Technical efficiency and CO_2 abatement policies in the Dutch glasshouse industry

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Abstract

This paper develops a short-run microeconomic simulation model of the Dutch glasshouse industry in order to investigate the relation between technical efficiency and marginal abatement costs of CO_2 emission. The model is also used to determine the effects of an emission tax and systems of tradable and non-tradable quota for groups of firms with different rates of technical efficiency. The results show that marginal abatement costs are very responsive to changes in technical efficiency. Furthermore, it is found that firms with a low technical efficiency are faced with a higher profit reduction under different abatement policies than firms with a high technical efficiency.
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1. Introduction

The implementation of cost efficient environmental policy, aiming at reducing undesirable emissions by firms, often requires knowledge of each firms' marginal abatement costs. Examples of policies where such knowledge is required are Pigouvian taxes (Baumol and Oates, 1988), deposition permits (Montgomery, 1972) and pollution offset permits (Krupnick et al., 1983). Marginal abatement costs may also be seen as a measure of the firms' willingness to pay for additional quota, and as such they provide valuable information about the direction of trade flows between firms in the event of quota trade.

Marginal abatement costs are likely to differ across firms, due for example to differences in technology. Technological differences between firms are frequently reflected in technical efficiency measures (e.g. Oude Lansink, 2000), since these relate the quantity of output produced by a firm to the quantity of output that is produced by the best practice firm, for given quantities of inputs (output based technical efficiency).[1] Therefore, the size of marginal abatement costs may be closely related to technical efficiency. However, the relationship between technical efficiency and marginal abatement costs is still a largely neglected area of research.

The objective of this paper is to investigate the relation between technical efficiency and marginal

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[1] The definition given here is an output based measure of technical efficiency. An alternative is an input based measure of technical efficiency (see e.g. Coelli et al., 1998).

abatement costs. The relation between technical efficiency and marginal abatement costs of CO_2 emissions by Dutch glasshouse firms is investigated in a regression model and by demonstrating the effects of a CO_2 emissions tax and systems of tradable and non-tradable quota on groups of firms with different technical efficiency ratios. Similar policy simulations were made by Brännlund et al. (1998) for emissions trading among Swedish paper and pulp firms. However, Brännlund et al. (1998) did not determine the effects of emission trading for firms with different technical efficiencies. This paper derives a measure of technical efficiency (based on Oude Lansink, 2000) from a short-run microeconomic model of producers engaged in polluting activities. The theoretical framework is applied to a rotating panel of Dutch glasshouse firms, whose production relies importantly on the use of natural gas causing CO_2 emission. Also, in the Dutch glasshouse industry, CO_2 is an intermediate input, since the firms produce CO_2 in order to improve growing conditions in the glasshouse. CO_2 emission of the whole glasshouse industry makes up for 4% of total CO_2 emission in The Netherlands. Under the Kyoto protocol, The Netherlands is obliged to reduce its CO_2 emissions in by 8% from its 1990 level by 2010 (United Nations, 1997).

The next section presents a microeconomic model of profit maximising firms that produce marketable outputs and CO_2 emissions. Next, a technical efficiency measure is derived from the microeconomic model. The case of Dutch pot-plant firms is the focus of the empirial application and the paper concludes with comments.

2. Theoretical model

This section presents a model of variable profit maximising firms that produce a single output y, using a vector of variable inputs (x) and a vector of fixed inputs (z). Moreover, these firms generate a vector of emissions e. Normalising all prices and profit by the price of outputs, the variable profit maximisation problem for firm h can be depicted as

$$\pi_h(w, z_h, e_h) = \max_{y_h, x_h}\{y_h - w'x_h | z_h, e_h\} \quad \text{s.t. } y_h$$
$$= F_h(x_h, z_h, e_h) \qquad (1)$$

where w is a vector of normalised input prices

and $F_h(\cdot)$ represents the (firm-specific) production function[2] of the hth firm.

The optimisation problem in (1) assumes that each firm has a unique production technology. Differences in production technology may arise because firms are operated by managers with different motivations and management qualities. Also, firm operators generally have different attitudes towards new technologies and/or capabilities to evaluate information on new technologies, resulting in differences in adoption rates. Differences in the rate of adoption of new technologies may also occur due to the adjustment costs of replacing existing firm capital or credit constraints.

