CO₂ and Energy Efficiency of Different Heating Technologies in the Dutch Glasshouse Industry

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Abstract. This paper uses Data Envelopment Analysis to compute input-based technical efficiency measures and CO₂ and energy technical efficiency of specialised vegetable firms in the Netherlands over the period 1991–1995. Input-based scale efficiency is also calculated for each firm. These efficiency measures are generated for firms with different heating technologies. The empirical results indicate that firms use energy quite efficiently and are less efficient in terms of CO₂ emissions. Differences in CO₂ (energy) efficiency across different technologies are (not) statistically significant. In particular, firms using traditional heating technologies are less efficient in terms of CO₂. Scale adjustments can provide an important contribution to further efficiency improvements.

Key words: CO₂ emission, energy use, heating technology, horticulture

JEL classifications: C6, N5, Q0, Q4

1. Introduction

The Dutch glasshouse industry is an important user of energy and accounts for approximately 4% of greenhouse gas emissions in the Netherlands. Recently, the Dutch glasshouse industry made a covenant with the government aiming at reducing the use of energy. In the covenant, the Dutch glasshouse industry has to improve its energy efficiency by 65% in 2010 compared to the level of 1980 (Stuurgroep Landbouw en Milieu 2000). The Dutch glasshouse industry may improve its energy efficiency by investing in new energy saving technologies or, alternatively by improving the efficiency of the current production potential. Information about the environmental performance of glasshouse firms can be used for assessing the potential for reducing the use of energy and emissions of carbon dioxide (CO₂) using different current available energy saving technologies. This information can be useful in guiding the process of energy efficiency improvement under the covenant and reduction of CO₂ emissions as required under the Kyoto protocol.

The Data Envelopment Analysis (DEA) approach has been proposed as a method for evaluating producers performance in the presence of adverse environmental impacts (e.g., Färe et al. 1989; Ball et al. 1994). Färe et al. (1989)
modify the efficiency measures proposed by Färe, Grosskopf and Lovell (1985) to allow for an asymmetric treatment of desirable and undesirable outputs. Pollutants are treated as weakly (costly) disposable outputs whereas desirable outputs are strongly (freely) disposable (Färe et al. 1989). Weak disposability involves a constraint on the production possibilities of the producers, i.e. producers cannot increase (reduce) undesirable input (output) levels without costs. Following Färe et al. (1989) and Pittman (1983), Ball et al. (1994) adjust a conventional measure of total factor productivity growth by incorporating undesirable outputs in the production process.

Environmental impacts are treated either as undesirable outputs (e.g. Färe et al. 1989; Ball et al. 1994) or undesirable inputs (e.g., Tyteca 1997; Ball et al. 2000); conceptually there is no difference between the two approaches. The DEA approach allows an asymmetric treatment of desirable and undesirable inputs and outputs. A nonparametric piecewise linear technology that satisfies weak disposability of undesirable inputs (outputs) and strong disposability of desirable inputs (outputs) can be constructed without imposing a functional form on the production technology. Nonparametric efficiency measures that satisfy those requirements can be calculated as solutions to (non-)linear programming problems. The DEA efficiency measures require data on output and input quantities rather than prices which is particularly useful when well-defined market prices for undesirable inputs or outputs do not exist.1

The purpose of this paper is twofold. First, this paper provides measures of overall technical efficiency and subvector technical efficiency in terms of energy use and CO2 emissions in the Dutch glasshouse industry. Moreover, statistical tests are performed to test for technical efficiency differences for different heating technologies. Clearly, providing technical efficiency measures and accounting for different technologies provides information that is relevant to policy makers and firm operators aiming at reducing energy use and CO2 emissions. Second, this paper statistically tests for the disposability of CO2 emissions for different heating technologies in the Dutch glasshouse industry. Testing for disposability provides insight in the effects of restrictions on CO2 emissions that might follow from future CO2 policy, i.e. restrictions on CO2 emissions (e.g. an emission quota) will involve costs. Statistical tests for disposability of pollutants in DEA models are lacking in previous studies (Färe et al. 1989; Ball et al. 1994, 2000; Tyteca 1997; Reinhard 1999).

