* **22** 811-818.

Stoneman, P. (1987) *The Economic Analysis of Technology Policy* . Clarendon, Oxford.

Sutherland, R.J. (1994) "Energy efficiency or the efficient use of energy resources?" *Energy Sources* **16** 257-268.

Verhoef, E.T. and P. Nijkamp (1997) "The regulation of input related externalities with heterogeneous firms" Discussion Paper TI 97-009/3, Tinbergen Institute, Amsterdam-Rotterdam.

Appendix: Some numerical examples

A.1 Examples involving individual and identical firms

In this section, we provide some numerical examples as an illustration for the propositions involving individual and identical firms. We start with a base case and next perform some sensitivity analyses around this base case. The parameters in the base case considered are as follows. We start with the situation in which none of the 100 identical firms have as yet adopted the innovation. For those firms, $\alpha_E=\alpha_L=1$. We set $w_E=w_L=10$ and $\beta=0.1$ so that k=20 and b=2. The innovation is characterized by I=50 and $\rho=1.5$, so that $\alpha_E^*=1.5$, and $k^*=16.67$, $b^*=1.67$ and f=0.83. On the demand side, d=100 and a=0.015, and the initial P=65.71 and y=100 ·q=2286. F=0 for simplicity, so that $\Pi=\pi=522$; CS=39184. Since for the first adopter, $\pi^*=722$, we find an initial

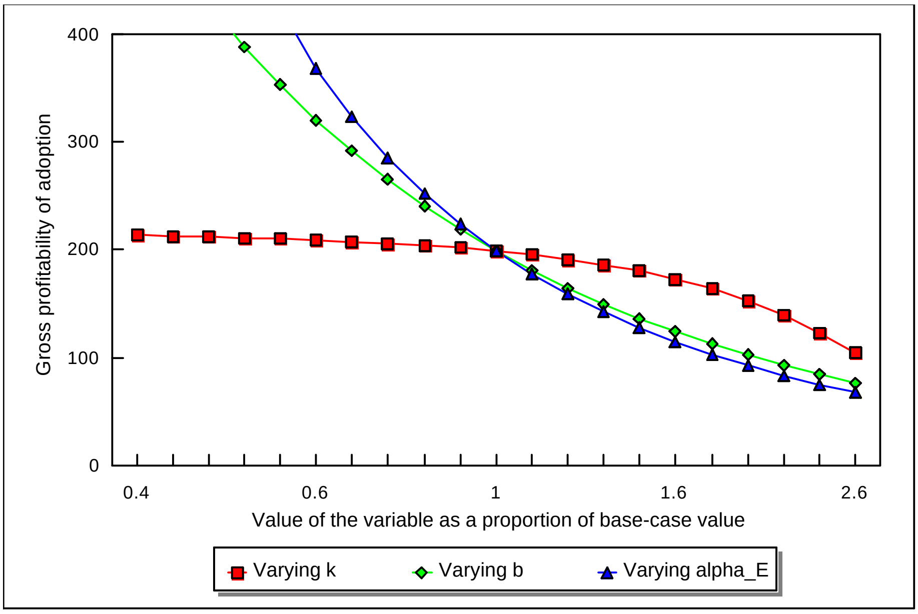

Figure A.1 The impact of k, b and $_E$ on the profitability of the adoption

$\Delta\pi=199$ (note the rounding error).

Figure A.1 gives a graphical demonstration of Proposition 4 for a first, single adopter; that is, using P=65.71, and assuming that the other firms' parameters remain as described in the base case. Three parameters (k, b and α_E) were subsequently increased with a factor 1.1 in each step (with the base case in the centre), keeping other parameters constant (as outlined in Footnote 2). Since the increase in α_E requires α_L to decrease in order to keep k and b fixed, and therefore implies f to increase, the claims in Proposition 4 that π is decreasing in k, b, f, and α_E, and increasing in α_L, keeping other parameters constant as indicated in Proposition 4, can be verified in Figure A.1. Note that the net profitability of adoption may be found by shifting the curves depicted downwards with I=50.

