THE DETERMINANTS OF SULFUR EMISSIONS FROM OIL CONSUMPTION

IN SWEDISH MANUFACTURING INDUSTRY, 1976-1995[1]

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Abstract: Using a structural decomposition analysis, we analyze the causes of reduction in emitted sulfur originating from the manufacturing industry in Sweden during 1976-1995. We also analyze how policy instruments work with respect to sulfur emissions. We conclude that the sulfur tax has been important for reducing sulfur emissions. It affects energy prices, and hence substitution from heavy fuel oil (HFO) to light fuel oil (LFO), as well as substitution from oil to other energy sources. The sulfur tax also addresses sulfur emissions through a reduction of sulfur content of oil directly.

Keywords: Sulfur emissions, decomposition analysis, oil consumption, manufacturing industry, sulfur tax, policy instruments, Sweden.

JEL-Codes: L60, Q41, Q48.

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INTRODUCTION

Sulfur emissions in Sweden dropped about 95% from the mid-1970s to the 1990s. The purpose of this paper is to contribute to the understanding of the causes of the reduction in emitted sulfur, and how policy instruments work with respect to sulfur emissions. Sweden is one of the countries that have pursued the most ambitious policy when it comes to combating the precursors of acid rain.[4] Sweden has used a series of strict policy instruments, including both mandatory limits on the sulfur content of fuel, and high sulfur taxes (introduced in 1991): roughly $3500 per ton of sulfur. This can be compared with permit prices in the US of $100 per ton, or with the tax in France of $20 per ton. In Sweden sulfur emissions have mainly been affected in four ways: through a regulation, a sulfur tax, CO_2 tax, and a more general energy tax.

With structural decomposition analysis (SDA) it is possible to distinguish and quantify changes in complex relationships. By applying SDA we hope to provide important information on the scope for policies addressing emissions from energy consumption. In general, we follow the approach taken by Torvanger (1991), in which, following the original definition of Divisia indices, see Ang (1995), he deduces the conventional Divisia index for energy-induced gas emissions (specifically, carbon-dioxide emissions in nine OECD countries). The same method was later applied by Ang and Choi (1997), who decomposed energy-induced gas emissions in general, and for Korean industry in particular. There are several studies done on carbon dioxide with this method, e.g., Ang and Choi (1997) and Casler and Rose (1998). Lin and Chang (1996) did a study on energy-induced gas emissions with respect to sulfur in Taiwanese industry. However, earlier decomposition analyses were

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[4] The reason for this is geographical. Scandinavian rock has very low buffering capacity, and severe effects of acid rain on lakes and forests were noticed very early (Odén, 1968). The main sources of acidification related to industry are the use of oil and coal containing sulfur and adherent nitrogen oxides.

limited in their direct policy conclusions; i.e., they did not relate emissions-changes to actual economic factors, such as tax changes and emissions-related regulations.

We here separate the effect of improved energy effectiveness from that of substitution between energy sources. These are the two effects, which anecdotal evidence and previous studies have indicated to be the most important when it comes to changes in energy consumption (see Walfridsson, 1987; Dargay, 1988; and Howarth et al., 1991). We will discuss our decomposition results in a policy framework, and in particular will show evidence of that relative prices of energy do matter, and in fact have large effects on sulfur emissions.

THE DATA

We decompose sulfur emissions from industrial oil consumption in Swedish manufacturing industry during 1976-1995, i.e. excluding the heat and power industry;[5] in particular, we decompose sulfur emissions from light fuel oil (LFO) [6] and heavy fuel oil (HFO). The sulfur content in both LFO and HFO has decreased over time as a result of desulfurization in the refinery industry. Pollution abatement at the plant level[7], is only undertaken in the heat and power industry and in some highly energy intensive industries; reduced sulfur emissions by abatement technologies are therefore seen here as marginal and are not analyzed.

The data set contains total and per sector consumption of LFO and HFO (in 1000 metric tons); total and per sector industrial production in Swedish kronor (SEK), at 1990 prices (IEA, 1998; IFS, 1999); and prices and taxes of LFO and HFO in Swedish kronor (SEK) per 1000

[5] In our case, LFO is primarily light heating oil for industrial and commercial uses.
[6] Sulfur emissions originating from industrial oil consumption were in the range of 6-12% of total sulfur emissions in Sweden during the period 1987 to 1995.
[7] The cement industry can be said to abate sulfur in the production process (personal communication with Roland Jarsin, Swedish Petroleum Institute).

liters (IEA 1992, 1995, 1997b).[8] Data on other energy sources used in the decomposition analysis is measured in kilotons of oil equivalent (ktoe) (IEA, 1997a).[9] Data on sulfur content is from Swedish Environmental Protection Agency, SEPA (1997). Actual sulfur content is only available from 1989 onwards, and is uncertain before 1991. A good approximation is to use the maximum allowed sulfur content before 1989.[10] Figure 1 shows sulfur emissions over time. Emissions decreased until about 1992, and have since been relatively constant.