Applying Hotellings' lemma to (1) yields a coherent system of input demand equations.

$$-x_h = \frac{\partial \pi_h(w, z_h, e_h)}{\partial w} = -x_h(w, z_h, e_h) \qquad (2)$$

The (numeraire) output supply equation is derived using the definition of normalised profit:

$$y_h = y_h(w, z_h, e_h) = \pi_h(w, z_h, e_h) + w'x_h(w, z_h, e_h) \qquad (3)$$

Finally, an equation for optimal emissions is derived from the following maximisation problem:

$$G_h(w, z_h) = \max_{e_h}\{\pi_h(w, z_h, e_h) | z_h\} \qquad (4)$$

Using the first-order condition for maximising profit in (4) gives:

$$\frac{\partial \pi_h(w, z_h, e_h)}{\partial e_h} = 0 \qquad (5)$$

and implicitly imposes the restriction $\partial F_h()/\partial e_h = 0$ on the underlying firm-specific production function. Solving for e_h in (5) gives the equation for optimal emissions:

$$e_h = e(w, z_h) \qquad (6)$$

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[2] In Eq. (1), $F_h(\cdot)$ is assumed to be increasing, twice differentiable and concave in x, and increasing, twice differentiable and concave in x_h and e_h, respectively These conditions are satisfied for $F_h(\cdot)$ if $\pi(\cdot)$ is increasing and convex in prices and increasing and concave in emissions.

3. Technical efficiency and marginal abatement costs

This section first derives a measure of technical efficiency from the microeconomic model that was developed in the previous section. Next, the relation between marginal abatement costs and technical efficiency is established.

3.1. A technical efficiency measure

Oude Lansink (2000) proposes a measure of relative technical efficiency that is based on the assumption that firms have different technologies. The concept of relative technical efficiency is clarified in Fig. 1, showing production functions of firm A (line AA) and B (line BB), having different slopes and intercepts. Input quantity X' gives output quantities a' and b' for firms A and B, respectively. At this level of input, firm A is more efficient then firm B; relative output technical efficiencies for A and B are given by 1 and b'/a', respectively. However, at input quantity X'', firm B is efficient relative to firm A with relative output efficiency being equal to 1 for firm B and a''/b'' for firm A.

The two-firm example in Fig. 1 demonstrates that relative technical efficiency of firms may depend on the input quantity level that is observed. At differ-

ent locations on the production curve, different firms can be efficient relative to other firms. In this framework, the production frontier is composed of different firm-specific production functions. In Fig. 1, there is the bold line, which is composed of the lower range of the production function of firm B and the upper range of the production function of firm A. From Fig. 1, it can also be seen that calculating relative technical efficiency requires that input quantities of firm A are inserted in the production function of firms A *and* B.

A problem arises when the dual model presented in the previous section is used to calculate technical efficiency. Note from (3) that dual output supply equation is defined in the space of the input *price*, the fixed input quantity and the emission quantity. However, calculating relative technical efficiency requires that output supply for each firm in the sample is expressed as a function of variable and fixed input quantities and emissions of all other firms in the sample. Therefore, the output supply function needs to be rewritten from the variable input price space to the variable input quantity space.

In order to express the output supply function in the variable input *quantity* space rather than the variable input *price* space, this paper uses the concept of shadow or virtual prices (Fulginiti and Perrin, 1993). Virtual or shadow prices are usually referred to in the literature in the context of rationing or quotas. However, in this paper, virtual prices are merely used as a calculation device that allows for the transformation of the output supply function from the variable input *price* space to the variable input *quantity* space.

Virtual prices $w^v_{j,h}$ are defined as the shadow price vector that would induce firm j to freely choose the input quantity vector x_h, chosen by firm h, given fixed input quantity z_h and emission e_h.[3]

$$x_h = x_j(w^v_{j,h}, z_h, e_h) \tag{7}$$

Note that $w = w^v_{h,h} \forall h$ implying that

$$x_h = x_h(w^v_{h,h}, z_h, e_h) = x_h(w, z_h, e_h) \tag{8}$$

Solving (7) for $w^v_{j,h}$ yields:

