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# Differences in CO2 emissions – A Cross-Country Structural Decomposition Analysis

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*Published in:*
Energy and Security in the Changing World. 27th Annual IAEE International Conference

*Publication date:*
2004

# Differences in $CO_2$ emissions
# – A Cross-Country Structural Decomposition Analysis

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**Abstract**

The main objective of the present article is to determine the reasons for the differences in $CO_2$ emissions between Denmark, Sweden and Germany. I apply input-output based structural decomposition analysis and decompose the effects on $CO_2$ emissions of energy mix, energy intensity, input mix and final demand. I find that the main contributor to the differences in $CO_2$ emissions is the size of the economy, i.e. the German emissions are greater than the emissions of Denmark and Sweden mainly because Germany is a much bigger country. However, I also show that the Danish energy intensity reduces the emissions, that the German final demand composition is favourable with respect to reducing $CO_2$ emissions, and finally that the Swedish energy mix has a positive effect with respect to $CO_2$ emissions. Furthermore, I estimate potential emission improvements from learning better practices. I estimate the learning gains under several scenarios ranging from a very optimistic upper bound scenario where energy mix, energy intensity, input mix and final demand can be changed, to a more realistic scenario where only energy intensity and input mix can be transferred. I find that there is great potential for reducing $CO_2$ emissions for Sweden and Germany by learning from the Danish energy intensity.

Keywords: $CO_2$, cross-country SDA, input-output

## 1 Introduction

In 1997, the Kyoto protocol was signed by 185 countries, and thus the first step was taken towards a joint reduction of global $CO_2$ emissions. The countries that were party to the agreement were assigned differentiated $CO_2$ emission reduction targets, confronting them with very divergent challenges as to how to obtain their reduction targets. Many different strategies and economic

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instruments have been discussed, but one of the questions that remains is if there are significant gains to be made learning from the countries with the best-practice technologies.

There are obvious differences in energy and emission structures across the various countries concerned. For example, coal makes up 21% of the total primary energy supply in Denmark, compared to 5% in Sweden (International Energy Agency 2004). The differences in energy composition give rise to a $CO_2$ emission of 61 tons per tera joule in production in Denmark compared to 22 tons in Sweden. However, the average energy intensity of Denmark is 5.5 tera joule per million EUR of industrial production, whereas the average energy intensity of Sweden is 9.3 tera joule per million EUR of production (IEA 2004). These differences in the energy structures of the two countries suggest that there are possibilities for reducing energy consumption and $CO_2$ emissions by learning from neighbouring countries.

The purpose of this article is twofold. First and foremost, the aim is to use input-output analysis and cross-country structural decomposition analysis to find out which characteristics determine the differences in the $CO_2$ emissions of Denmark, Sweden and Germany. I investigate the areas in which Denmark, Sweden and Germany have energy structures or industrial structures which are markedly different to those of the other two countries. Second, I estimate potential learning effects by considering fictive $CO_2$ emissions for the three countries on the basis of "transferable elements", the factors which it would be politically and physically possible to alter, namely energy intensity and industrial structure. "Transferable elements" are defined as those factors which determine a country's $CO_2$ emissions that could be transferred directly from one country to the others, e.g. energy intensity or industrial structure.

I find that the Danish energy intensity reduces emissions, that the German final demand composition is favourable with respect to reducing $CO_2$ emissions, and finally that the Swedish energy mix is attractive with respect to $CO_2$ emissions. I find also that there is limited learning potential for Denmark, but Sweden and Germany could with advantage learn from the Danish energy intensity.

First, based on the Leontief extended input-output production functions (Leontief and Ford, 1972) of Denmark, Germany and Sweden, I investigate whether one country produces goods more $CO_2$-

efficiently than the others by benchmarking the production technologies of the three countries. The origins of these differences are then investigated by applying cross-country structural decomposition analysis (SDA) (Jensen-Butler and Madsen 2005; Chung and Rhee 2001; Ang and Zhang 1999; Alcántara and Duarte 2004; Schipper et al. 2001; Zhang and Ang 2001). The analyses are based on data from 1997 for Denmark, Germany and Sweden.

The article is structured as follows. In Section 2 the modelling behind the analyses is outlined and relevant literature is presented. Data collection and preparation are presented in Section 3. Section 4 outlines the analytic procedure, and the results of the analyses are presented in Section 0. Finally, Section 6 contains a discussion and concluding remarks.

# 2 Modelling

The purpose of the following section is to set up a model capable of explaining the national $CO_2$ emissions caused by industrial production. I introduce a general model, $M(\cdot)$, in order to create clarity and simplify the notation. The general model expresses the total annual $CO_2$ emissions of a country, depending on energy use, input mix and final demand:

$$CO_2 = M(E, A, Y) \quad (1)$$

The parameters explaining the $CO_2$ emissions are

| | |
|---|---|
| $E$ | is a fuel mix matrix, i.e. the demand for *m* energy types for all the *n* production sectors, GJ (m×n) |
| $\mathbf{A}$ | is a coefficient matrix, supply by domestic industry to domestic industry per total industrial output, €/€ (n×n) |
| $\tilde{\mathbf{Y}}$ | is a matrix of the domestically-produced final demand of the *n* sectors, € (n×1) |
| $\varepsilon$ | is a residual containing the emissions not explained by the model. |

The model explaining the $CO_2$ emissions could be an econometric model, a computable general equilibrium model or an input-output model, for example.[1] In contrast to an econometric model where it is not possible to replicate actual $CO_2$ emissions using, i.e. $\varepsilon \neq 0$, the residual in CGE analysis and input-output analysis is zero, i.e. $\varepsilon = 0$.

[1] In principle, IO analysis is a special case of CGE analysis setting the substitution elasticities equal to zero (Burniaux and Troung 2002).

The methodology behind the structural decomposition analysis is the extended input-output system introduced by Leontief and Ford (1972). The extended input-output system deals with inter-industrial relationships connected to environmental data, e.g. emissions data. This is very useful for calculating the energy and $CO_2$ emissions incorporated in products because the entire production cycle is covered, including the infinite chain of derived effects throughout the economy.