Figure 1. Sulfur emissions from industrial oil consumption in Sweden, 1976-1996, in kilotons.
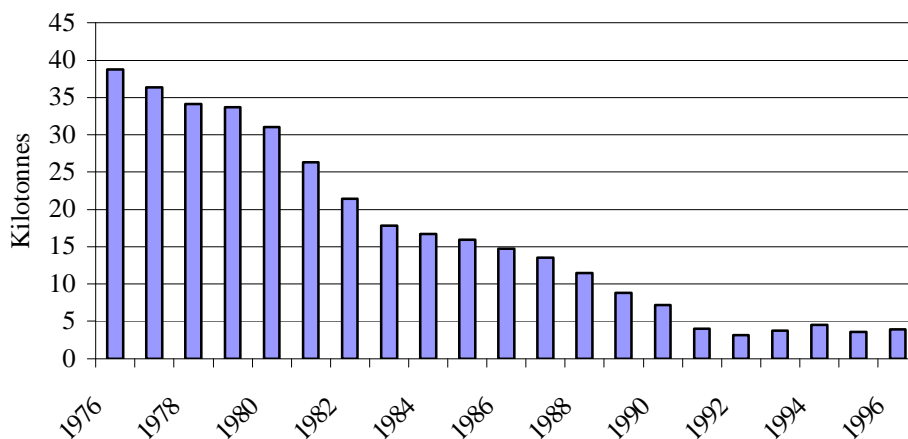
Sources: IEA (1990, 1992, 1995, and 1998), SEPA (1997).

Figure 2 below shows the actual average sulfur content and the maximum allowed sulfur content (regulation) in Sweden for the period, 1976-1996.

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[8] The sectors are divided according to the industrial categories in OECD (1995). From IEA statistics defined with reference to their ISIC (International Standard Industrial Classification of All Economic Activities) division or group number. The ISIC numbers refers to series M, N°4/Rev.3, United Nations, New York, 1990.

[9] 1 Mtoe = 11630 GWh. Assumptions regarding conversion between energy sources are the same for both Statistics Sweden and OECD (personal communication with Hans Elfsberg, Statistics Sweden).

[10] Personal communication with Roland Jarsin, Swedish Petroleum Institute.

Figure 2. Sulfur tax as share of total energy tax (including CO_2 tax) and sulfur content HFO, LFO, 1976-1996.
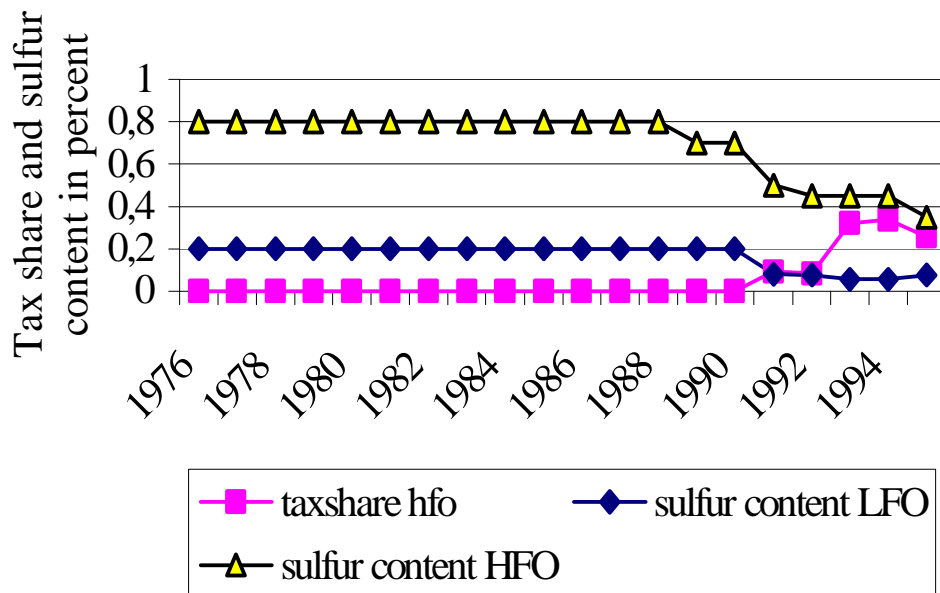
There has been a considerable difference between actual and the maximum allowed sulfur content during the later years of the period. The Swedish sulfur tax was introduced in 1991, levied on the sulfur content of fuel (oil, peat, and coal).[11] The tax rate is 30,000 SEK/ton of sulfur,[12] and is only paid on oil which contains more than 0.1 % sulfur. Liable to taxation are both oil companies and large-scale consumers who declare their use of taxable fuels. For oil with sulfur content above 0.1 %, the sulfur tax is just added to the price that firms buy from oil companies. The major expected effect of the tax was to reduce the sulfur content in LFO below 0.1% (SEPA, 1997), and this effect is in fact corroborated in Figure 2. Thus no sulfur tax was ever actually charged on LFO. For HFO first sulfur levels dropped below the allowed maximum (0.8%) already two years before the tax went into effect, due to some sort of "announcement effect". The sulfur level dropped considerably more when the

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[11] For an overview of other countries using a sulfur tax, see e.g. Cansier and Krumm (1997).
[12] i.e. 34 EURO/ton (1 SEK=0,11 EURO, December 1999).

tax went into effect, and then declined progressively to less than half the former level. Even as the sulfur level declined, however, the sulfur tax share in total energy tax rose, as Figure 2 shows, but this was due rather to a decrease in other energy taxes.