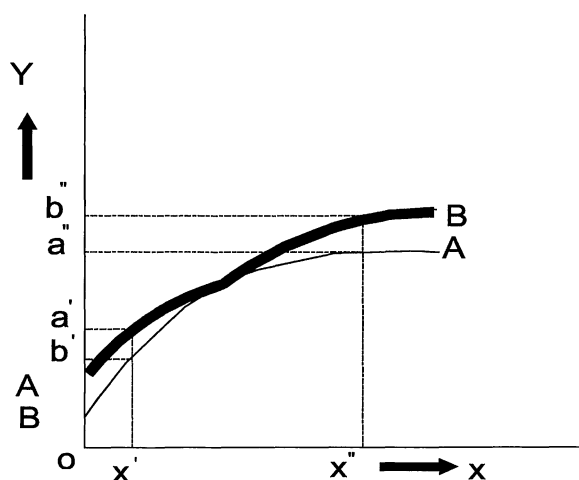$$w^v_{j,h} = w^v_j(x_h, z_h, e_h) \tag{9}$$

Fig. 1. Relative output technical efficiency in input–output space. This figure depicts a one input, one output situation. In the case of multiple inputs, the picture can be seen as a two-dimensional mapping of a multi-dimensional space. X denotes the quantity of variable or fixed inputs.

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[3] In the following Eqs. (7)–(10) and (12), the reader should note that Eqs. (2) and (6) imply that x_h and e_h reflect profit maximising levels of variable inputs and emissions, given the firm's own technology.

Inserting (9) in the output supply Eq. (3) yields $y_{j,h}$, which is the output that firm j would produce with the input quantities (x_h and z_h) and emissions (e_h) that are observed on firm h:

$$y_{j,h} = y_j(w_{j,h}^v(x_h, z_h, e_h), z_h, e_h) = y_j(x_h, z_h, e_h) \tag{10}$$

Maximum obtainable output for firm h given input bundles x_h and z_h and emission levels e_h is given by

$$y_h^* = \max_{j \in H} \{y_{j,h}\} \tag{11}$$

where H is the set of comparison firms of firm h. The relative output technical efficiency[4] of firm h ($\lambda_h(\cdot)$) is determined as the ratio of observed output to maximum obtainable output:

$$\lambda_h(x_h, z_h, e_h) = \frac{y_h(x_h, z_h, e_h)}{y_h^*(x_h, z_h, e_h)} \tag{12}$$

3.2. Relation between technical efficiency and marginal abatement costs

The theoretical model developed in Section 2 assumes an optimal allocation of emissions by imposing the constraint in (5). However, emissions may be below their economic optimum in case of an emission quota. If emissions by firm h are fixed at the level $\bar{e}_h$, then constrained variable profit associated with the emission level $\bar{e}_h$ is the solution of the following maximisation problem:

$$\pi_h(w, z_h, \bar{e}_h) = \max_{y_h, x_h} \{y_h - w'x_h | z_h, \bar{e}_h\}$$
$$\text{s.t. } y_h = F_h(x_h, z_h, \bar{e}_h) \tag{13}$$

The relation between technical efficiency and marginal abatement costs is established by using (12) and specifying output observed at firm h as

$$y_h = \lambda_h(x_h, z_h, \bar{e}_h) F^*(x_h, z_h, \bar{e}_h) \tag{14}$$

Incorporating (14) in (13) gives an equivalent expression for constrained variable profit:

$$\pi_h(w, z_h, \bar{e}_h) = \max_{x_h} \{\lambda_h(x_h, z_h, \bar{e}_h) F^*(x_h, z_h, \bar{e}_h) - w^t x | \bar{e}_h, z_h\} \tag{15}$$

Marginal abatement costs of emissions for firm h (MC_h) are defined as the first derivative of $\pi_h(w_h, z_h, \bar{e}_h)$ to emissions $\bar{e}_h$:

$$\frac{\partial \pi_h(w, z_h, \bar{e}_h)}{\partial \bar{e}_h} = \frac{\partial \lambda(\cdot)}{\partial \bar{e}_h} F_h^*(\cdot) + \frac{\partial F_h^*(\cdot)}{\partial \bar{e}_h} \lambda(\cdot)$$
$$= MC_h(x_h(w, z_h, \bar{e}_h), z_h, \bar{e}_h, \lambda_h(x_h$$
$$\times (w, z_h, \bar{e}_h), z_h, \bar{e}_h)) \tag{16}$$

The definition in (16) shows that marginal abatement costs are an implicit function of variable and fixed input quantities, constrained emissions and technical efficiency.