Using input-output analysis, the annual industrial $CO_2$ emissions caused by production satisfying final demand are given by (2).

$$CO_2 = M(\mathbf{c}, \mathbf{E}, \mathbf{R}, \mathbf{A}, \mathbf{Y}, y) \quad (2)$$

where

| | |
|---|---|
| $CO_2$ | is the total yearly $CO_2$ emissions caused by production, kg (1×1) |
| $\mathbf{c}$ | is an emission coefficient vector, i.e. $CO_2$ emissions in kg per GJ energy used, kg/GJ (1×m), for the *m* different fuel types |
| $\mathbf{E}$ | is a coefficient fuel mix matrix, i.e. demand for the *m* energy types per unit of total demand for energy for all the *n* production sectors, GJ/GJ (m×n) |
| $\mathbf{R}$ | is a diagonal matrix of energy intensities, i.e. total annual energy consumption per unit of production in the *n* sectors, GJ/€ (n×n) |
| $\mathbf{I}$ | is the unity matrix (n×n) |
| $\mathbf{A}$ | is a coefficient matrix, supply by domestic industry to domestic industry per total industrial output, €/€ (n×n) |
| $(\mathbf{I}-\mathbf{A})^{-1}$ | is the Leontief inverse |
| $\mathbf{Y}$ | is a (n×1) coefficient matrix of domestic final demand from the *n* sectors, €/€ |
| $y$ | is a (1×1) scalar, being the total annual value of final demand, € |

I include only the domestic inter-industrial supply and the final demand from domestic industries. The imported part of the A-matrix and the imported final demand are not the “responsibility” of the producers in the importing country. Furthermore, including the imports in the A-matrix would be similar to presuming that the imports were produced with technology similar to that of the importing country, which is not necessarily correct. The way imports are handled in these calculations enables me to determine the $CO_2$ emissions actually connected with production in

Denmark, Sweden and Germany, and it is the production-related $CO_2$ emissions that are incorporated in the Kyoto protocol, not those related to consumption or imports.

Structural decomposition analysis has, been widely applied to analysing the origins of changes over time. For example, Munksgaard et al. (2000), Wier (1998) and Lee and Lin (2001) have used structural decomposition to analyse trends in $CO_2$ emissions. Wier (1998) also included the emissions of $SO_2$ and $NO_x$ in the analysis. Greening et al. (1998, 1999, 2001) and Greening (2004) apply the Adaptive Weighted Divisia rolling base year index specification to ten OECD countries over a 20- to 25-year period. They analyse the changes in $CO_2$ emissions in four sectors in the ten countries: manufacturing (Greening et al. 1998), residential end-uses (Greening et al. 2001), personal transport (Greening 2004) and freight (Greening et al. 1999), comparing the causes of the changes in the different countries. Furthermore, Wier and Hasler (1999) have analysed the changes in the nitrogen content in the Danish aquatic environment 1966-1988. Chen and Wu (1994) and Kagawa et al. (2002) have analysed changes in electricity use and energy use respectively. For a thorough review see Hoekstra and van den Bergh (2002).

Another application of structural decomposition analyses is as a cross-country decomposition analyses tool which can identify the sources of differences between countries. In the field of energy and $CO_2$ emissions analysis, cross-country structural decomposition analysis has been carried out by Chung and Rhee (2001), decomposing the differences in $CO_2$ emissions between Japan and South Korea into differences in energy use techniques, input techniques, final demand composition, the size of economy, and finally a residual. They find that the largest contributor to the difference in $CO_2$ emissions between Japan and South Korea is the difference in the size of the countries, followed by the energy use techniques, composition of final demand, and input techniques. Ang and Zhang (1999) decompose the differences in energy-related $CO_2$ emissions in three OECD regions and in three world regions. The differences in energy-related $CO_2$ emissions are decomposed into emission factors, fuel consumption, energy intensity and GDP per capita (income level), presented as pair-wise comparisons. Alcántara and Duarte (2004) conduct an input-output based structural decomposition analysis and compare the energy intensities of the European Union countries with the European Union average for fifteen sectors. They decompose the energy intensities into the “intensity effect”, which measures the part of the difference due to different energy consumption of the sectors, the “structure effect”, which measures the difference due to different input mix of the sectors, the "demand effect", which measures the difference due to differences in demand structure, and a residual. They find that, in general, the direct energy intensity and final demand play important roles. They also find that the contribution of each country to the aggregate energy intensity of the EU is not equally distributed across all the sectors of the economy. Schipper et al. (2001) compare the $CO_2$ emissions of fourteen International Energy Agency members, among these Denmark, Sweden and the former West Germany. They decompose the $CO_2$ emissions into sectoral activity, structure, energy intensity, final fuel mix, and utility carbon intensity. They analyse the $CO_2$ emissions of manufacturing, households, the service sector, travel and freight, comparing each country's emissions to the average of all the other countries. In this way, Schipper et al. are able to determine which characteristics of a country cause the emissions to differ from the average. They find that apart from the per capita activity level, the most important determinants of the differences in emissions are the utility carbon intensity and the energy intensities. Finally, Zhang and Ang (2001) describe methodological considerations regarding cross-country decomposition of energy and environment indicators.