Figures A.2–A.4 illustrate Propositions 1 and 2. Figure A.2 shows that with an increasing number of adopters, the market price as well as the per firm production for both types of firm (adopters and non-adopters) decreases. Nevertheless, total production increases, because the per firm production for an adopter exceeds that of a non-adopter. Figure A.3 shows the favourable impacts of voluntary adoption on social welfare and on the consumers' surplus. Nevertheless, although individual firms benefit from their own voluntary adoption, the impact on the total producers' surplus is ambiguous due to the negative *pecuniary* externality that firms impose on each other. It is conceivable that firms end up in a prisoners' dilemma, where each individual firm prefers to adopt, but all firms would be better off if none of them would adopt.

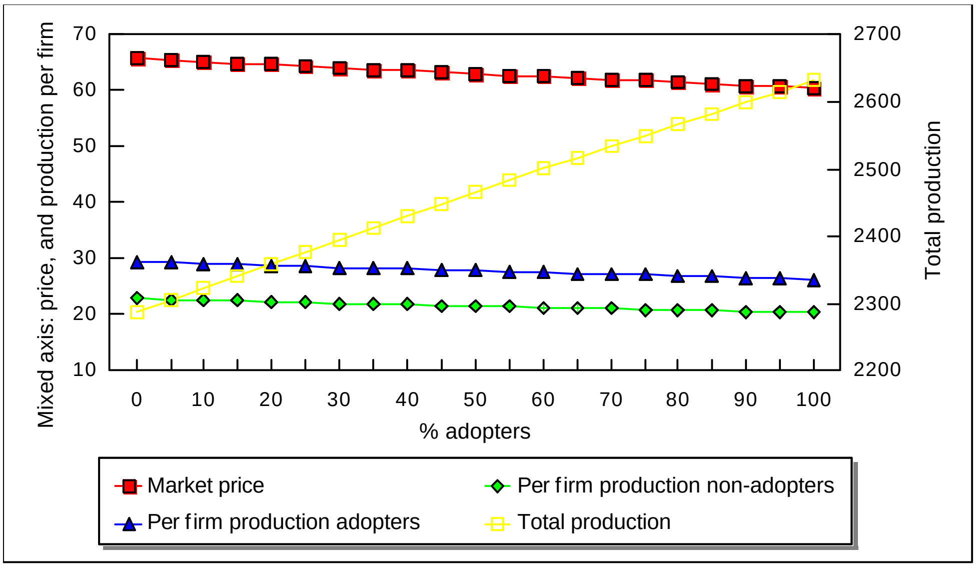

Figure A.2 *Voluntary adoption: prices and quantities*

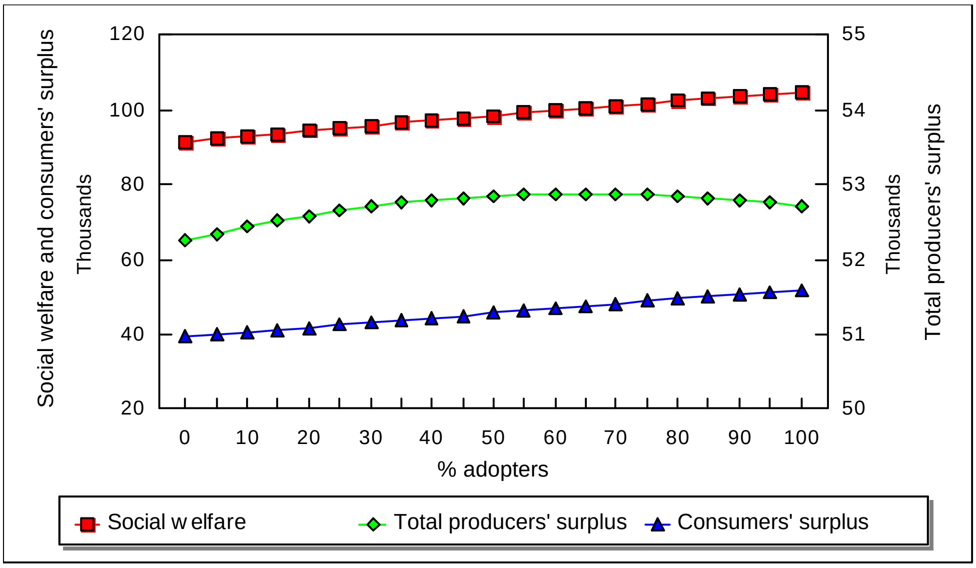

Figure A.3 *Voluntary adoption: welfare implications*

Figure A.4 shows that each other firm's producer's surplus decreases due to the adoption by another firm. The figure also illustrates the efficiency of the voluntary adoption process under the assumption that energy is efficiently priced. For that purpose the cost of adoption I was raised to 175, a level for which adoption is not profitable for all firms. The figure shows that in that case, social welfare increases over the range of adoptions for which firms would voluntarily adopt; that is, in the case considered, up to a penetration rate of some 75%. Beyond that