Figure 3 shows the total real price including energy, sulfur, and CO_2 taxes of LFO and HFO over time. The sulfur tax introduced in 1991 narrowed the gap between the prices, but HFO still remained cheaper than LFO. Thus, the incentive effect of the sulfur tax to substitute HFO for LFO was weakened.

Figure 3. Real prices including taxes for LFO and HFO for industrial use, 1978-1995, in Swedish crowns per thousand liters and metric tons, respectively.
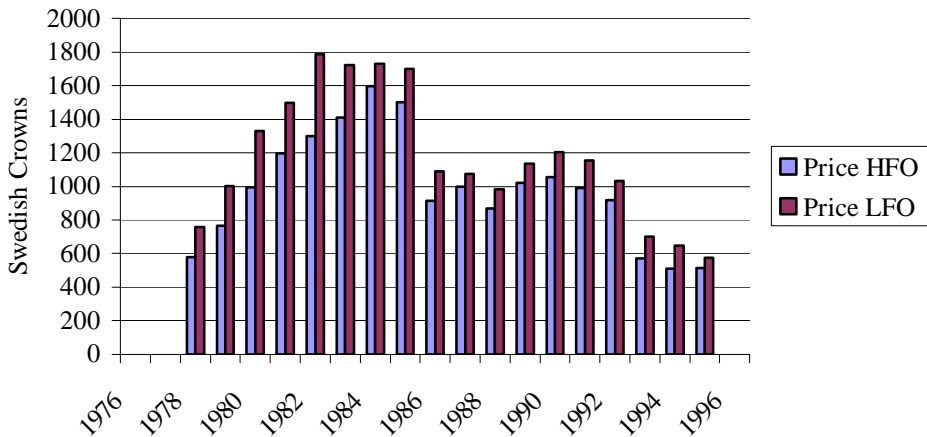
Source: IEA (1990, 1992, and 1995).

Figure 4 shows the energy tax share (including sulfur tax and CO_2) of the total price of HFO and LFO. An energy tax reform was implemented the 1st of January 1993, and a sharp cut in tax shares can be observed. The tax share for LFO has ranged from less than 10% in 1979 for LFO to over 50% in 1992, while for HFO the tax share has ranged from about 15% to almost 70%.

Figure 4. Tax energy tax share of total HFO and LFO prices for industry, 1978-1995.
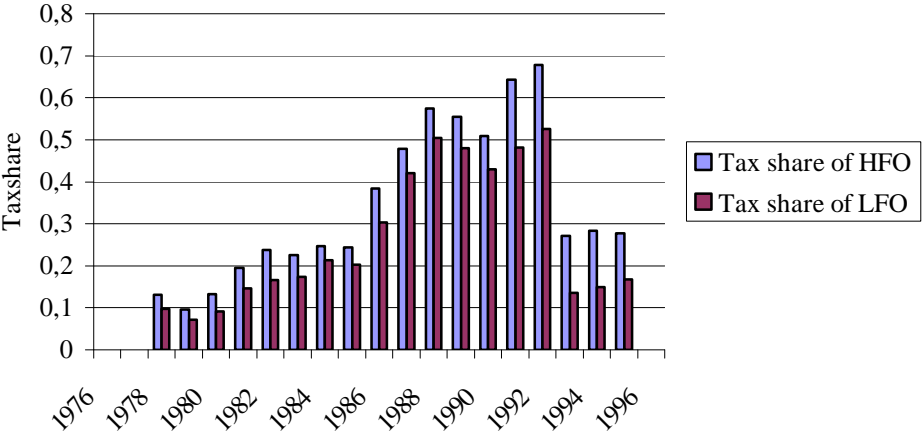
Source: IEA (1990, 1992, and 1995).

There are other possible substitutes besides LFO and HFO. The most important is electricity, which is an alternative especially for those firms – primarily in light industry - that want to have flexibility in their energy consumption. Other possible energy sources are natural gas and coal, which are mainly used by energy intensive industries. Such industries, where energy costs stand for a large part of total costs, have an incentive to invest in flexibility among energy sources; in particular between oil and electricity. These industries are then responsive to relative price changes, and can to a large extent, for example, switch from oil to electricity overnight. For those firms, where energy costs stand for a small part of total costs, substitution between energy sources is much less probable in the short run, because these firms are not likely to have invested in flexibility regarding energy use. The choices of energy source, and hence investment in furnaces, boilers etc, have long run implications for industrial energy use. Figure 5 shows how energy consumption for the various energy sources in Swedish manufacturing industry has changed during the period studied. The consumption of electricity, natural gas, and energy from waste and renewables

have increased, while oil consumption has decreased over time, and coal has been relatively steady.