The paper proceeds with a graphical demonstration of the DEA approach in computing overall input-based technical efficiency and subvector efficiency in terms of energy and CO2. This is followed by a presentation of the nonlinear programming models and a discussion of the data and empirical results. Conclusions are presented in the last section.
2. **DEA Input-Based Technical Efficiency Measures**

In this paper, CO₂ emissions are modelled as an undesirable input that is not freely or costlessly disposable. Measurement of overall technical efficiency and subvector efficiency (in terms of CO₂ and energy) using DEA is illustrated in Figure 1, where each dot represents a combination of energy and CO₂ emissions of firms producing the same quantity of desirable output. In Figure 1, firms are labelled A, B and C. The DEA approach constructs a piecewise linear isoquant from the observed combinations of CO₂ and energy. The piecewise linear isoquant is constructed from the energy and CO₂ combinations of firms B and C. Therefore, firms B and C are technically efficient firms. Firm A uses more of energy and CO₂ emissions while producing the same quantity of desirable output as firms B and C.

In Figure 1, the overall technical efficiency measure of firm A, assuming weak disposability of CO₂ emissions is given by the ratio \( \theta_W = 0W/0A \). Note that this measure of technical efficiency assumes that both energy and CO₂ emissions can be contracted radially, i.e. with an equal proportion given by \( 1 - \theta_W \). Assuming strong disposability of CO₂ emissions, the overall technical efficiency is given by the ratio \( \theta_S = 0S/OA \). Note that weak disposability results in a technical efficiency ratio that is larger than or equal to the efficiency ratio obtained under the assumption of strong disposability.

The notion of subvector efficiency can be used to generate technical efficiency measures for a subset of inputs rather than for the entire vector of inputs (Färe, Grosskopf and Lovell 1994). In terms of Figure 1, subvector efficiency for CO₂ emissions (energy) indicates the possibility to contract the CO₂ emissions (energy) holding energy (CO₂ emissions) and output constant. For firm A, subvector effi-
ciency of CO₂ emissions is given by the ratio $\gamma^C_W = 0'A'/0'A$. Therefore, firm A could reduce CO₂ emissions by a proportion given by $1 - \gamma^C_W$, holding energy and output constant. In this particular case, subvector efficiency of CO₂ emissions is independent of its own disposability assumption, i.e. it is the same under weak and strong disposability of CO₂ emissions. However, firm A’s subvector efficiency of energy does depend on the disposability assumption of CO₂ emissions. Assuming weak disposability of CO₂ emissions, energy subvector efficiency is given by $\gamma^E_W = 0''A''/0'A''$, whereas under strong disposability, it is given by $\gamma^E_S = 0''A''/0'A''$.

3. DEA Analytical Framework

The discussion of the DEA models starts from a set of observations of firms in a sample that use a vector of desirable variable inputs ($x^v$), CO₂ emissions ($w$) and a vector of fixed inputs ($x^f$) to produce a desirable output ($y$).

Assuming weak disposability of CO₂ emissions, input-oriented overall technical efficiency for each firm $i$, $i = 1, \ldots, N$, is calculated from the following non-linear programming problem:

$$\begin{align*}
\text{Min} & \quad \theta_W \\
\text{s.t.} & \quad -y_i + Y \lambda \geq 0 \\
& \quad \theta_W x^v_i - X^v \lambda \geq 0 \\
& \quad \theta_W w_i = W \lambda \\
& \quad \theta_W x^f_i - X^f \lambda = 0 \\
& \quad N1' \lambda = 1 \\
& \quad \lambda \geq 0 \\
& \quad 0 < \sigma \leq 1
\end{align*}$$