penetration level, social welfare would decrease due to further adoptions. However, since the cost of adoption then exceeds its gross profitability, voluntary adoption will no longer occur. The voluntary adoption process terminates exactly when the social welfare has reached its maximum; hence, the voluntary adoption process is Pareto efficient, provided energy is efficiently priced.

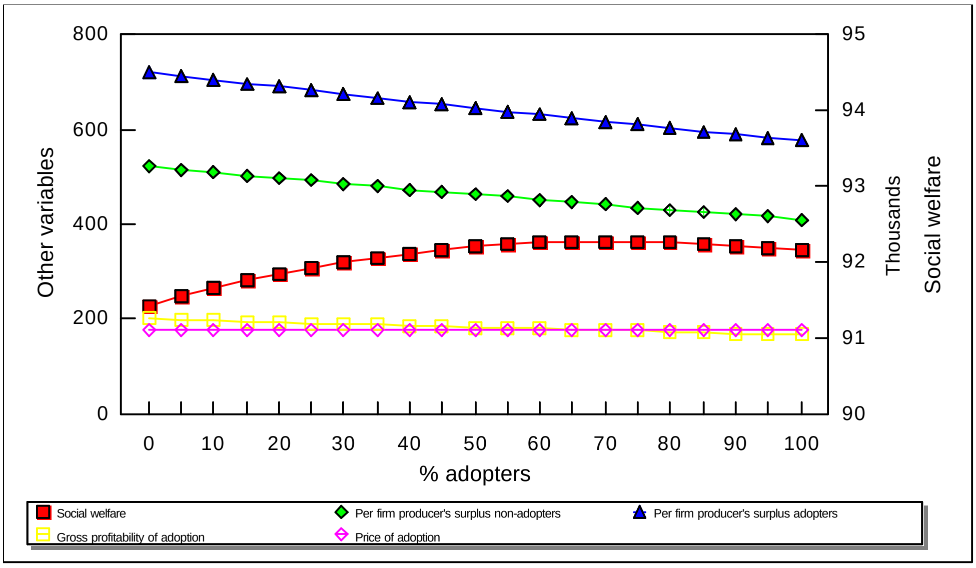

Figure A.4 *Voluntary adoption: efficiency*

Finally, Figure A.5 illustrates that, according to Proposition 5, the impact of an energy tax on the net profitability of adoption is ambiguous. Keeping in all three cases presented b and k at the same value as in the base case, case A shows the impact of an energy tax for the base-case parameters, while B represents the case where all firms are relatively energy-extensive (α_E=2 and α_L=2/3) and case C where they are all relatively energy-intensive (α_E=2/3 and α_L=2). Under the assumption that ε=10, an optimal energy tax τ_E=10 is found for each case, as is demonstrated by the three upper curves showing the level of (broadly defined) social welfare. The three lower curves, depicting the first adopter's net profitability, show that this tax (and actually any energy tax level) causes a sharper fall in the net profitability of adoption, the more energy-intensive the firms are. The fact that the net profitability is nevertheless higher for more energy-intensive firms throughout the parameter range considered is caused by the restriction that k and b were kept at the base-case values, but is certainly not generally true.