Figure 5. Energy consumption in Swedish manufacturing industry, 1975-1995, by type, in kilotoe.
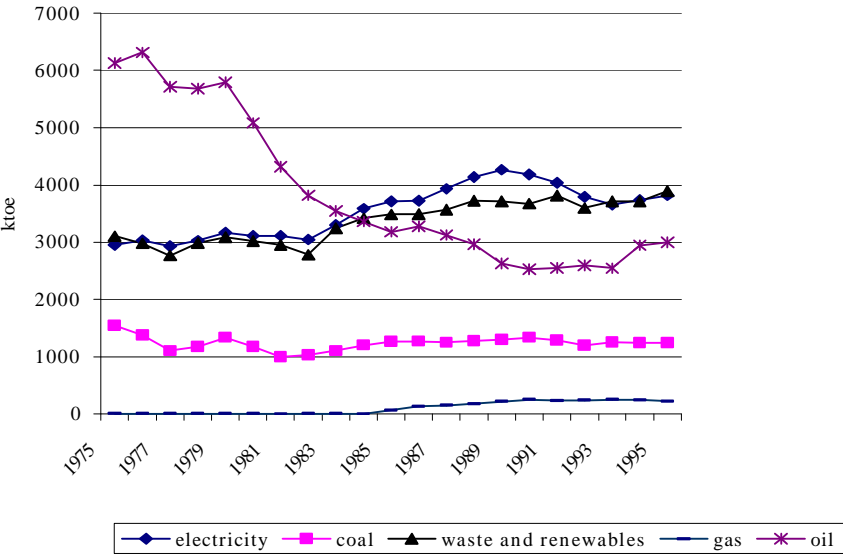
Source: IEA (1997a).

METHOD

This section starts with a definition of variables and derivation of the method - structural decomposition analysis (SDA) approach -, and is followed by a discussion on how the decomposition terms are to be interpreted. In our decomposition of oil-induced sulfur emissions we will use the following variables:

E_i = Total energy consumption (electricity, natural gas, oil, and waste and renewables[13]) in sector i

O = Total industrial oil consumption

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[13] Consumption of coal has been relatively constant during the period studied (see Figure 5). Data on the sulfur content of coal is highly uncertain, but assuming a constant sulfur content, emissions originating from coal

O_i = *Oil consumption in industrial sector i*

o_{ij} = *Consumption share of oil j (LFO or HFO) in sector i (O_{ij} / O_i)*

Y = *Total value of industrial production*

Y_i = *Value of production in sector i*

y_i = *Production share of sector i (= Y_i / Y)*

I = *Aggregate oil intensity (= O / Y)*

I_i = *Oil intensity of sector i (= O_i / Y_i)*

A_i = *Energy intensity of sector i (= E_i / Y_i)*

B_i = *Oil share of total energy consumption in sector i (= O_i / E_i)*

S = *Total sulfur emissions arising from industrial oil consumption*

S_i = *Sulfur emissions arising from oil consumption in sector i (=S_jS_{ij})*

S_{ij} = *Sulfur emissions arising from consumption of fuel j in sector i*

s_{ij} = *The share of total industrial sulfur emissions arising from consumption of fuel j in sector i (S_{ij} / S)*

U_{ij} = *Sulfur emission coefficient of fuel j in sector i, given by emissions per unit of energy use (S_{ij} / O_i)*

Torvanger (1991) decomposed emission intensity (emissions divided by value added), by deriving and using a Divisia index decomposition (an exponential of a weighted sum of growth rates). Ang and Choi (1997) used the method derived by Torvanger, with one exception: They used a multiplicative error term, instead of an additive one. Instead of decomposing emission intensity, however we will here decompose changes in actual emissions, S, and we note first that:

(i) $S = \sum U_{ij} y_i o_{ij} I_i Y \Leftrightarrow S_{ij} = U_{ij} y_i o_{ij} I_i Y$ and $S_{ij} = s_{ij} S$

Dividing I_i into two parts, we get: $I_i = A_i B_i$ where $A_i = \dfrac{E_i}{Y_i}$ and $B_i = \dfrac{O_i}{E_i}$

Taking the derivative of S w.r.t. time, we get:

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have thus not varied. There, to simplify calculations, coal was simply dropped from total energy. No other energy source emits sulfur.