where $\theta_W$ is the overall technical efficiency score ($\theta_W \in [0, 1]$) for the $i$-th firm under the assumption of weak disposability of CO₂ emissions, $Y$ is the $(1 \times N)$ vector of observed outputs, $X^v$ is the matrix of observed desirable variable inputs, $W$ is $(1 \times N)$ vector of CO₂ emissions, $X^f$ is the matrix of observed fixed inputs and $\lambda$ is a $N \times 1$ vector of intensity variables (firm weights). The value of the firm weights identifies the firms that determine the production frontier. The first and second constraints reflect strong disposability (SD) of outputs and desirable variable inputs, respectively. The third and fourth constraints are equality constraints reflecting weak disposability (WD) of CO₂ emissions and fixed inputs. The constraint $N1' \lambda = 1$ (with $N1$ being an $N \times 1$ vector of ones) implies the sum of the lambda’s equals one and allows for a variable returns to scale (VRS) technology. The scaling parameter $\sigma$ is selected such that there is a feasible solution of the DEA problem with weakly disposable inputs under variable returns to scale.

Overall technical efficiency represents the maximum proportional reduction of all inputs subject to the constraints imposed by the observed outputs and the tech-
nology. The overall technical efficiency measure is also generated under constant returns to scale (CRS). In this case, problem (1) is solved for each firm by deleting the constraint \( N' \lambda = 1 \) and eliminating the parameter \( \sigma \) from the third and fourth constraints. An input scale efficiency measure is generated as the ratio of the overall input technical efficiency measure under CRS and the overall technical efficiency measure under VRS. A particular firm \( i \) is input scale efficient if it is equally (technically) efficient relative to CRS and VRS technologies.

The measure of technical efficiency in (1) is obtained under the assumption of WD of CO\(_2\) emissions. Assuming SD of CO\(_2\) emissions, firm \( i \)'s overall technical efficiency is obtained from the following programming problem:

\[
\begin{align*}
\text{Min } & \theta_S \\
\text{s.t. } & -y_i + Y \lambda \geq 0 \\
& \theta_S x_i^v - X^v \lambda \geq 0 \\
& \theta_S w_i \geq W \lambda \\
& \theta_S \sigma x_i^f - X^f \lambda = 0 \\
& N' \lambda = 1 \\
& \lambda \geq 0 \\
& 0 < \sigma \leq 1
\end{align*}
\]

(2)

Note that the difference between (1) and (2) is that the equality constraint on \( W \) has been converted to an inequality constraint, similar to the constraint on variable inputs, \( X^v \). A producer-specific measure of the costs of WD of CO\(_2\) emissions (in terms of a potential increase in variable and fixed inputs) can be assessed by using the difference between \( \theta_W \) and \( \theta_S \):

\[
C_W^i = (\theta_W - \theta_S) \cdot (pv x_i^v + pf x_i^f),
\]

where \( pv \) and \( pf \) are prices of variable and fixed inputs, respectively.\(^2\)

The effects of ignoring CO\(_2\) emissions in the computation of technical efficiency can be determined by calculating the ‘conventional’ input efficiency measure for each firm \( i \) as the solution to the following problem:

\[
\begin{align*}
\text{Min } & \theta \\
\text{s.t. } & -y_i + Y \lambda \geq 0 \\
& \theta x_i^v - X^v \lambda \geq 0 \\
& \theta \sigma x_i^f - X^f \lambda = 0 \\
& N' \lambda = 1 \\
& \lambda \geq 0 \\
& 0 < \sigma \leq 1
\end{align*}
\]

(3)