4. Empirical model

This section starts with the specification of a functional form for the profit function that is used to recover relative output efficiency at a later stage. The Normalised Quadratic (Lau, 1986) is used here because it is a flexible and self-dual functional form. The Normalised Quadratic is flexible, because it does not restrict substitution possibilities between inputs a priori.[5] Also, it has a Hessian of constants implying that convexity in prices can be tested and/or imposed globally. A further advantage of the Normalised Quadratic that is relevant in this study is its empirical simplicity. Using the price of output as the *numeraire*, the Normalised Quadratic profit function for firm h

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[4] Note that the methodology used here assumes that given their own technology all firms are allocatively efficient (Coelli et al., 1998; Färe et al., 1994) in the use of variable inputs and emissions, i.e. their quantities are at profit maximising values. This is because allocative efficiency given the own technology is implicitly assumed for y and x when maximising short-term profit; allocative efficiency of emissions is imposed through (5).

[5] Energy and CO_2 emissions may be expected to have limited substitution possibilities a priori. However, substitution possibilities may arise here because in Dutch horticulture, CO_2 emissions are generated for the sake of CO_2 fertilisation in the glasshouse. As such they can be seen as a substitute for some other inputs used produce a given bundle of outputs. Furthermore, in general there is no fixed proportional relation between energy and CO_2 emissions because the energy variable in this paper consists of many different components, i.e. fossil fuels (natural gas, oil), electricity and thermal deliveries by neighbouring energy plants. Each component has a different functional relation to CO_2 emission (and some components involve no CO_2 emissions at all the firm level). The possibility to vary the composition of the energy variable creates additional substitution possibilities between energy, CO_2 emissions and other inputs.

takes the form:

$$\pi_h = \alpha_{h0} + \sum_{i=1}^{3}\alpha_{hi}w_i + \sum_{k=1}^{4}\beta_k z_{hk} + \rho_h e_h$$

$$+ 0.5\sum_{i=1}^{3}\sum_{j=1}^{3}\alpha_{ij}w_i w_j + 0.5\sum_{k=1}^{4}\sum_{j=1}^{4}\beta_{kj}z_{hk}z_{hj}$$

$$+ 0.5\kappa e_h^2 + \sum_{i=1}^{3}\sum_{k=1}^{4}\gamma_{ik}w_i z_{hk}$$

$$+ \sum_{i=1}^{3}\eta_i w_i e_h + \sum_{k=1}^{4}\mu_k z_k e_h \qquad (17)$$

where π is normalised profit and w_i are normalised input prices with $i = 1$ (energy), 2 (materials) and 3 (services); z_{hk} are quantities of fixed inputs with $k = 1$ (structures), 2 (machinery and installations), 3 (labour) and 4 (trend); e_h are CO_2 emissions and all α, β, κ, μ, η, ρ and γ are parameters to be estimated. Note that α_{h0}, α_{hi} and ρ_h are firm-specific parameters. Input demand equations can be derived by applying Hotellings' lemma:

$$-x_h = \alpha_{hi} + \sum_{j=1}^{3}\alpha_{ij}w_j + \sum_{k=1}^{4}\gamma_{ik}z_{hk} + \eta_i e_h \qquad (18)$$

The equation of the optimal emissions[6] consistent with (6) is given by

$$e_h = \frac{-1}{\lambda}(\rho_h + \sum_{i=1}^{3}\eta_i w_i + \sum_{k=1}^{4}\mu_k z_k) \qquad (19)$$

The (numeraire) output supply equation is obtained using the definition of normalised profit:

$$\pi_h = y_h - \sum_{i=1}^{3}w_i x_{hi},$$

$$y_h = \alpha_{h0} + \sum_{k=1}^{4}\beta_k z_k + \rho_h e_h - 0.5\sum_{i=1}^{3}\sum_{j=1}^{3}\alpha_{ij}w_i w_j$$

$$+ 0.5\sum_{k=1}^{4}\sum_{j=1}^{4}\beta_{kj}z_k z_j + 0.5\kappa e_h^2 + \sum_{k=1}^{4}\mu_k z_k \qquad (20)$$

The output supply equation contains only one firm-

specific slope parameter in the input price space (α_{h0}). However, it should be noticed that the firm-specific intercepts from the input demand and emission equations (α_{hi} and ρ_h) also enter the supply equation as slope parameters when the output supply equation is transformed from input price to input quantity space.[7] Therefore, the underlying production function has several firm-specific slope parameters and a firm-specific intercept.