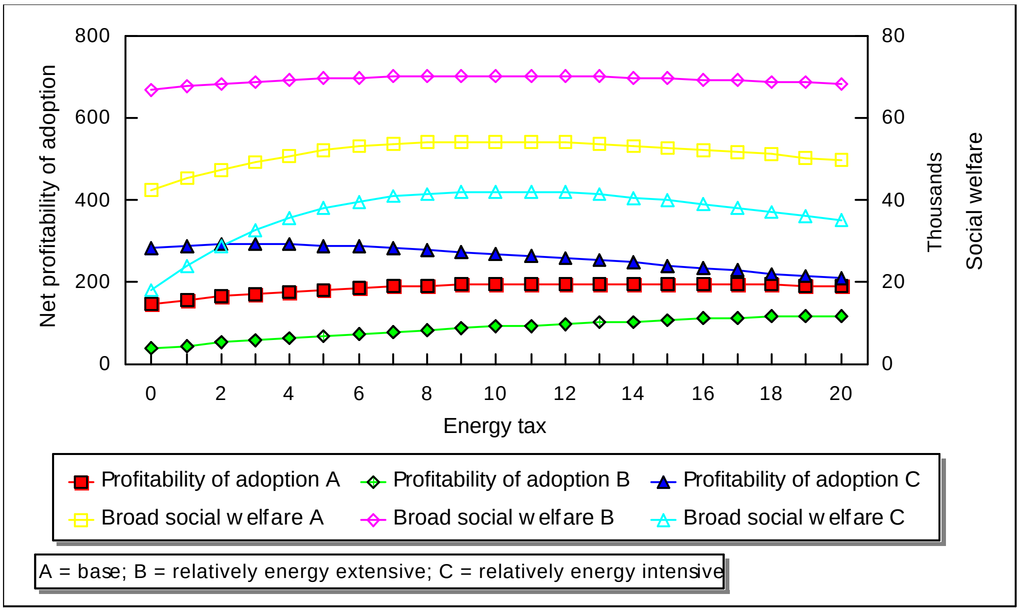

Figure A.5 Energy intensity and the impact of energy taxes on adoption

A.2 Examples involving heterogeneous firms

We now proceed by extending the example presented in the previous section to the case of heterogeneous firms. In order to be able to illustrate the claims made in the main body of the paper, it is sufficient to introduce a mild form of heterogeneity: 50 firms (denoted i) retain the parameter values used above, and the other 50 are assumed to be more energy intensive and have $\alpha_{E,j}=2/3$ and $\alpha_{L,j}=2$. This secures that all firms are equally profitable in the initial situation if no energy taxes are levied: $k_i=k_j=20$ and $b_i=b_j=2$, so that the initial prices and quantities in the absence of energy taxes are the same as those found above. Finally, for the present simulations, the parameters I and ρ are changed to values of 100 and 1.2, respectively; and $\varepsilon=\tau_E=8$ was assumed.

A simulation where the demand curve is 'tilted' around the original initial non-intervention market equilibrium was found to be the most useful one to illustrate most points of importance in the main text in as few as possible diagrams. The figures below thus give an illustration of the impact of the demand elasticity in the initial market equilibrium upon the effects of the availability of a new energy-efficiency enhancing technology on market performance under various policy regimes. The base case is always found in the middle of the figures, and when moving leftward (rightward), the absolute value of the slope of the inverse demand curve, a, decreases (increases) with a factor 1.5 in each step, while the intercept d is adjusted simultaneously in order to obtain the same initial market equilibrium in absence of energy taxes. Before discussing the diagrams, it should be noted that the only aim is to give a *qualitative* demonstration of some of the features discussed in the main text. No inferences should be made on basis of *quantitative* differences depicted below, as these are fully determined by the specific (combinations of) parameters chosen.