Distortions in the magnitude and the ranking of the efficiency scores due to ignoring CO\(_2\) emissions can be evaluated by comparing the conventional input-based technical efficiency measure, \( \theta \), in (3) and the input efficiency measure in (1), \( \theta_W \).
Using the notion of subvector efficiency proposed by Färe, Grosskopf and Lovell (1994), CO₂ technical efficiency is calculated for each firm \( i \) by solving the following problem:

\[
\begin{align*}
\text{Min} & \quad \gamma_C W_x \quad \lambda, \sigma \\
\text{s.t.} & \quad -y_i + Y\lambda \geq 0 \\
& \quad x_i^f - X^\nu \lambda \geq 0 \\
& \quad \gamma_C W \sigma w_i = W\lambda \\
& \quad \sigma x_i^f - Xf \lambda = 0 \\
& \quad N\lambda = 1 \\
& \quad \lambda \geq 0 \\
& \quad 0 < \sigma \leq 1
\end{align*}
\]

where \( \gamma_C W_x \) is the CO₂ technical efficiency score for firm \( i \) and all the other variables are defined as before. CO₂ technical efficiency represents the maximum contraction of this input, holding outputs and other inputs constant. Therefore, the CO₂ efficiency model involves finding a frontier that minimises the quantity of CO₂ emissions.

Energy (subvector) technical efficiency under WD and SD of CO₂ emissions (i.e. \( \gamma_E W \) and \( \gamma_E S \)) is calculated by solving a problem similar to (4) and imposing \( \sigma w_i = W\lambda \) and \( w_i \geq W\lambda \), respectively. The technical efficiency score of energy represents the maximum contraction of energy to the isoquant under WD or SD of CO₂, holding outputs and all other inputs (including the CO₂ emissions) constant.

4. Data

Data on specialised vegetables firms covering the period 1991–1995 come from a stratified sample of Dutch glasshouse firms keeping accounts on behalf of the LEI accounting system. The firms typically remain in the panel for a maximum of eight years, so the panel is incomplete. Firms rotate in and out the sample to avoid a selection bias which arises when firms improve their performance by their presence in the accounting system. The data set used for estimation contains 345 observations from 123 firms.

One output and six inputs (energy, materials, services, structures, machinery and installations and labour) are distinguished. Output consists mainly of vegetables. Other outputs included are fruits, potplants and flowers. Energy consists of gas, oil and electricity, as well as heat deliveries by electricity plants. Materials consist of seeds and planting materials, pesticides, fertilisers and other materials. Services are those provided by contract workers and 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,
different heating technologies

Table I. Variables and descriptive statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dimension</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>100.000 Guilders</td>
<td>12.48</td>
<td>7.76</td>
</tr>
<tr>
<td>Energy</td>
<td>100.000 Guilders</td>
<td>2.00</td>
<td>1.31</td>
</tr>
<tr>
<td>Materials</td>
<td>100.000 Guilders</td>
<td>1.67</td>
<td>1.13</td>
</tr>
<tr>
<td>Services</td>
<td>100.000 Guilders</td>
<td>1.06</td>
<td>0.59</td>
</tr>
<tr>
<td>Structures</td>
<td>100.000 Guilders</td>
<td>10.99</td>
<td>7.75</td>
</tr>
<tr>
<td>Machinery and installations</td>
<td>100.000 Guilders</td>
<td>3.65</td>
<td>2.89</td>
</tr>
<tr>
<td>Labor</td>
<td>Man years</td>
<td>7.60</td>
<td>4.19</td>
</tr>
<tr>
<td>CO2 emission</td>
<td>100.000 Ton</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>

and includes family as well as hired labour. Labour is assumed to be a fixed input because a large share of total labour consists of family labour. Flexibility of hired labour is further restricted by the presence of permanent contracts and by the fact that hiring additional labour involves search costs for the firm operator. The quality correction of labour is performed by the LEI and is necessary to aggregate labour from able-bodied adults with labour supplied by young people (e.g., young family members) or partly disabled workers. Capital in structures, machinery and installations is measured at constant 1985 prices and is valued in replacement costs.4

Data on CO2 emissions have been obtained from the LEI and are measured as tons of CO2 emission per year. CO2 emissions are calculated from physical quantities of fossil fuels (mainly methane gas) that are used for heating and CO2 fertilisation in the glasshouse (see Cordenier (1999) for more details). Therefore, CO2 emissions and energy are independent factors, since energy consists of components that do not cause CO2 emissions on the firms, i.e. heat delivery and electricity. The CO2 emissions are partly incorporated in plants because CO2 serves as a fertiliser. Therefore, the data overestimate the true CO2 emissions, although the degree of overestimation is small (Cordenier 1999).