5. Data and estimation procedure

5.1. Data

Output mainly consists of pot-plants. Other outputs included are fruits, vegetables and flowers. Energy consists of gas, oil and electricity, as well as thermal energy delivered by electricity plants. Materials consist of seeds and planting materials, pesticides, fertilisers and other materials. Services are services by contract workers and services from storage and delivery of outputs. Fixed inputs are structures (buildings, glasshouses, land and paving), machinery and installations and labour. Labour is measured in quality-corrected man years, and includes family as well as hired labour. Labour is assumed to be a fixed input in the short term, because family labour represents a large share of total labour. Capital in structures and machinery and installations is measured at constant 1985 prices.

CO_2 emissions are measured as tons of CO_2 emission per year and are calculated from physical quantities of fossil fuels (mainly methane gas) that are used for heating and CO_2 fertilisation in the glasshouse (see Cordenier (1999) for more details). Energy consists of

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[6] An equation for optimal emissions is valid in this case, because firms in the Dutch glasshouse industry produce CO_2 as an intermediate input and are expected to optimise CO_2 production.

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[7] To see this point, note that the shadow price in vector notation can be derived from Eq. (18) as follows:

$$w_{j,h}^v = \alpha^{-1}(x_h - \alpha_j - \gamma(z_h, e_h))$$

where α is matrix of cross price terms (hessian), α_j vector of firm specific parameters on firm j, γ matrix of cross terms of prices and fixed inputs and emissions, z_h vector of fixed inputs on firm h, e_h vector of emission on firm h, x_h vector of variable inputs on firm h, and $w_{j,h}^v$ is vector of shadow prices on firm j when demanding variable input quantities observed on firm h. Inserting these shadow prices in the output supply equation gives the production function that is firm-specific in slope parameters and the intercept.

fossil fuels, but also of components that do not cause CO_2 emissions on the firms, i.e. heat delivery and electricity. Therefore, CO_2 emissions and energy may be assumed to be statistically independent factors, i.e. they are not necessarily perfectly collinear.

Tornqvist price indexes are calculated for output and the three composite variable inputs with prices obtained from the LEI/CBS (1988, 1990, 1994, 1997). The price indexes vary over the years but not over the firms, implying that differences in the composition of inputs and output or quality differences are reflected in quantities (Cox and Wohlgenant, 1986). Implicit quantity indexes are generated as the ratio of value to the price index.

A time trend is included in the empirical model to account for technological change in the estimation period.

5.2. Estimation procedure

Before estimation, error terms are added to Eqs. (17)–(20) in order to account for omitted variables that are peculiar to the individual firm and the time period. The error term of the ith equation is assumed to be independently identically distributed with a zero mean and variance σ_i^2. The system of Eqs. (17)–(20) is estimated by Full Information Maximum Likelihood (FIML) to account for the possible correlation of error terms across equations and the endogeneity of CO_2 emissions (e_h) in (17), (18) and (20). In order to account for heterogeneity of the firms in the sample, it is assumed that each firm has a firm-specific intercept (fixed effects assumption) in each equation of the system. Estimation is enabled by transforming the data prior to estimation (see Judge et al., 1988, pp. 470–472).

6. Estimation results

Estimates of the slope parameters and their estimated t-values can be found in Appendix A: Table A.1. The 25% of the slope parameters are significant at the critical 5% level. An explanation for the rather low percentage of significant parameters may be the relatively short time period (5 years) for which data are available; this limits in particular the variation of prices. The implication is that results of the model have to be

Table 1
Average technical efficiency in 1991–1995

Year	Technical efficiency
1991	0.34
1992	0.40
1993	0.38
1994	0.42
1995	0.46

interpreted with care. A firm-specific intercept is also estimated for each equation (58 firms and five equations make 290 firm-specific intercepts). R^2-values for equations of output supply, energy, materials and service demand and CO_2 emissions are 0.99, 0.97, 0.99, 0.96 and 0.92, respectively. Convexity in prices is assessed using the determinantal test and indicates that the profit function is convex in prices.[8]

Relative output technical efficiency consistent with (12) is computed as the ratio of predicted output to maximum obtainable predicted output. Both predicted output and predicted maximum obtainable output in (12) use predicted quantities of variable inputs, predicted CO_2 emission and the observed quantities of fixed inputs on each firm.