(ii)
$$\frac{\partial S}{\partial t} = \sum_{ij} \left(\frac{\partial U_{ij}}{\partial t} y_i o_{ij} A_i B_i Y + \frac{\partial y_i}{\partial t} U_{ij} o_{ij} A_i B_i Y + \frac{\partial o_{ij}}{\partial t} U_{ij} y_i A_i B_i Y + \frac{\partial A_i}{\partial t} U_{ij} y_i o_{ij} B_i Y + \right.$$

$$\left. + \frac{\partial B_i}{\partial t} U_{ij} y_i o_{ij} A_i Y + \frac{\partial Y}{\partial t} U_{ij} y_i o_{ij} A_i B_i \right)$$

Multiplying (ii) by Sw_{ij} / Sw_{ij} on the right hand side (inside the summation), we get:

(iii)
$$\frac{\partial S}{\partial t} = \sum_{ij} \left(\frac{\partial U_{ij}}{\partial t} \div U_{ij} + \frac{\partial y_i}{\partial t} \div y_i + \frac{\partial o_{ij}}{\partial t} \div o_{ij} + \frac{\partial A_i}{\partial t} \div A_i + \frac{\partial B_i}{\partial t} \div B_i + \frac{\partial Y}{\partial t} \div Y \right) Ss_{ij}$$

Growth rates can be expressed as derivatives of logarithms; i.e., in general:

(iv)
$$\frac{d \ln X}{dt} = \frac{1}{X} \frac{dX}{dt} \quad \text{where} \quad X = U_{ij}, y_{ij}, o_{ij}, A_i, B_i, Y$$

Rewriting (iii) using (iv) and taking the integral, we get for the continuous case:

(v)
$$\int_t^{t+1} \frac{\partial S}{\partial t} = \Delta S = \left(\int_t^{t+1} \sum_{ij} \frac{\partial \ln U_{ij}}{\partial t} s_{ij} S + \int_t^{t+1} \sum_{ij} \frac{\partial \ln y_i}{\partial t} s_{ij} S + \int_t^{t+1} \sum_{ij} \frac{\partial \ln o_{ij}}{\partial t} s_{ij} S + \right.$$

$$\left. + \int_t^{t+1} \sum_{ij} \frac{\partial \ln A_i}{\partial t} s_{ij} S + \int_t^{t+1} \sum_{ij} \frac{\partial \ln B_i}{\partial t} s_{ij} S + \int_t^{t+1} \sum_{ij} \frac{\partial \ln Y}{\partial t} s_{ij} S \right)$$

Rewriting for the discrete case yields:

(vi)
$$\Delta S = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{U_{ij,t+1}}{U_{ij,t}})(\frac{S_{t+1} + S_t}{2}) + \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{y_{i,t+1}}{y_{i,t}})(\frac{S_{t+1} + S_t}{2}) +$$

$$+ \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{o_{ij,t+1}}{o_{ij,t}})(\frac{S_{t+1} + S_t}{2}) + \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{A_{i,t+1}}{A_{i,t}})(\frac{S_{t+1} + S_t}{2}) +$$

$$+ \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{B_{i,t+1}}{B_{i,t}})(\frac{S_{t+1} + S_t}{2}) + \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{Y_{t+1}}{Y_t})(\frac{S_{t+1} + S_t}{2})$$

Hence, the actual change in emitted sulfur can be decomposed into six parts, which are weighted sums of growth rates, where the weights are changing over time. We will label the six parts as follows:

$$D_{tot} = D_{sul} + D_{str} + D_{fsh} + D_{eff} + D_{sub} + D_{prod} \qquad \textit{(plus a residual),}$$

where (from above)

$$D_{sul} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{U_{ij,t+1}}{U_{ij,t}})(\frac{S_{t+1} + S_t}{2})$$

$$D_{str} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{y_{i,t+1}}{y_{i,t}})(\frac{S_{t+1} + S_t}{2})$$

$$D_{fsh} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{o_{ij,t+1}}{o_{ij,t}})(\frac{S_{t+1} + S_t}{2})$$

$$D_{eff} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{A_{i,t+1}}{A_{i,t}})(\frac{S_{t+1} + S_t}{2})$$

$$D_{sub} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{B_{i,t+1}}{B_{i,t}})(\frac{S_{t+1} + S_t}{2})$$

$$D_{prod} = \sum_{ij} \frac{(s_{ij,t+1} + s_{ij,t})}{2} \ln(\frac{Y_{t+1}}{Y_t})(\frac{S_{t+1} + S_t}{2})$$

If time series are available, then time series decompositions are preferred (Ang and Lee, 1994). We have therefore chosen base years consecutively, and decomposed each year with respect to the year before. In this way we take advantage of all information in the data set for explaining the pattern of sulfur emitted over the period.

The sulfur emission coefficient effect (D_{sul}) tells how much of the reduction in emitted sulfur is due to the reduced sulfur content of LFO and HFO. If the sulfur content did not change from one year to the next (D_{sul}) will be zero. The structural effect (D_{str}) captures changes *between* sectors, not *within* sectors. For example, if sectors that use relatively little oil increased their share of total production value, there was a reduction of emitted sulfur, and this term will be negative. The fuel share effect (D_{fsh}) captures substitution between LFO and HFO. If the share of LFO increased compared to the year before, then D_{fsh} will be negative. The energy effectiveness effect (D_{eff}) captures the reduction in emitted sulfur due to increased energy effectiveness, due mainly to more efficient technology (less energy consumption per unit of production value). The substitution effect (D_{sub}) reflects substitution

between oil and other energy sources. Decreasing the share of oil (substituting to other energy sources) reduces emitted sulfur, and hence results in a negative D_{sub} term. There is a potential residual in the substitution and/or in the energy effectiveness term, which is the structural effect *within* sectors; both the terms can be affected by changes in product mix within sectors, but our assessment is that the major effects are substitution to other energy sources and increased energy effectiveness, so we will ignore this.[14] Finally, the production term (D_{prod}) captures emission changes due to changes in total production value. An increase in production will yield a positive term.