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

The firms in the sample use different heating technologies. Most firms (55%) use traditional heating based on the use of a central heating boiler; 31% of the firms use traditional heating in combination with heat storage and 10% and 4% of the firms in the sample use co-generators5 and heat deliveries by electricity generating plants, respectively. A more detailed description of the data can be found in Table I.
Table II. Overall, energy and CO2 technical efficiency (VRS and WD of CO2), 1991–1995

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>0.86</td>
<td>0.90</td>
<td>0.84</td>
<td>0.85</td>
<td>0.92</td>
</tr>
<tr>
<td>Energy</td>
<td>0.93</td>
<td>0.98</td>
<td>0.94</td>
<td>0.92</td>
<td>0.96</td>
</tr>
<tr>
<td>CO2</td>
<td>0.50</td>
<td>0.51</td>
<td>0.52</td>
<td>0.53</td>
<td>0.74</td>
</tr>
</tbody>
</table>

5. Empirical Results

Overall technical efficiency measures and subvector technical efficiency scores for energy and CO2 are obtained using the program ONFRONT (Färe and Grosskopf 2000). Annual averages of overall and subvector technical efficiency scores under VRS and WD of CO2 emissions in the years 1991–1995 are found in Table II. Results in Table II show that specialised vegetables producers have high overall technical efficiency, with annual averages ranging between 84% and 92%. The annual average of technical efficiency for energy is slightly higher than the overall technical efficiency score (more than 92%), whereas the annual average of CO2 technical efficiency is lower, ranging between 50% and 74%.

The results indicate that firms have a poor performance in terms of CO2 efficiency that may be due to the absence of regulations on CO2 emissions. The low CO2 efficiency also shows that there is considerable scope for decreasing CO2 emissions using the currently available technologies.

Table III shows averages of overall technical efficiency and energy and CO2 technical efficiency scores for firms with different energy saving technologies. Under the hypotheses of VRS and WD of CO2 emissions, firms with traditional heating technologies are found to have an overall technical efficiency score that is, on average, 3–4 percent lower than the overall technical efficiency score of firms using more advanced heating technologies. Energy efficiency of traditional firms is slightly below that of firms with storage and co-generator technologies, but it is higher than that of firms with heat deliveries. Furthermore, the empirical results on CO2 efficiency indicate that CO2 emissions can be reduced substantially if firms switch from the traditional heating technology to either co-generator or heat delivery. The heat storage technology is not found to improve CO2 efficiency.

Results of the input-based scale efficiency scores for different heating technologies show that firms with traditional heating operate on a less optimal scale than firms with more advanced heating technologies. The scale efficiency score of firms with co-generators shows that these firms operate on an optimal scale.

An indication of the degree to which CO2 emissions restrict production can be obtained by comparing the overall technical efficiency score under VRS in Table III with the efficiency score from a DEA model that excludes CO2 emissions. The average of the overall technical efficiency score (under VRS) is equal to 0.83 and
Table III. Overall technical and scale efficiency, energy and CO₂ efficiency for firms with different heating technologies