The annual $CO_2$ emissions caused by production given in (2) can be presented as a general model (Jensen-Butler and Madsen, 2005), $M$ , i.e. as a function of the emission coefficients, energy mix, energy intensity, input mix, final demand composition and final demand level:

$$CO_2 = M(\mathbf{c}, \mathbf{E}, \mathbf{R}, \mathbf{A}, \mathbf{Y}, y) \qquad (3)$$

Then the differences in $CO_2$ emissions between countries $i$ and $j$ can be expressed as

$$\Delta CO_2 = CO_2^i - CO_2^j = M(\mathbf{c}^i, \mathbf{E}^i, \mathbf{R}^i, \mathbf{A}^i, \mathbf{Y}^i, y^i) - M(\mathbf{c}^j, \mathbf{E}^j, \mathbf{R}^j, \mathbf{A}^j, \mathbf{Y}^j, y^j) \qquad (4)$$

The differences in $CO_2$ emissions between countries $i$ and $j$ can be decomposed so that the elements are changed one at a time in order to isolate the contribution of each element in the production technology. The order in which the elements are decomposed is given by an assumption of controllability. First I detect the effect of the most controllable element then I add the effect from the second most controllable element etc. I assume that the most controllable element is the energy intensity, followed by the input mix. Since final demand composition, energy mix, emissions coefficients are elements which are determined by natural factors (through the energy mix) or determined by activity outside the country (as exports, included in the final demand composition) these are assumed to be less alterable. Finally the final demand level is assumed to be the least alterable element. This is represented in (5)

$$\Delta CO_2 = \begin{bmatrix} M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^j,\mathbf{Y}^j,y^j) - M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^j,\mathbf{A}^j,\mathbf{Y}^j,y^j) \\ +M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^j,y^j) - M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^j,\mathbf{Y}^j,y^j) \\ +M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) - M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^j,y^j) \\ +M(\mathbf{c}^j,\mathbf{E}^i,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) - M(\mathbf{c}^j,\mathbf{E}^j,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) \\ +M(\mathbf{c}^i,\mathbf{E}^i,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) - M(\mathbf{c}^j,\mathbf{E}^i,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) \\ +M(\mathbf{c}^i,\mathbf{E}^i,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^i) - M(\mathbf{c}^i,\mathbf{E}^i,\mathbf{R}^i,\mathbf{A}^i,\mathbf{Y}^i,y^j) \end{bmatrix} = \begin{bmatrix} \Delta\mathbf{R} \\ +\Delta\mathbf{A} \\ +\Delta\mathbf{Y} \\ +\Delta\mathbf{E} \\ +\Delta\mathbf{c} \\ +\Delta y \end{bmatrix} \tag{5}$$

(5) is interpreted as follows:

$\Delta CO_2$ = effects of differences in energy intensity
+ effects of differences in intermediate demand/input mix
+ effects of differences in composition of final demand
+ effects of differences in energy mix
+ effects of differences in emission coefficients
+ effects of differences in level of final demand.

Decomposition of the $CO_2$ emissions across countries is then calculated as presented in (6).

$$\Delta CO_2 = \Delta\mathbf{R} + \Delta\mathbf{A} + \Delta\mathbf{Y} + \Delta\mathbf{E} + \Delta\mathbf{c} + \Delta y \tag{6}$$

The value of each of the elements in the structural decomposition analysis indicates its contribution to the differences in total $CO_2$ emissions between two countries. One element itself can contribute more than the total difference as long as other elements contribute in the opposite direction.

### *2.1 Non-uniqueness of decomposition results*

A problem connected to SDA is the non-uniqueness of the decomposition results. This methodology suffers from that the results are affected by the order in which the components are applied. This is because the difference in an element between the countries, e.g. $\Delta\mathbf{R}$, influences the calculation of the effects of succeeding elements, i.e. $\Delta\mathbf{A}$, $\Delta\mathbf{Y}$ and $\Delta y$ (Jensen-Butler and Madsen 2005). Therefore the magnitude as well as the sign of the contribution of the elements might vary if the order is changed.[2] One way to deal with the problem is to perform the decomposition as a set of isolated calculations where the remaining elements are held fixed at the value of one of the countries and the calculations are made step by step on the value of the other country. The disadvantage of this method is that the sum of the isolated elements of the decomposition will not

[2] I am graetful to the anonymous referee making this important point clear to me. However, it is beyond the scope of this article to investigate the effect on the decomposition results from diverging orders of elements. See Rørmose and Olsen (2005) for further discussion.

necessarily (and will not usually) equal the total difference between the two countries (Jensen-Butler and Madsen 2005) and will instead result in a residual not explained in the SDA analysis (Rørmose and Olsen 2005). According to Rørmose and Olsen (2005), this problem is often addressed in an ad-hoc manner so that the residual is avoided. As noted above, in the present article I choose to base the decomposition analysis on a specific order of elements founded on an assumption of controllability (Jensen-Butler and Madsen 2005). I assume that the most controllable element is the energy intensity, followed by the input mix. Final demand composition, energy mix, emissions coefficients and finally the final demand level are assumed to be the least alterable elements, in that order.

# 3 Data

In the analyses I have used data from Denmark, Germany and Sweden for the year 1997. The data used to perform the analyses are national input-output data, $\mathbf{A}$ (industry×industry), $\mathbf{Y}$ (industry×consumption) and $\mathbf{X}$ (industry×output); and the energy account $\overline{\mathbf{E}}$ (energy use×industry) and $\mathbf{c}$ (emission coefficients×energy types). The structure of the data is illustrated in Table 1

| Country | Data source | Account | Industries | Products | Final demand categories | Energy types |
|---|---|---|---|---|---|---|
| Denmark | Danmarks | Input-output | 130 | 130 | 1 | - |
| | Statistik | Energy account | 130 | - | - | 40 |
| Sweden | Statistiska | Input-output | 39 | 39 | 1 | - |
| | centralbyrån | Energy account | 39 | - | - | 29 |
| Germany | Statistisches | Input-output | 59 | 59 | 1 | - |
| | Bundesamt Deutschland | Energy account | 59 | - | - | 37 |

Table 1 Data structure, 1997

The energy intensity matrices, $\mathbf{R}$, are calculated from the energy mix matrices, $\overline{\mathbf{E}}$, and the total output vector, $\mathbf{X}$. The energy mix coefficient matrices, $\mathbf{E}$, are determined from the energy mix matrices, $\overline{\mathbf{E}}$.