EMPIRICAL RESULTS

From our analysis it is clear that there was a major substitution from oil to other energy sources (D_{sub}) in manufacturing industry (see Figure 6), and sulfur emissions also decreased drastically as a result of increased energy effectiveness (D_{eff}). Some of the decrease was also due to reduced sulfur content of oil (D_{sul}), mainly as a result of the introduction of the sulfur tax[15], and substitution from HFO to LFO (D_{fsh}). Finally, there were also small structural (D_{str}), and production (D_{prod}) effects. The decomposition results are easily accessible in figure 6. In 1976 total sulfur emissions were approximately 38.7 kilotons, but by 1996 they were down to approximately 4.0 kilotons, a reduction of 34.7 kilotons of emitted sulfur.

Figure 6. The cumulative change of emitted sulfur by decomposition term, 1976-1995, in kilotons (the starting point is total emitted sulfur in 1976).

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[14] Our estimation results also show a residual close to zero, which can be seen as a performance test of our model.
[15] This decrease is in fact quite large acknowledging the relatively short time period the sulfur tax has been in effect.
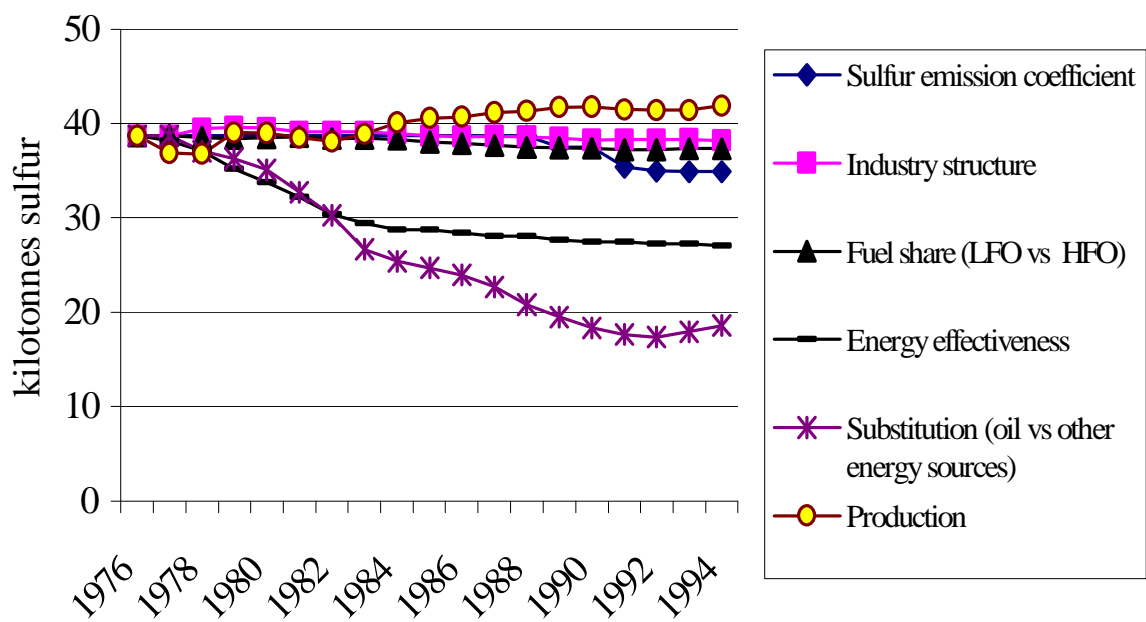
Sources: IEA (1998) and SEPA (1997).

Below we will discuss the contribution of each decomposition term separately. Table 1 presents the decomposition results as yearly changes in emitted sulfur for easier comparisons over time.

Table 1. Decomposition results (kilotons of sulfur), 1976-1995*.