Table 1 gives the average values of technical efficiency for all years in the period 1991–1995, which are in the range of 0.34–0.46. Technical efficiency is a measure of the efficiency of the use of all inputs. Oude Lansink (2000), using a model that does not account for CO_2 emissions and data from the same firms found values for technical efficiency in the range of 0.74–0.81. An explanation for this difference may be that pot-plant firms use CO_2 less efficiently than the other variable and fixed inputs. Oude Lansink and Silva (2002) also reached this conclusion for specialised Dutch vegetables firms.

7. Marginal abatement costs and technical efficiency

In this section, the model that was developed in this paper is used to investigate the relation between marginal abatement costs and technical efficiency.

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[8] A sufficient condition for convexity of π in prices is that all principle minors of the discriminant of the matrix of second order partial derivatives of π with respect to prices are positive definite. This condition holds.

This relation is investigated by demonstrating the effects of different policies that aim at reducing CO_2emissions on firms with different technical efficiencies and by regressing technical efficiency on marginal abatement costs. The policies that are simulated are a tax on CO_2 emissions and systems of tradable and non-tradable emission quota.

Three different policy simulations are made with the model. The first simulation is a tradable quota with initial quota rights allocated according to the principle of 'grandfathering', i.e. each firm obtains a quota that equals 95% of its emissions in a base year. The quota level of 95% is illustrative and is not been derived from any (perceived) policy measure. It is assumed that CO_2 quotas are exchanged between firms in the pot-plant sector only, i.e. there is no inflow or outflow of emission quota to or from the pot-plant sector. The economic optimum conditions for this simulation require that the marginal abatement costs are equal for all firms (Klaassen, 1996). If quota trade takes place without restrictions, then the system of tradable quota results in the same allocation of CO_2 emissions across firms as a uniform CO_2 tax that achieves the same overall reduction in CO_2 emissions. The effects of such a CO_2 emission tax are calculated in the second simulation. The difference between the system of tradable quota and the uniform CO_2 emission tax is reflected in the effect on profit (assuming that tax receipts are not reimbursed to the firms). The third simulation is a non-tradable quota on CO_2 emissions, where the fixed CO_2 emission quota for each firm is based on the same principle of 'grandfathering'. The effects of these pol-

icy simulations are calculated for different groups of firms and for the sector. The classification of firms in different groups is done on the basis of technical efficiency scores. High efficiency firms (class 1) are firms with a technical efficiency between 0.7 and 1. Medium efficiency firms have a technical efficiency score between 0.3 and 0.7 and low efficiency firms have an efficiency score between 0 and 0.3.

Table 2 gives the effects of the uniform CO_2 emission tax and non-tradable quota for firms in different classes. The uniform tax that results in a 5% overall reduction in CO_2 emissions is calculated as 0.04461 guilder per kg CO_2. The effects are calculated relative to a base simulation which generates predicted values of profit, output, energy, materials, services and CO_2 emissions in 1995. The results of the base simulation are presented in the appendix (Table A.2).

Table 2 shows that all policy measures result in a reduction of all variable inputs and output for all classes of firms. It can also be seen that the reduction of energy use is an important determinant behind the reduction in CO_2 emissions. However, the reduction of CO_2 emissions also comes at the cost of an output reduction. Another result is that all simulations generate the highest reduction of profit for low efficiency firms.

The results of the uniform tax and tradable quota are identical except for their effects on profit, because the tax receipts are not reimbursed to the firms by assumption. In the case of a tax, the rent is collected by the agency that implements the tax; in case of a tradable quota, the rent stays in the sector: it is (partly) redistributed from firms that buy additional

Table 2
The effects of a tradable quota, CO_2 tax and a non-tradable quota for different classes of firms (percentage change compared to base simulation)

Class	Output	Energy	Materials	Services	CO_2 emission	Profit[a]
Tradable quota and CO_2 emission tax[a]						
All firms	−1.83	−4.41	−2.36	−0.53	−5.00	−1.33 (−51.75)
High efficiency	−2.88	−9.79	−3.82	−0.94	−11.60	0.26 (−30.63)
Medium efficiency	−1.65	−4.67	−2.75	−0.49	−5.65	−0.79 (−35.41)
Low efficiency	−1.79	−3.09	−1.60	−0.48	−3.23	−4.24 (−123.07)
Non-tradable quota						
All firms	−2.06	−4.41	−2.37	−0.53	−5.00	−1.79
High efficiency	−1.05	−4.22	−1.65	−0.41	−5.00	−0.54
Medium efficiency	−1.54	−4.13	−2.43	−0.44	−5.00	−1.05
Low efficiency	−3.44	−4.79	−2.48	−0.74	−5.00	−5.25