The following 'regimes' are distinguished. The initial situation is given by the non-intervention market equilibrium in the absence of energy taxes, before the new technology has become available. Next, we consider the same situation after the voluntary adoption process has terminated. The third regime introduces 'naïve' subsidies on adoption, and again considers the situation where the associated adoption process has terminated. With 'naïve', we mean that these subsidies are set at a level that secures that all firms adopt, without considering the impacts on broadly defined social welfare.[3] It will turn out that in some cases, the optimal level of such a subsidy would actually be negative (i.e., a tax); hence the qualification 'naïve'. The following three regimes are comparable to the previous three, but are different in that energy is assumed to be optimally priced by means of an optimal energy tax. The seventh regime, denoted 'late taxes', assumes that such an optimal energy tax is introduced only after the voluntary adoption process, in the absence of energy taxes, has terminated. For this regime, it is implicitly assumed that firms, when deciding to adopt, do not foresee the introduction of the energy tax.

For the interpretation of the diagrams, Table A.1 may be helpful. The table depicts for both types of firm whether they do (+) or do not (–) adopt for a give demand structure and under a given policy regime. Firms i will never adopt without optimal energy taxes, and will only adopt with energy taxes (regardless of whether this tax is 'late') when the demand curve is sufficiently steep; that is, when from the firms' perspective, the market price adjusts sufficiently in response to the tax. Firms j, on the other hand, will always adopt in the absence of energy taxes, and will only adopt with energy taxes when the demand curve is sufficiently steep, where the critical slope has a lower value than for firms i. Firms j never adopt due to late taxes, because they have already done so before the late tax was introduced. Note that the two regimes involving naïve subsidies are not included in the table, since these would produce +'s throughout by definition.

1000*a	**0.3**					**2**					**15**					**114**					**860**
Firms i, no tax	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Firms i, tax	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	+	+
Firms i, late tax	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	+	+
Firms j, no tax	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Firms j, tax	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Firms j, late tax	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

Note: + (–) indicates (no) adoption. For 'late taxes', + indicates induced adoption only after introduction of the late tax

Table A.1 Adoption table for the numerical example in Appendix-section A.2

Figure A.6 shows the total energy use in the industry. Focusing first on the regimes without optimal energy taxes, the left-hand side of the figure shows an illustration of the possibility that the total energy use in the industry may actually increase due to the adoption of an energy-efficiency enhancing technology, especially when demand is relatively elastic. In that case, the effect of the increase in total output dominates the favourable effect of a more efficient usage of energy. Note that in this case, the naïve subsidy actually dampens this effect, perhaps contrary to what one would expect. The reason is that the subsidy here encourages also the more energy-extensive firms to adopt, and to expand their market share at the expense of the more energy-intensive firms. In Figure A.7, which shows broadly defined social welfare as a proportion of the

[3] Since the subsidy *payments* are merely a redistribution of money, this regime is in terms of real impacts and overall economic efficiency identical to a technology standard, where all firms are obliged to use the new technology. Subsidies and technology standards would diverge as soon as not all firms would adopt under a subsidy, or when different technologies were available.

optimal welfare level (associated with optimal energy taxes after the adoption process has finished), it can be seen that as a result of the increased energy use, social welfare here actually decreases due to voluntary adoption under imperfect prices. Furthermore, although the naïve subsidy has a favourable impact on energy use, Figure A.7 demonstrates that these benefits do not outweigh the social cost of the adoption by firms i, so that social welfare is even lower in this regime. Beyond a certain slope of the demand curve, these welfare rankings are reversed. In those cases, naïve subsidies may actually increase social welfare in the absence of energy taxes.