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Traditional</th>
<th>Storage</th>
<th>Co-generator</th>
<th>Heat delivery</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical (VRS and WD CO₂ emissions)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>0.86</td>
<td>0.89</td>
<td>0.90</td>
<td>0.90</td>
<td>0.88</td>
</tr>
<tr>
<td>Energy</td>
<td>0.94</td>
<td>0.95</td>
<td>0.96</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.53</td>
<td>0.54</td>
<td>0.72</td>
<td>0.73</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>Scale (WD CO₂ emissions)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>0.95</td>
<td>0.97</td>
<td>1</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>Technical (VRS and SD CO₂ emissions)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>0.81</td>
<td>0.85</td>
<td>0.87</td>
<td>0.90</td>
<td>0.83</td>
</tr>
<tr>
<td>Energy</td>
<td>0.56</td>
<td>0.56</td>
<td>0.73</td>
<td>0.73</td>
<td>0.59</td>
</tr>
</tbody>
</table>

*CO₂ efficiency scores are not reported, since they do not differ under strong and weak disposability of CO₂ emissions.

differs from the efficiency score of 0.88 (Table III). This indicates that firms would decrease all desirable inputs more (at given outputs) if CO₂ emissions did not restrict production. This result provides indirect evidence for the hypothesis that a regulation on the disposability of CO₂ emissions would, on average be restrictive for the firms.⁶

Comparison of overall and energy technical efficiency under weak and strong disposability of CO₂ emissions provides further support for the restricting effects on production decisions of weak disposability of CO₂ emissions. The difference between overall technical efficiency under strong and weak disposability of CO₂ emission is, on average, 0.05. However, for firms with heat delivery, the difference is close to zero. For energy efficiency, the differences are much larger, indicating that energy use could benefit (in terms of reduction of use) more than other inputs from strong disposability of CO₂ emissions. Also for energy efficiency, the difference between weak and strong disposability is smallest for firms with heat delivery.

The statistical significance of differences in overall, energy and CO₂ efficiency across different technologies is assessed using an ANOVA test. The results are found in Table IV and show that overall technical efficiency and energy efficiency do not differ significantly at the critical 5% level across technologies. CO₂ efficiency differs significantly at the critical 5% level among firms with different technologies.

A t-test is used to test the difference between CO₂ efficiency and energy efficiency for all firms in the sample. The t-value of 23.62 indicates that the difference is statistically significant at the critical 5% level.
Table IV. Summary test results

<table>
<thead>
<tr>
<th>Test</th>
<th>Hypothesis</th>
<th>Test result</th>
<th>Critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All technologies equal efficiency&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$H_0 : \theta_1^W = \theta_2^W = \theta_3^W = \theta_4^W$; $H_1 : \theta_1^W \neq \theta_2^W \neq \theta_3^W \neq \theta_4^W$</td>
<td>2.27</td>
<td>( F_{3,341}^{0.05} = 3.16 )</td>
</tr>
<tr>
<td>– Energy</td>
<td>$H_0 : \gamma_1^E = \gamma_2^E = \gamma_3^E = \gamma_4^E$; $H_1 : \gamma_1^E \neq \gamma_2^E \neq \gamma_3^E \neq \gamma_4^E$</td>
<td>1.77</td>
<td>( F_{3,341}^{0.05} = 3.16 )</td>
</tr>
<tr>
<td>– CO₂</td>
<td>$H_0 : \gamma_1^C = \gamma_2^C = \gamma_3^C = \gamma_4^C$; $H_1 : \gamma_1^C \neq \gamma_2^C \neq \gamma_3^C \neq \gamma_4^C$</td>
<td>4.92</td>
<td>( F_{3,341}^{0.05} = 3.16 )</td>
</tr>
<tr>
<td>CO₂ efficiency equals energy efficiency</td>
<td>$H_0 : \gamma_1^E = \gamma_1^C$; $H_1 : \gamma_1^E \neq \gamma_1^C$</td>
<td>23.62</td>
<td>( t_{344}^{0.05} = 1.645 )</td>
</tr>
<tr>
<td>Strong/Weak disposability CO₂&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$H_0 : \theta_1^W - \theta_S = 0$; $H_1 : \theta_1^W - \theta_S &gt; 0$</td>
<td>10.60</td>
<td>( t_{189}^{0.05} = 1.645 )</td>
</tr>
<tr>
<td>– All firms</td>
<td>$H_0 : \theta_1^W - \theta_3^S = 0$; $H_1 : \theta_1^W - \theta_3^S &gt; 0$</td>
<td>8.41</td>
<td>( t_{104}^{0.05} = 1.658 )</td>
</tr>
<tr>
<td>– Traditional</td>
<td>$H_0 : \theta_1^W - \theta_2^S = 0$; $H_1 : \theta_1^W - \theta_2^S &gt; 0$</td>
<td>6.06</td>
<td>( t_{33}^{0.05} = 1.697 )</td>
</tr>
<tr>
<td>– Storage</td>
<td>$H_0 : \theta_1^W - \theta_3^S = 0$; $H_1 : \theta_1^W - \theta_3^S &gt; 0$</td>
<td>2.49</td>
<td>( t_{15}^{0.05} = 1.753 )</td>
</tr>
<tr>
<td>– Co-generator</td>
<td>$H_0 : \theta_1^W - \theta_4^S = 0$; $H_1 : \theta_1^W - \theta_4^S &gt; 0$</td>
<td>1.23</td>
<td>( t_{15}^{0.05} = 1.753 )</td>
</tr>
<tr>
<td>– Heat delivery</td>
<td>$H_0 : \theta_1^W - \theta_5^S = 0$; $H_1 : \theta_1^W - \theta_5^S &gt; 0$</td>
<td>1.23</td>
<td>( t_{15}^{0.05} = 1.753 )</td>
</tr>
</tbody>
</table>