[a] Effects of tradable quota and CO_2 emission tax are identical for all variables except for the effect on profit. The effect of the CO_2 emission tax on profit is in parentheses.

emission permits to firms that sell emission permits. The uniform tax/tradable quota simulations show that the percentage reduction in CO_2 emission by high efficiency firms is larger than the percentage reduction by low efficiency firms. Furthermore, it can be seen that the uniform tax results in a large reduction of profit, especially for low efficiency firms, since these maintain their CO_2 emissions at a high level. Compensation by reimbursing the revenues of the tax to the firms (e.g. regulatory levy) will offset the negative effects of the tax on profits. However, if the compensation scheme is designed such that the compensation increases with technical efficiency, then low efficiency firms continue to be faced with the highest percentage reduction of profit.

The non-tradable quota results in a 5% reduction of CO_2 emissions by low, medium and high efficiency firms. Therefore, high efficiency firms do not reduce CO_2 emission more (in relative terms) than low efficiency firms. The results of this simulation show that the profit reduction is small compared to profit reduction under CO_2 emission tax. Low efficiency firms still have the highest profit reduction after the introduction of the quota. Comparing the tradable and non-tradable quota makes clear that permitting quota trade after an initial 5% cut in emission quotas induces a shift of quota from high efficiency firms to low efficiency firms. Comparison of the profit change shows that all firms gain from tradability of quota; profit reductions are smaller under tradable quota than under a system of non-tradable quota. Compared with the base simulation, high efficiency firms are on average better off under the system of tradable quota than, because they receive a high quota rent from the firms that buy additional quota.

The relation between technical efficiency (λ) and marginal abatement costs (MC) after a 5% reduction of CO_2 emissions, i.e. the firm-specific shadow price of the (non-tradable) emission quota is assessed using a regression model consistent with (16):

$$\ln(\text{MC}) = \alpha + \beta\lambda + \omega x + \sigma z + \upsilon e \qquad (21)$$

Note in (16) that λ and x are functions of variable input prices, fixed input quantities and CO_2 emissions so that technical efficiency and all variable inputs may be endogenous variables in the model. In order to account for possible endogeneity of λ, a 2SLS-regression method (Judge et al., 1988) is employed; instruments

Table 3
Estimation results of (20)

Parameter	Estimate	t-value
α	1.007	3.641
β	−1.339	−3.806
ω_1	0.004	6.747

are CO_2 emissions, all fixed inputs and their quadratic and cross terms. Removing all insignificant terms from the model using a backward elimination procedure (critical P-value is 0.05) results in the regression model presented in Table 3.

The remaining parameters are an intercept as well as coefficients associated with technical efficiency (β) and energy use (ω_1). The R^2 of 0.88 indicates that the model explains a large proportion of the total variance in marginal abatement costs. The estimate for β indicates that marginal abatement costs are very responsive to changes in technical efficiency, i.e. firms with a 1% higher technical efficiency have a 1.34% lower marginal abatement costs for the same percentage reduction of CO_2 emissions. Firms with lower marginal abatement costs (e.g. high efficiency firms) are also firms that are less affected by the regulation, i.e. these firms have lower profit reductions. Lower marginal abatement costs of CO_2 emissions for firms with high technical efficiency may be explained by the fact that they are operated by better managers who are more successful in keeping costs of abatement low. The parameter ω_1 indicates that, ceteris paribus, firms with 1000 guilders higher energy use have a 0.004% higher marginal abatement costs. This relation reflects the dependence between fossil energy and CO_2 emissions.

8. Conclusions and discussion

In this paper, a microeconomic model of CO_2 emitting glasshouse firms is developed and a technical efficiency measure is derived, based on the assumption that each firm has a unique technology. The model is estimated on panel data of Dutch pot-plant firms over the period 1991–1995. Results are used to investigate the relation between marginal abatement costs and technical efficiency.

The results of policy simulations show that low efficiency firms have higher marginal abatement costs for a given percentage reduction of CO_2 emissions.