Next, the figures show that the difference between regimes with and without energ y taxes in terms of total energy use and social welfare levels are particularly large for a relatively elastic demand. This partly reflects the relatively large reduction in output that results from optimal energy taxes when demand is relatively elastic. For social welfare, in the case of a relatively inelastic demand, however, the difference in levels with and without energy taxes is in a way deflated, because the consumers' surplus, which increases rapidly with the slope of the demand curve, dominates the welfare levels at a relatively inelastic demand. For that reason, also Figure A.8 is included, which shows the index of relative welfare improvement (ω) for five regimes. This index is defined as the welfare gain in a certain regime compared with the welfare level in the initial situation (i.e. before adoption and without energy taxes), relative to the optimal welfare gain that can be obtained under optimal energy taxes after the (voluntary) adoption process has terminated, again compared with the welfare level in the initial situation. Clearly, because social welfare is maximized with optimal energy taxes after the voluntary adoption process has terminated (see also Proposition 2c), ω cannot exceed 1. A negative value of ω simply indicates that social welfare has actually gone down the level obtained in the initial situation.

On the left-hand side of Figures A.6–A.8, it can be seen that an optimal energy tax before the adoption has become available already produces the optimal outcome when it is not socially desirable for any firm to adopt. The stimulation of adoption by means of a naïve subsidy in those cases has a perverse effect on both energy use and social welfare. The figures also demonstrate that a late energy tax, introduced after firms j have adopted contrary to what would be socially desirable, results in below-optimal welfare levels and above-optimal energy use. This is an example of what was meant in the main body of the paper when it was stated that voluntary adoption in absence of optimal energy taxes may make the overall optimum unattainable. The figures show that this perverse effect is increased when 'naïve' subsidies on adoption are used in conjunction with energy taxes, in which case not only firms j but also firms i adopt contrary to what would be socially desirable. Clearly, an 'optimal' subsidy in these simulations would either be zero (when optimal energy taxes apply) or negative (when energy is not priced optimally and firms j ought to be prevented to adopt).

Moving rightward, we next come in the region where it is actually socially optimal for firms j to adopt. Here, the energy tax, before the adoption process has taken place, no longer coincides with the first-best optimum. Although broad social welfare increases due to the voluntary adoption by firms j under optimal energy taxes, it is interesting to see that this actually leads to a higher level of total energy use in the industry. This demonstrates that also with optimal energy prices, the adoption of an energy-efficiency enhancing technology may actually lead to an increase in energy use. Because from this point onwards, a late tax does not lead to a different set of firms having adopted, the late tax regime further coincides with the first-best situation. Only once we have passed the point where firms i also adopt with energy taxes does the naïve subsidy in conjunction with energy taxes no longer negatively affect social welfare. In that case, the subsidy only redistributes money without having any real effects.

On the right-hand side of Figure A.8, one can find some details that get lost on the right-hand side of Figure A.7. The most important of these is that when the demand becomes more inelastic, the relative efficiency of energy taxes before adoption decreases, and that of adoption without taxes increases. This underlines the intuitive general tendency that, starting from the initial situation, output reductions are particularly important for improving social welfare when demand is relatively elastic, whereas technological change becomes important particularly in case of an inelastic demand. This is consistent with the upward (downward) slopes of the curves 'with energy taxes' ('without energy taxes') in Figure A.6, and the tendency in Figure A.7 that the relative impact of the absence of energy taxes on social welfare decreases when demand becomes more inelastic.

This concludes our brief discussion of the numerical example. The reader may verify that the most important claims made in the main body of the text could be reproduced with this admittedly simple simulation model. Moreover, the intersections of many curves in Figures A.6–A.8 demonstrate that it is difficult, if not impossible, to make any general statements about the relative performance of the various regimes considered.