	D_{tot}	D_{sul}	D_{str}	D_{fsh}	D_{eff}	D_{sub}	D_{prod}	D_{res}
	Sulfur change	Sulfur emission coefficient	Industry structure	Fuel share (LFO vs HFO)	Energy effectiveness	Substitution (oil vs other energy sources)	Production	Residual
1976	-2.40	0.00	-0.08	0.04	-0.53	-0.02	-1.81	0.00
1977	-2.23	0.00	0.83	-0.20	-1.12	-1.60	-0.14	0.00
1978	-0.44	0.00	0.13	-0.16	-1.89	-0.79	2.28	0.00
1979	-2.60	0.00	-0.11	0.10	-1.42	-1.16	-0.02	0.00
1980	-4.71	0.00	-0.38	0.13	-1.52	-2.42	-0.53	0.01
1981	-4.92	0.00	0.01	-0.23	-1.88	-2.46	-0.38	0.02
1982	-3.66	0.00	-0.02	0.03	-0.90	-3.56	0.79	0.01
1983	-1.05	0.00	-0.15	-0.10	-0.72	-1.29	1.22	0.00
1984	-0.79	0.00	-0.26	-0.27	0.00	-0.72	0.46	0.00
1985	-1.20	0.00	-0.10	-0.17	-0.31	-0.73	0.12	0.00
1986	-1.22	0.00	0.08	-0.17	-0.32	-1.27	0.45	0.00
1987	-2.06	0.00	-0.04	-0.23	-0.09	-1.88	0.18	0.01
1988	-2.67	-1.25	-0.16	-0.07	-0.31	-1.28	0.39	0.02
1989	-1.61	0.00	-0.20	-0.04	-0.24	-1.20	0.07	0.01
1990	-3.14	-2.12	0.01	-0.15	0.02	-0.68	-0.30	0.09
1991	-0.89	-0.37	0.00	-0.01	-0.21	-0.24	-0.07	0.01
1992	0.65	-0.05	0.05	0.11	0.00	0.55	-0.01	0.00
1993	0.76	0.01	-0.12	0.01	-0.21	0.61	0.46	0.00
1994	-1.01	-0.92	-0.31	-0.03	-0.02	-0.13	0.39	0.00
Total	-35.19	-4.70	-0.82	-1.41	-11.68	-20.26	3.55	0.18

*Year stands for base year; e.g., 1976 means that it is decomposition between 1977 and 1976 with 1976 as base year.

Sulfur emission coefficient

As is evident from data, there was no change in emitted sulfur due to a reduction of sulfur content of oil (D_{sul}) from 1976 through 1987. From 1988 to 1989, however (when

sulfur tax was announced), a reduction in the sulfur content of HFO from 0.8% to 0.7% (see Figure 2 above), resulted in a reduction of 1.25 kilotons of emitted sulfur, approximately 47% of the total change that year. The largest reduction attributable to a change in sulfur content (2.12 kilotons) was in 1991 coinciding with the actual introduction of the sulfur tax. Hence, the decomposition results again indicate the importance of the sulfur tax.

Structural changes

Structural changes (D_{str}) in industry over the period resulted in a small reduction of emitted sulfur (0.82 kiloton), reflecting relative growth in sectors that use less oil. The most striking change is that the transport equipment and machinery sector increased from approximately 39% in 1976 to 50% in 1996. All other sectors – except the chemical sector - decreased their share of production value with as the only exception.

Fuel share

There was net substitution from HFO to LFO (D_{fsh}) for the period as a whole; overall reduced sulfur emissions of 1.41 kilotons, and this was true for all but six individual years; between 1979 and 1981, and between 1992 and 1994. LFO and HFO are, to some degree, substitutes regarding technical properties. If we run a simple regression of changes in sulfur emissions captured in the fuel share decomposition term, on the price difference between LFO and HFO, we get an indication on the importance of the relative price. The model is estimated by OLS and corrected for autocorrelation (the t-value of ρ_{t-2} estimates of 2nd order autocorrelation - is 0.52). With t-statistics in parantheses the result is:

$$D_{fsh} = -1.34 + 0.23(P_{LFO} - P_{HFO}) \qquad R^2 = 0.77 \tag{1}$$
$$(-6.74) \quad (2.75)$$

Thus the bigger the price difference between LFO and HFO (price of oil is SEK per thousands liters) the more sulfur is emitted; conversely, increasing the tax share on HFO relative to LFO, e.g. in the form of a higher sulfur tax, will result in lower sulfur emissions. Calculating elasticity at the sample mean, a one percent increase in the price difference between light and heavy fuel oil will give an increase of 0.03% in emitted sulfur.

Substitution between oil and energy (electricity, waste, renewables, and natural gas)

Substitution from oil to other energy sources yielded the highest sulfur reduction over the period (20.26 kilotons, or almost two thirds of the total reduction). The only years with increasing emissions from this source were between 1992 and 1994, which are also the years with increases in total emissions. This trend break coincides with abolition of the industrial energy tax (although the CO_2 tax remained in effect) on January 1, 1993, and indicates that substitution *to oil* from other energy sources occurred then due to the tax reform. Market prices of electricity and oil[16] are of course not in themselves policy instruments, but they are amenable to change through policy instruments such as energy or sulfur taxes, which thus can affect substitution possibilities and sulfur emissions. Model 2 shows the expected effects that a lower price on electricity will decrease sulfur emissions. [17]

$$D_{sub} = -37.24 - 0.55 P_{OIL} + 0.019 P_{EL} \qquad R^2 = 0.86 \qquad (2)$$
$$(-3.71) \ (-1.55) \quad (2.62)$$

Calculating elasticity at the sample mean, a one percent decrease in the price of electricity gave a 1.83% decrease in emitted sulfur. The price effect of oil on emitted sulfur,

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[16] Price of oil is SEK per thousands litres and electricity is average price; SEK per GWh. The oil price is weighted with consumption share of LFO and HFO respectively.