*3.1 Aggregation*

In order to perform the analyses, the matrices containing data for the three countries had to be conformable. As the numbers of industries and energy types are the lower for Sweden than for Denmark and Germany, the Danish and German data were aggregated to fit the Swedish accounts. The numbers of Danish and German industries were aggregated using the aggregation matrices formed by Lenzen et al. (2004, App. A).

The energy types were aggregated taking two side constraints into consideration. The first was the similarity between energy types; for example, different types of coal products were aggregated into one group of coal products. Second, the similarity between the emission coefficients was taken into consideration, i.e. if there were two aggregations of coal products, the coal product was aggregated into the group of coal products with the most similar emission coefficients.

Next, having aggregated the energy types, it was necessary that the emission coefficients should be aggregated as well. I chose to aggregate the emission coefficients under the condition that the total yearly $CO_2$ emissions should be the same using the original national number of energy types (energy use and emission coefficients) and using the aggregated common number of energy types. Therefore, the emission coefficients were adjusted in order to maintain the following condition:

$$\mathbf{c}^i_{1k}\mathbf{E}^i_{kn} = \mathbf{c}^i_{1m}\mathbf{E}^i_{mn} \qquad (7)$$

where $i = DK, DE$. $k$ is the initial number of energy types (40 for Denmark and 37 for Germany) and $m$ is the common number of energy types (29 for Sweden). $n$ is the common number of industries (39 for Sweden).

The aggregation was carried out as illustrated in (8)-(12)

$$\mathbf{c}^i_{1m} = \mathbf{c}^i_{1k}\mathbf{T}^{'}_{mk} \qquad (8)$$

$$\mathbf{E}^i_{mn} = \mathbf{T}_{mk}\mathbf{E}^i_{kl}\mathbf{T}_{ln} \qquad (9)$$

$$\mathbf{X}^i_{n1} = \mathbf{T}^{'}_{ln}\mathbf{X}^i_{l1} \qquad (10)$$

$$\mathbf{A}^i_{nn} = \mathbf{T}^{'}_{ln}\mathbf{A}^i_{ll}\mathbf{T}_{ln} \qquad (11)$$

$$\mathbf{Y}^i_{n1} = \mathbf{T}^{'}_{ln}\mathbf{Y}^i_{l1} \qquad (12)$$

where $l$ is the initial number of industries (130 for Denmark and 59 for Germany), and $\mathbf{T}_{xy}$ are the aggregation matrices containing ones and zeroes. As the A-matrices are in fact coefficient matrices they cannot be aggregated directly. In order to aggregate the A-matrices I took the point of departure in the flow matrices of inter-industrial deliveries and aggregated those. Then I turned them into coefficient matrices with the proper dimensions.

Thus, the analyses are based on the common number of industries, 39 (Appendix A), and the common number of energy types, 29 (Appendix B), with differentiated emission coefficients (Appendix C).

# 4 Analysis

The analysis is as follows:

I. The $CO_2$ emissions due to industrial production in each country are calculated on the basis of national emission coefficients, energy mix, energy intensity, input mix and final demand composition and level in order to establish a reference to potential learning.

$$CO_2 = c^i E^i R^i (I - A^i)^{-1} Y^i y^i \quad (13)$$

$i = DK, DE, SW$ . These $CO_2$ emissions correspond to replicating the model, $\varepsilon = 0$

II. The $CO_2$ emissions caused by industrial production in each country are calculated on the basis of the emission coefficients, energy mix, energy intensity and input mix of the other countries.

$$CO_2^{ij} = c^j E^j R^j (I - A^j)^{-1} Y^i y^i \quad (14)$$

$i, j = DK, DE, SW$ and $i \neq j$

These emissions are compared to the national emissions in order to find out if one country possesses a more favourable energy structure or industrial structure compared to the other countries.

III. The cross-country structural decomposition analysis is conducted as described in Section 2.

IV. The results from the cross-country structural decomposition analysis indicate "best practice" regarding energy intensity, input mix, final demand composition, energy mix and $CO_2$ emission coefficients. The "best practice combination" is then defined on the basis of "best practice" for the different elements. The "best practice $CO_2$ emissions" caused by production in each country are estimated on the basis of the "best practice combination".

$$CO_2^{ij} = c^j E^j R^j (I - A^j)^{-1} Y^j y^i \quad (15)$$

$i = DK, DE, SW$ and $j =$"best practice" for each element.

V. I examine the non-uniqueness problem by comparing the "best practice emissions" found under IV with the "optimal emissions". The optimal emissions are found by calculating the $CO_2$ emissions of the three countries based on all possible combinations ($5^3 = 243$) of energy mix, energy intensity, input mix and final demand composition, i.e.

$$\min_{j,k,l,m,n} CO_2^{min,i} = c^j E^k R^l (I - A^m)^{-1} Y^n y^i$$

VI. Finally, I calculate learning potentials based on assumptions of transferability, i.e. I estimate the $CO_2$ emissions based on the "best practice" and "optimal" *transferable* elements detected under V:

$$CO_2^i(R^j, A^j) = c^i E^i R^j (I - A^j)^{-1} Y^i y^i$$

$i = DK, DE, SW$ and $j =$"best practice" or "optimal" for each element.

# 5 Results

### 5.1 Replicating the model

The $CO_2$ emissions caused by industrial production are 54 Mt, 799 Mt and 69 Mt in Denmark, Germany and Sweden respectively. The diagonal (*italicised*) of Table 2 illustrates the replicated $CO_2$ emissions caused by industrial production in the different countries, $\varepsilon = 0$.

### 5.2 $CO_2$ emissions caused by industrial production based on the emission coefficients, energy mix, energy intensity and input mix of the other countries

In order to determine whether there are potential gains to be obtained by learning from the other countries, the $CO_2$ emissions caused by industrial production in the three countries calculated on the basis of the elements of the other countries are shown in Table 2. Furthermore, the table shows potential $CO_2$ reductions using the known combination of elements for Denmark, Germany and Sweden respectively, producing the final demand for Denmark, Germany and Sweden respectively.