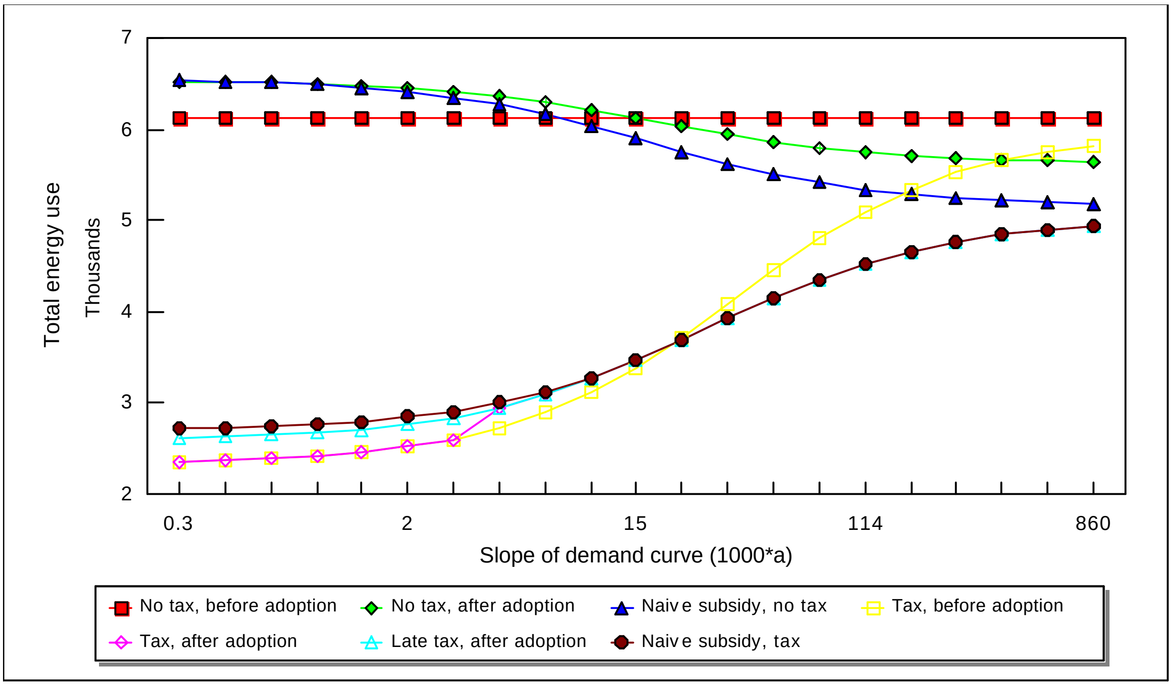

Figure A.6 Total energy use under different configurations

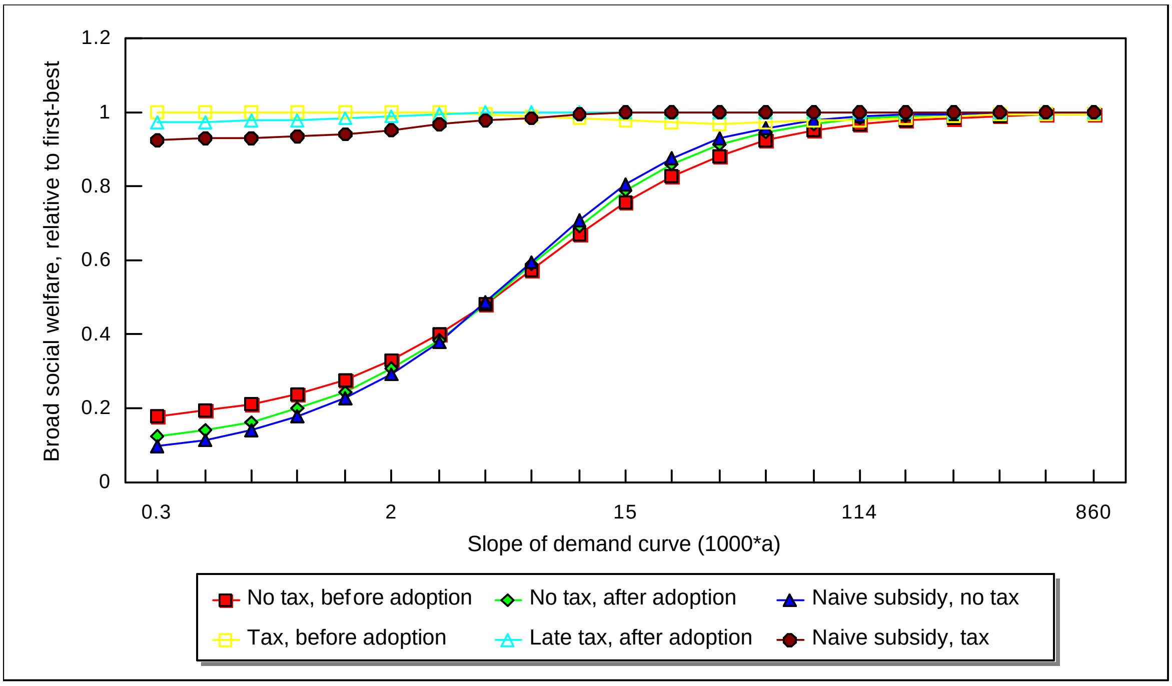

Figure A.7 Broadly defined social