[17] t-statistics are again presented in parentheses. The model was estimated by OLS. AR (2) correction did not solve the problem of autocorrelation. The results are insensitive to specification of the lag structure of the error term.

however, was statistically insignificant.[18] Thus we found no evidence that a lower price of oil would induce an increase in emitted sulfur. Nevertheless, acknowledging that our estimations are based on relatively few observations, we still find it relevant to calculate the elasticity at sample mean. It is –0.37; i.e., a one percent reduction of the price of oil resulted in a 0.37% increase in sulfur emissions. Thus, the elasticities indicate that, with respect to sulfur emitted, lowering the price of oil is not equivalent to increasing the price of electricity.

Energy effectiveness

About one third of the total reduction in emitted sulfur was due to increased energy effectiveness (11.68 kilotons). Economic theory suggests that higher energy prices in relation to other production factors induce technological progress, which in our case is captured in the effectiveness term. Our results indicate that technological improvements during the period have been substantial. Figure 7 explores the relation between energy prices and labor prices.

Figure 7. Real price indices of energy (oil and electricity costs for industry, weighted by consumption) and of labor (labor costs for wage-earners in mining and manufacturing), 1980-1995 (1980=100).
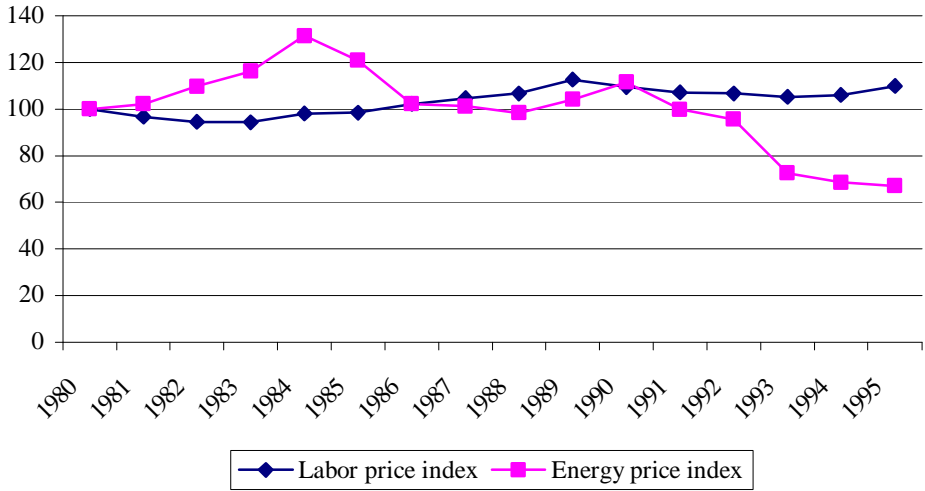
Sources: IEA (1990, 1992, and 1995) and Statistics Sweden (1981, 1985, 1989, 1992, and 1996)

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[18] The t-value of -1.55 corresponds to a p-value of 0.1465.

From 1980 through 1984 the price of energy relative to labor increased, and this was a period of higher D_{eff} terms – in other words, of greater, energy saving technological change. After that the price of energy fell relative to labor, and the D_{eff} terms are considerably smaller. It seems reasonable to think that these changes reflect the changes in the relative price of energy and labor. When the relative price of energy in relation to labor increased the incentive for firms to invest in energy effectiveness, both in the short run and the long run increased. A firm can increase energy effectiveness in the short run (every year) by trimming or by buying new technology. In the long run technological progress occurs through innovation. Still, in the short run, changes in relative prices cannot affect investment decisions already made, which might explain why the D_{eff} term was negative for most years after 1984 with a few exceptions, when it was approximately zero. There may also have been expectations following from the first and second oil crises, which require the inclusion of complex lag structures. A deeper analysis lies beyond the scope of this paper.

Production effect

Not surprisingly, emissions increased over the period due to increased production (D_{prod}), Though the effect was negative in the late seventies and early nineties reflecting economic recessions.

CONCLUSIONS

We draw five important conclusions regarding industrial oil use and resultant sulfur emissions. First, there has been substantial substitution from oil to other energy sources in the manufacturing industry, and the econometric evidence shows that energy prices do matter and can be used as a policy variable. Second, sulfur emissions have decreased as a result of

increased energy effectiveness; i.e., technological progress has been an important source for decreasing sulfur emissions. Third, structural and production effects exist, but are of less importance. Fourth, the introduction of the sulfur tax resulted in large reductions in emitted sulfur. Finally, increasing the tax would increase substitution from HFO to LFO and hence further reduce emitted sulfur.

To summarize, the sulfur tax has been important for reducing sulfur emissions. The sulfur tax affects energy prices, and hence substitution between LFO and HFO, as well as substitution from oil to other energy sources. It even acts to reduce the sulfur content of oil directly.

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