Table 2 shows that if Danish final demand were met using the Swedish combination of elements, the $CO_2$ emissions would be 52 Mt (**bold**). The $CO_2$ emissions caused by German production using Danish production technology would be 594 Mt (**bold**). This implies that the Swedish composition would be favourable with regard to $CO_2$ emissions produced in meeting the Danish final demand. More surprisingly, the composition of the German final demand is such that the Danish combination of elements would lead to a lower $CO_2$ emission compared to either German or

Swedish production technology. As the Swedish $CO_2$ emissions caused by production based on the Swedish combination of elements are lower than if the Danish or German combinations were used, there is no apparent potential for reducing $CO_2$ by learning from the other countries at the aggregated level.

| | | Production in | | | |
|---|---|---|---|---|---|
| | | Denmark | Germany | Sweden | Total |
| Production technology of | Denmark | *54* | **594** | 76 | 725 |
| | Germany | 69 | *799* | 106 | 974 |
| | Sweden | **52** | 667 | ***69*** | 789 |
| | Δ emissions, % | 4% | 26% | 0% | 22% |

Note: The total difference in emissions of 22% is based on the sum of the actual (*italic*) $CO_2$ emissions (922 Mt) compared to the sum of the minimum (**bold**) $CO_2$ emissions (715 Mt)

Table 2 Total $CO_2$ emissions caused by production, Mt, 1997

### *5.3 Cross-country structural decomposition analysis*

The differences in the total $CO_2$ emissions of Germany from the emissions of Denmark and Sweden are not surprising, being primarily due to the different levels of final demand of the countries.

The decomposition results are shown in Table 3 and reveal that apart from the activity level, the main contributor to the difference in $CO_2$ emissions between Denmark and Germany is the energy intensity, $\Delta \mathbf{R}$, where the Danish energy intensity gives relatively lower $CO_2$ emissions of 249 Mt. Furthermore, the German final demand composition, $\Delta \mathbf{Y}$, reduces the $CO_2$ emissions by 51 Mt.

The total difference in $CO_2$ emissions between Sweden and Denmark is only 15 Mt. However, there are two elements which each contribute much more than this to the total difference: the Danish energy intensity, $\Delta \mathbf{R}$, reduces the $CO_2$ emissions by 33 Mt compared to the Swedish energy intensity, and Swedish energy mix, $\Delta \mathbf{E}$, reduces the $CO_2$ emissions by 35 Mt compared to the Danish energy mix.

Apart from the activity level, the main contributor to the difference between the $CO_2$ emissions for Germany and Sweden is the energy mix, with the German energy mix contributing an additional 29 Mt to $CO_2$ emissions. Furthermore, the German final demand composition contributes a reduction in $CO_2$ emissions of 17 Mt.

| | Denmark-Germany | | Denmark-Sweden | | Germany-Sweden | |
|---|---|---|---|---|---|---|
| $\Delta CO_2$ emissions | -744 | | -15 | | 729 | |
| Δenergy intensity | -249 | 34% | -33 | 219% | 0 | -0.03% |
| Δinput mix | -11 | 2% | -1 | 8% | -1 | -0.1% |
| Δfinal demand composition | 51 | -7% | -2 | 15% | -17 | -2% |
| Δenergy mix | 105 | -14% | 35 | -235% | 29 | 4% |
| Δemission coefficients | -30 | 4% | 1 | -10% | 4 | 0.5% |
| Δfinal demand level | -610 | 82% | -15 | 103% | 715 | 98% |

Table 3 Decomposition results, Mt, per cent, 1997

### 5.4 *"Best practice"*

Having determined the origins of the differences of the $CO_2$ emissions, I define "best practice" with regard to energy intensity, input mix, final demand composition, energy mix and $CO_2$ emission coefficients as the elements which are most favourable with respect to $CO_2$ emissions. Based on the direction in which any given element contributes to total $CO_2$ emissions, I define the symbol $\succ$ as expressing "better than" in the sense that the element for one country, e.g. energy mix or energy intensity, that is "better than" the element of another country, in that it reduces $CO_2$ emissions. The following relationships are derived from Table 3:

$$\mathbf{R}^{DK} \succ \mathbf{R}^{DE}, \mathbf{R}^{DK} \succ \mathbf{R}^{SW}, \mathbf{R}^{DE} \succ \mathbf{R}^{SW} \Rightarrow \mathbf{R}^{DK} \succ \mathbf{R}^{DE} \succ \mathbf{R}^{SW}$$

$$\mathbf{A}^{DK} \succ \mathbf{A}^{DE}, \mathbf{A}^{DK} \succ \mathbf{A}^{SW}, \mathbf{A}^{DE} \succ \mathbf{A}^{SW} \Rightarrow \mathbf{A}^{DK} \succ \mathbf{A}^{DE} \succ \mathbf{A}^{SW}$$

$$\mathbf{Y}^{DE} \succ \mathbf{Y}^{DK}, \mathbf{Y}^{DK} \succ \mathbf{Y}^{SW}, \mathbf{Y}^{DE} \succ \mathbf{Y}^{SW} \Rightarrow \mathbf{Y}^{DE} \succ \mathbf{Y}^{DK} \succ \mathbf{Y}^{SW}$$

$$\mathbf{E}^{DE} \succ \mathbf{E}^{DK}, \mathbf{E}^{SW} \succ \mathbf{E}^{DK}, \mathbf{E}^{SW} \succ \mathbf{E}^{DE} \Rightarrow \mathbf{E}^{SW} \succ \mathbf{E}^{DK} \succ \mathbf{E}^{DE}$$

$$\mathbf{c}^{DK} \succ \mathbf{c}^{DE}, \mathbf{c}^{SW} \succ \mathbf{c}^{DK}, \mathbf{c}^{SW} \succ \mathbf{c}^{DE} \Rightarrow \mathbf{c}^{SW} \succ \mathbf{c}^{DK} \succ \mathbf{c}^{DE}$$

In order to summarise the structural decomposition results, the effects of energy intensity, input mix, final demand composition, energy mix and $CO_2$ emission coefficients are shown in Table 4.