<sup>a</sup>Superscripts 1, ..., 4 refer to traditional, storage, co-generator and heat delivery, respectively.
Table V. Costs of weak disposability of CO2 emissions

<table>
<thead>
<tr>
<th></th>
<th>Difference technical efficiency</th>
<th>Costs all inputs $b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All firms</td>
<td>0.04</td>
<td>0.46</td>
</tr>
<tr>
<td>Traditional</td>
<td>0.05</td>
<td>0.51</td>
</tr>
<tr>
<td>Storage</td>
<td>0.04</td>
<td>0.46</td>
</tr>
<tr>
<td>Co-generator</td>
<td>0.03</td>
<td>0.28</td>
</tr>
<tr>
<td>Heat delivery</td>
<td>0.00</td>
<td>0.03</td>
</tr>
</tbody>
</table>

$^a$Costs have been calculated at the sample mean. $^b$In 100,000 guilders of 1985.

A one sided $t$-test is conducted to test whether the difference between overall technical efficiency under WD of CO2 emissions and technical efficiency under SD is significantly larger than zero. Results in Table IV show that the null hypothesis (no difference) is rejected for the whole sample of firms ($10.60 > 1.645$). A test on SD of CO2 emissions for firms with different technologies reveals that the null hypothesis is not rejected for firms with heat delivery. This provides empirical evidence that a regulation on CO2 emissions would be a restrictive factor on firms using traditional, storage and co-generator technologies. However, regulating CO2 emissions would not be restrictive on firms using heat delivery, implying these firms can dispose of CO2 without costs.

The costs of WD of CO2 emissions have been calculated for all firms and for firms with different technologies and are found in Table V. It can be seen that costs of WD of CO2 emissions are higher for firms with traditional heating and storage technologies and lower for firms using co-generator and heat delivery. This result is consistent with the fact that CO2 emissions are found to be binding on firms using traditional, storage and co-generator and not on firms using heat delivery.

6. Conclusions

This paper uses DEA to compute input-based measures of overall technical efficiency and CO2 and energy technical efficiency for different heating technologies in the Dutch glasshouse industry over the period 1991–1995. The technical efficiency measures are generated under the hypotheses of weak and strong disposability of CO2 emissions and statistical tests are conducted to investigate whether there are significant efficiency differences across heating technologies. In addition, a scale efficiency score is calculated for each firm as the ratio of the overall technical efficiency under constant returns to scale and overall technical efficiency under variable returns to scale.