Furthermore, it is found that a uniform CO_2 emission tax induces high efficiency firms to a higher percentage CO_2 emission reduction than low efficiency firms. The CO_2 emission tax results in an overall reduction of profit of more than 50% (if the tax receipts are not reimbursed to the firms), where the profit reduction for low efficiency firms is substantially higher than for high efficiency firms. The non-tradable quota regime leads to an overall profit reduction of approximately 1.8%; for the tradable quota the profit reduction is 1.3%. The results of the tradable and non-tradable quota regimes are based on the assumption that the initial emission quota is allocated for free to the firms in the sector. A regression of technical efficiency on marginal abatement costs shows that marginal abatement costs are very responsive to changes in technical efficiency, i.e. a 1% increase of technical efficiency decreases the marginal abatement costs by approximately 1.3%. Improving technical efficiency has two important dimensions. First, CO_2 emissions are reduced substantially if firms improve technical efficiency. Second, firms with higher technical efficiency have lower marginal abatement costs for the same percentage reduction of CO_2 emissions in case of a non-tradable quota. Firms with lower marginal abatement costs generally also incur lower overall costs due to the regulation.

A number of caveats should be noted. First, the model used in this study is a static (short-term) model that does not explain adjustments in the availability of fixed inputs. In the long term, changes in the availability of fixed inputs (especially structures, machinery and installations) have a large impact on CO_2 emissions, abatement costs and technical efficiency. Therefore, the reader should keep in mind that the effects of different policies reported in this paper are short-term effects. Second, the policy simulations ignore the administrative costs of different policy measures. Incorporating these costs increases the social costs especially of the tradable and non-tradable quota systems. Therefore, the changes in profit that are reported in this study only indicate the costs for the sector and are not an indication of the social welfare costs.

Acknowledgements

Appendix A

See Tables A.1 and A.2.

Table A.1
Results of estimation

Parameter	Estimate	t-value
β_1	−0.23	−0.19
β_2	0.69	0.52
β_3	−17.43	−0.15
β_4	51.40	0.38
α_{11}	376.43	3.49
α_{12}	92.87	0.74
α_{13}	45.63	1.25
α_{22}	98.15	0.20
α_{23}	50.82	0.39
α_{33}	169.96	2.03
β_{11}	−0.00	−0.52
β_{12}	0.00	0.61
β_{13}	−0.04	−0.73
β_{14}	0.08	0.78
β_{22}	−0.00	0.71
β_{23}	−0.07	−0.15
β_{24}	−0.08	−0.86
β_{33}	6.16	0.54
β_{34}	−7.33	−0.45
β_{44}	37.50	0.71
κ	−0.99	−47.23
γ_{11}	0.00	0.23
γ_{12}	−0.03	−1.71
γ_{13}	−4.03	−1.23
γ_{14}	−5.95	−2.18
γ_{21}	−0.06	−1.33
γ_{22}	0.06	1.16
γ_{23}	−20.87	−3.40
γ_{24}	1.93	0.23
γ_{31}	−0.08	−2.68
γ_{32}	0.03	0.95
γ_{33}	−19.91	−7.83
γ_{34}	−8.48	−2.59
η_1	−2.23	−2.00
η_2	−1.61	−1.72
η_3	−0.17	−0.35
μ_1	0.00	0.70
μ_2	−0.00	−0.27
μ_3	2.63	5.07
μ_4	−0.35	−0.50

Source: own calculations/estimation.

Table A.2
Characteristics of different firm classes in 1995 (mean values)

Variable	Unit	Class			
		All firms	Low efficiency	Medium efficiency	High efficiency
Quantities					
Output	1985 guilders (in thousands)	1520.13	1556.31	1684.15	967.76
Energy	1985 guilders (in thousands)	226.53	323.48	214.14	102.08
Materials	1985 guilders (in thousands)	314.36	464.96	270.63	194.57
Services	1985 guilders (in thousands)	180.43	201.20	195.01	102.10
CO_2 emissions	Tonnes per year	88.96	137.73	78.74	38.33
Structures	1985 guilders (in thousands)	795.74	390.56	921.50	812.47
Machinery/installations	1985 guilders (in thousands)	441.30	234.46	513.09	436.17
Labour	Man years	7.60	4.94	8.83	6.99
Trend	1991 = 0	4	4	4	4
Prices					
Energy	Base year = 1985	0.68	0.68	0.68	0.68
Materials	Base year = 1985	1.36	1.36	1.36	1.36
Services	Base year = 1985	1.06	1.06	1.06	1.06
Efficiency ratios					
Technical output efficiency	Ratio	0.46	0.20	0.49	0.82
CO_2 efficiency	Ratio	0.47	0.29	0.49	0.66

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