The table shows that the Danish energy intensity and input mix also reduce the $CO_2$ emissions. The German final demand composition has a beneficial effect on $CO_2$ emissions. Finally, the Swedish energy mix reduces $CO_2$ emissions.

| | Denmark | Germany | Sweden |
|---|---|---|---|
| | Denmark | Germany | Sweden |
| Energy intensity | Reduce | | Increase |
| Input mix | Reduce | | Increase |
| Final demand composition | | Reduce | Increase |
| Energy mix | Increase | | Reduce |
| Emission coefficients | | Increase | Reduce |

Table 4 Contribution to the $CO_2$ emissions of the elements

On the basis of the findings summarised in Table 4, I define the "best practice combination of elements" as being given by the Swedish emission factors ($\mathbf{c}$) and energy mix ($\mathbf{E}$), Danish energy intensity ($\mathbf{R}$), Danish input mix ($\mathbf{A}$) and German final demand composition ($\mathbf{Y}$), as illustrated in (16). I then calculate fictive the $CO_2$ emissions which would be brought about by Danish, German and Swedish final demand levels given the best-practice elements.

$$CO_2^{bestpractice} = c^{SW} E^{SW} R^{DK} (I - A^{DK})^{-1} Y^{DE} y^i \quad (16)$$

where $i = DK, DE, SW$

The fictive $CO_2$ emissions calculated by applying the "best practice combination" are illustrated in Table 5, and would correspond to 62% lower $CO_2$ emissions.

### 5.5 *Analysing the non-uniqueness problem*

The non-uniqueness problem mentioned in relation to the order of the elements means that using this methodology to benchmark the elements of the production technologies *may* lead to ambiguous figures for the contributions of each element. In order to clarify whether the results I have obtained are affected by the order in which the components are applied, I determine the "optimal" $CO_2$ emission for each country using any combination of $\mathbf{c}$, $\mathbf{E}$, $\mathbf{R}$, $\mathbf{A}$ and $\mathbf{Y}$ ($5^3$=243 combinations)

$$\min_{j,k,l,m,n} CO_2^{min,i} = c^j E^k R^l (I - A^m)^{-1} Y^n y^i \quad (17)$$

$i = DK, DE, SW$ and $j, k, l, m, n = DK, DE, SW$

I find that the "optimal" combination of elements is

$$CO_2^{min,i} = c^{SW} E^{SW} R^{DK} (I - A^{DE})^{-1} Y^{DE} y^i$$

The "optimal" $CO_2$ emissions are shown in Table 5. Comparing the "best practice" $CO_2$ emissions with the "optimal" $CO_2$ emissions reveals that the differences between the results are insignificant, limiting to 1.7% for Denmark and Germany and 1.3% for Sweden. The estimations of "optimal" and "best practice" $CO_2$ emissions serve to illustrate that there are technological differences between the countries that might suggest in which areas the different countries could make an effort with respect to obtaining $CO_2$ emission reductions.

| | Final demand in | | |
|---|---|---|---|
| | Denmark | Germany | Sweden |
| Actual | 54.3 | 799 | 69 |
| "Best practice technology" | 24.3 | 298 | 31.2 |
| "Optimal" combination | 23.9 | 293 | 30.8 |
| Danish Energy intensity | (54.3) | 549 | 36.5 |
| Danish Input mix | (54.3) | 753 | 78 |
| German Input mix | 53.8 | (799) | 74.3 |
| Danish Energy intensity Input mix | (54.3) | 538 | 35.3 |
| Danish Energy intensity and German Input mix | (53.8) | (549) | 35.3 |

Note: The figures in parenthesis equal figures other places in the table

Table 5 Learning potentials for $CO_2$ emissions, Mt

### *5.6 Learning potentials based on transferable elements*

The energy mixes of Denmark, Sweden and Germany differ significantly, mainly due to differences in natural conditions which are beyond the power of policy to alter. It is therefore not feasible that Denmark and Germany could learn from the desirable Swedish energy mix. Furthermore, a significant share of a country's final demand is determined by economic activity external to the country, i.e. the share determined by exports. It could be argued that those emissions are the responsibility of another nation (Lenzen et al. 2004; Kondo et al. 1998; Machado et al. 2001;

Munksgaard and Pedersen 2001; Sanchez-Chóliz and Duarte 2004), but it is definitely beyond the power of policy to alter them. However, it is more feasible that the countries could learn from each other's industrial structures and energy intensities.[3] Through an active climate policy, the incentive mechanisms in a country might change the industrial structure in such a way that the derived effects from inter-industrial supply of goods would lead to lower $CO_2$ emissions. Further, an active climate policy might equally encourage energy savings, which would lead to improved energy intensity. I therefore assume that the energy mix and final demand are beyond the scope of policy to alter, and I restrict the potential learning effects considered to energy intensity and industrial structure. Since the decomposition analysis points in the direction of the Danish energy intensity and input mix being the most favourable, but the total enumeration showed that the German input mix was the most attractive, the following combinations have been studied:

$$CO_2^{DK}(A^{DE}) = c^{DK}E^{DK}R^{DK}(I - A^{DK})^{-1}Y^{DK}y^{DK}$$
$$CO_2^{DE}(R^{DK}) = c^{DE}E^{DE}R^{DK}(I - A^{DE})^{-1}Y^{DE}y^{DE}$$
$$CO_2^{DE}(A^{DK}) = c^{DE}E^{DE}R^{DE}(I - A^{DK})^{-1}Y^{DE}y^{DE}$$
$$CO_2^{DE}(R^{DK}, A^{DK}) = c^{DE}E^{DE}R^{DK}(I - A^{DK})^{-1}Y^{DE}y^{DE}$$
$$CO_2^{SW}(R^{DK}) = c^{SW}E^{SW}R^{DK}(I - A^{SW})^{-1}Y^{SW}y^{SW}$$
$$CO_2^{SW}(A^{DK}) = c^{SW}E^{SW}R^{SW}(I - A^{DK})^{-1}Y^{SW}y^{SW}$$
$$CO_2^{SW}(A^{DE}) = c^{SW}E^{SW}R^{SW}(I - A^{DE})^{-1}Y^{SW}y^{SW}$$
$$CO_2^{SW}(R^{DK}, A^{DK}) = c^{SW}E^{SW}R^{DK}(I - A^{DK})^{-1}Y^{SW}y^{SW}$$
$$CO_2^{SW}(R^{DK}, A^{DE}) = c^{SW}E^{SW}R^{DK}(I - A^{DE})^{-1}Y^{SW}y^{SW}$$

where the right hand side expresses for the last equation: "Swedish CO2 emissions if it learns energy intensity, $\mathbf{R}$, from Denmark and industrial structure, $\mathbf{A}$, from Germany.