welfare relative to optimum under different configurations

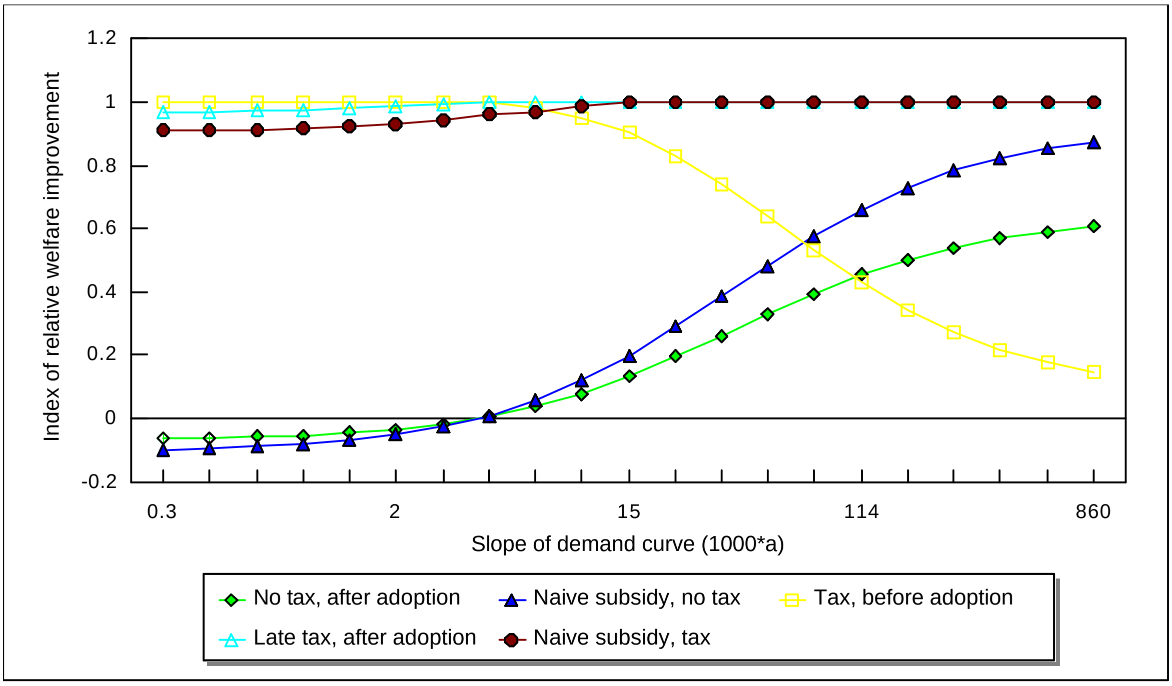

Figure A.8 Index of relative welfare improvement under different configurations