Results show that most firms use energy quite efficiently and that they are less efficient in terms of CO2 emissions. Differences in CO2 (energy) efficiency across different technologies are (not) statistically significant. In particular, firms using traditional heating technologies are less efficient in terms of CO2. Also, differ-
ences between overall technical efficiency under weak disposability and strong disposability of CO\textsubscript{2} emissions are found to be statistically significant for all technologies, except for heat delivery. This result indicates that weak disposability of CO\textsubscript{2} emissions can be binding on firms using traditional, storage and co-generator technologies. However, regulating CO\textsubscript{2} emissions would not be restrictive on firms using heat delivery. Firms using heat delivery are also found to be more efficient in using CO\textsubscript{2} emissions than other firms. Therefore, it may be expected that a regulation on CO\textsubscript{2} emissions that is costly from the perspective of the firm will induce glasshouse firms to switch to heat delivery.

Results on the scale efficiency indicate that firms using traditional heating technology operate on a less efficient scale than other firms and that scale adjustments can provide an important contribution to further efficiency improvements on firms with traditional heating.

DEA is a flexible approach in generating efficiency scores and has the virtue of being nonparametric. The DEA efficiency measures require data on output and input quantities rather than prices which reveals particular useful when well-defined market prices do not exist for undesirable inputs or outputs. However, this approach is deterministic, implying that statistical noise may be confounded with inefficiency. Future research might focus on disentangling the effects of statistical noise from inefficiency in the overall and subvector efficiency measures that were presented in this paper (see e.g. Reinhard et al. 1999). Future research should also investigate the dynamic aspects of efficiency, i.e. switches of technologies and investments in new technologies. These dynamic aspects are particularly relevant in analysing efficiency differences between technologies.

Notes

1. Ball et al. (1994, 2000) show how to generate shadow or virtual prices for the environmental impacts as by products of the DEA efficiency calculations.
2. Färe et al. (1989) propose a producer-specific measure of desirable output loss due to the lack of strong disposability of undesirable outputs. This output loss measure can be used to quantify the impact of regulation in restricting the disposability of undesirable outputs (Färe et al. 1989). Following Färe et al. (1989), Chang (1999) uses the output loss measure to calculate the regulatory costs of the credit departments of farmers’ associations in Taiwan in order to comply with the regulations.
3. The problems to be solved for energy efficiency under weak and strong disposability are:

\[
\begin{align*}
\text{Min} & \quad \gamma_{E}^{W} \\
\text{s.t.} & \quad -y_{i} + y_{E} \lambda \geq 0 \\
& \quad x_{v-E}^l - x_{v-E} \lambda \geq 0 \\
& \quad \gamma_{E}^{W} x_{v-E} - x_{E} \lambda \geq 0 \\
& \quad \sigma w_{i} = W \lambda \quad \text{and} \quad w_{i} \geq W \lambda \\
& \quad \sigma x_{l}^E - x_{l} \lambda = 0 \\
& \quad N \lambda = 1 \\
& \quad 0 < \sigma \leq 1 \\
& \quad \lambda \geq 0 \\
\end{align*}
\]

where the superscript \( v-E \) denotes the subset of all variable inputs except energy.
4. The deflators for capital in structures and machinery and installations are calculated from the data supplied by the LEI accounting system. Comparison of the end balance value in year $t$ and the beginning balance value in year $t - 1$ gives the yearly price correction used by the LEI. This price correction is used to construct a price index for capital and a price index for machinery and installations. These price indices are used as deflators.

5. Co-generators are installations that combine the generation of electricity and heat.

6. Färe et al. (1989) found a similar, though more pronounced effect of ignoring undesirable outputs for a sample of U.S. paper and pulp mills.

References