The results are illustrated in Table 5. Table 5 shows that the possible learning effects are rather small for Denmark but substantial for Sweden and Germany. However, if Sweden only learned from the German or Danish input mix without learning from the Danish energy intensity, Sweden would be worse off compared to using their own technology. Intuitively, it would seem from this that the German and Danish input mixes are linked to energy types in the Swedish energy composition that are burdened by higher $CO_2$ intensities than the energy types linked to the Swedish input mix. Without the desirable Danish energy intensity, the German and Danish input mixes would increase the Swedish emissions. Germany could reduce CO2 emissions substantially by

[3] I would to thank an anonymous referee for making this important point to me.

learning from Danish energy intensity and industrial structure. Denmark would be best off by learning from German input mix, as the Danish energy intensity is the most preferable for Denmark.

# 6 Discussion

It is important to emphasise that "best practice emissions" and the "optimal emissions" determined in Section 5.6 and 5.7 are based on unrealistic assumptions, e.g.: "What if Germany and Denmark were as rainy and hilly and as sparsely populated as Sweden?" The attractive energy mix in Sweden is mainly due to the country using a large proportion of hydro power and nuclear power. It would be impossible for Denmark and Germany to directly copy the hydro power of Sweden, and there is political opposition against nuclear power. The estimations of "optimal" and "best practice" $CO_2$ emissions serve to illustrate that there are technological differences between the countries that might suggest in which areas the different countries could make an effort with respect to obtaining $CO_2$ emission reductions.

The learning potentials estimated in this article are based on the transferable elements energy intensity and industrial structure. These are more likely to be affected by the political interventions necessary for achieving the Kyoto targets. Political interventions could include a carbon tax or the introduction of tradable quotas. This would provide incentives for reducing energy consumption, or requiring the use of intermediate products with lower carbon intensity.

The analysis in the present article is based on an input-output analysis founded on the assumption of a Leontief (1972) production function. In input-output analysis there is zero substitution between the inputs and the outputs; i.e. intermediate demand, energy consumption, and final demand composition. Therefore the model is not useful for analysing the effects of climate policy. However, one of the best applications of input-output analysis is the structural, static analysis providing a precise picture of a given situation. For the purpose of this article, namely to measure the effects of the structural differences between countries in terms of $CO_2$ emissions, the input-output based structural decomposition analysis is quite useful.

The decomposition methodology applied in this paper suffers from the weakness that the results are affected by the order in which the components are applied, and consequently the methodology is not useful for pointing out best practice. In order to identify the "optimal production technology" it was necessary to calculate the total effect of each of the 243 possible combinations. However, the decomposition analysis performed in the present article is founded on the assumption of controllability, and on this basis the analysis is capable of determining what causes the differences in $CO_2$ emissions between the three countries.

In both this analysis and that by Chung and Rhee (2001) using an input-output based SDA, the results suggest that the energy-use technique is quite important and that the input technique is less important. Ang and Chang (1999) use a different methodology and find that energy intensity and income level are the most important factors, both for the analysis of the differences between the three OECD regions and for that of the differences between the three world regions. For the latter, the effect from the income level was found to be even more significant. Schipper et al. (2001) find that the per capita activity level, the utility carbon intensity and the energy intensities are the most important determinants of the differences in emissions. They explicitly include Denmark, Sweden and West Germany in the analysis and find that at the aggregated level the energy intensity of Denmark is below average, that of Sweden slightly above average and that of Germany below average. Further, the effect of the fuel mix on the $CO_2$ emissions is below average for both Sweden and Denmark, while it is above average for Germany. The utility carbon intensity is far below average for Sweden, but above average for both Denmark and Germany. The results obtained by Schipper et al. (2001) do not contradict with the results obtained in the present analysis. In the present analysis, the utility carbon intensity is not separated, i.e. it is not included in the effect of the fuel mix, and therefore in perfect accordance with the results obtained by Schipper et al. (2001). A direct comparison of the results is not possible, however, since the base year for Schipper et al. (2001) is 1994 and for my analysis is 1997. More importantly, the present analysis compares the countries with each other and therefore provides useful knowledge on the specific differences between countries, while the study by Schipper et al. (2001) compares the countries with an average of 13 other countries. The input-output based SDA conducted by Alcántara and Duarte (2004) shows that the direct energy intensity and final demand play important roles. Not surprisingly, all of these studies find, like the present one, that energy technology is an important factor in determining $CO_2$ emissions. However, only the present study and the study by Schipper et al. (2001) separate energy technology into energy mix and energy intensity, thus providing additional information.

# 7 Concluding remarks

In this paper I have analysed the differences in production technologies with regard to total $CO_2$ emissions between Denmark, Germany and Sweden. I found that apart from the activity level given by the final demand level, the main contributor to the differences in $CO_2$ emissions between Denmark and Germany is the energy intensity, where the Danish intensity is the most favourable, followed by the final demand composition, with Germany having the best composition with respect to $CO_2$ emissions. Regarding the differences between Denmark and Sweden, the two main contributors to differences are energy mix and energy intensity, with these factors pulling in different directions. It appears that Germany and Sweden are rather alike, since the final demand level accounts for 98% of the differences in $CO_2$ emissions; however, the energy mix and the final demand composition also have an effect.

When I investigated the possibilities for Denmark, Sweden and Germany to learn from one another with respect to reducing $CO_2$ emissions based on transferable elements I find that there is limited potential for learning in the case of Denmark, but that Sweden and Germany could with advantage learn from the Danish energy intensity. Denmark and Germany could learn from Sweden with regard to energy mix. Since it is physically impossible to copy Sweden's hydro power and not politically popular to copy their nuclear power, the obvious alternative strategy is to develop the carbon-free technologies such as wind, solar and biomass energy in Germany and Denmark.

**Acknowledgements**

This article is a part of my Ph.D. project funded by the Nordic Energy Research under the programme NEMIEC. I am very grateful for valuable comments from Associate Professor Jesper Munksgaard, akf, Director of Research Bjarne Madsen, akf and Professor Peter Bogetoft, KVL. I would like to thank Cand.merc.mat Marianne Schiöpffe, Danske Bank and Laura Mørch Andersen, MSc, akf, for their great help with the technical aspects of this study. However, I am of course solely responsible for any shortcomings in this article.

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# 9 Appendices

Appendix A. Energy aggregation based on Swedish national account

| | Energy types | |
|---|---|---|
| Sweden | Germany | Denmark |
| Blast furnace gas | Refinery gas | |
| Coke oven coke | Coke oven coke from brown coal | Brown coal briquettes |
| | Coke oven coke from brown coal | Coke |
| | Coke oven coke from brown coal | Furnace coke |
| | Brown coal briquettes | Petroleum coke |
| | Brown coal briquettes | |
| | Petroleum coke | |
| | Patent fuels | |
| | Coke oven coke from hard coal | |
| Coke oven gas | Blast furnace gas | Refinery gas |
| Coking coal | Brown coal | Brown coal |
| | Brown coal | Coal (Anden stenkul) |
| | Brown coal | Coal (Elværkskul) |
| | Hard brown coal | |
| | Hard coal | |
| | Hard coal | |
| | Hard coal | |
| Diesel oil | Diesel oil | |
| Electricity | Electricity | Electricity |
| Gas works gas | Coke oven/gas works gas | Town gas |
| Gas/diesel oil | Gas oil | Gas oil |
| | | Gas oil |
| | | Marine gas oil |

| Energy types | | |
|---|---|---|
| Sweden | Germany | Denmark |
| Gasoline | Naphtha | Light virgin naphtha |
| | | Petrol, leaded |
| | | Petrol, unleaded |
| | | Tax free petrol |
| Heat | Heat | District heating |
| Hydro power | Hydro power | Water power |
| Jet gasoline | Aviation fuels | (Flybenzin) |
| | Aviation fuels | JP1 |
| | | JP4 |
| Liquefied petroleum gas | Liquefied petroleum gases | LPG 1 |
| | | LPG 2 |
| Municipal solid waste, elec., gas, DH | | |
| Municipal solid waste, industry | Sewage sludge, wastes etc. | Straw |
| | | Waste |
| Natural gas | Natural gas from crude oil extraction | Natural gas 2 |
| | Natural gas from coal mines | Natural gas 3 |
| Nuclear power | Nuclear power | |
| Other kerosene | Other mineral oil products | Kerosene |
| Other renewables | Other renewables | Biogas |
| Peat, elec., gas, DH | | |
| Peat, industry | Peat | |
| Residual fuel oil | Residual oil | Heavy fuel oil |
| | | Waste oil |
| Sulphur lies (black liquor) | Crude oil | Crude oil |
| | | Light fuel oil |

| Energy types | | |
|---|---|---|
| Sweden | Germany | Denmark |
| | | Natural gas 1 |
| | | Refinery feed stocks |
| Transformation losses, coke | | (Orimulsion) |
| Transformation losses, refineries | | |
| Wind power | Wind power | Wind power |
| Wood waste | | Wood |
| | | Wood waste |

Appendix B. Emission coefficients for the common energy types, kg/GJ

| | Emission coefficients | | |
|---|---|---|---|
| Energy type | Denmark | Germany | Sweden |
| Other kerosene | 72 | 80 | 73.1 |
| Gasoline | 73 | 80 | 72.6 |
| Diesel oil | 75.3 | 74 | 75.3 |
| Gas/diesel oil | 74 | 74 | 75.3 |
| Residual fuel oil | 78 | 78 | 76.2 |
| Jet gasoline | 72 | 72.9 | 72.3 |
| Other kerosene | 73.1 | 73.1 | 73.1 |
| Liquefied petroleum gas | 65 | 65 | 65.1 |
| Coke oven coke | 100.7 | 104.2 | 103 |
| Coke oven gas | 56.9 | 105 | 60 |
| Blast furnace gas | 103 | 60 | 103 |
| Natural gas | 56.9 | 57 | 56.5 |
| Transformation losses, coke | 80 | 79 | 79 |
| Transformation losses, refineries | 76.2 | 76.2 | 76.2 |
| Municipal solid waste, elec., gas, DH | 0 | 0 | 0 |
| Municipal solid waste, industry | 0 | 0 | 0 |
| Gas works gas | 56.9 | 44 | 77.5 |
| Coking coal | 95 | 100.5 | 90.7 |

| | Emission coefficients | | |
|---|---|---|---|
| Energy type | Denmark | Germany | Sweden |
| Peat, elec., gas, DH | 107.3 | 107.3 | 107.3 |
| Peat, industry | 97.1 | 80 | 97.1 |
| Wood waste | 102 | 96 | 96 |
| Sulphur lies (black liquor) | 0 | 0 | 0 |
| Sulphur lies (black liquor) | 108 | 108 | 108 |
| Nuclear power | 0 | 0 | 0 |
| Hydro power | 0 | 0 | 0 |
| Wind power | 0 | 0 | 0 |
| Other renewables | 0 | 0 | 0 |
| Electricity | 0 | 0 | 0 |
| Heat | 0 | 0 | 0 |