Environmental Science and Policy 77 (2017) 32–39

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

The impact of Swedish SO_2 policy instruments on SO_2 emissions 1990–2012

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ARTICLE INFO

Keywords:
Air pollution
SO_2 policy
Decomposition analysis
Policy impact analysis

ABSTRACT

Sulphur dioxide (SO_2) emissions cause acidification and human health problems which are, despite present policy instruments, projected to remain even after 2030 in Europe. Additional instruments are needed to solve the problems, and impact analysis of already used policy instruments would contribute to the development of new effective instruments. We present a study on how much of the decoupling of SO_2 emissions from economic growth 1990–2012 that was due to SO_2 policy instruments in general and to what extent it is possible to estimate the impact of individual instruments. Focus is on Sweden, a country with problems reaching its SO_2-related environmental policy targets and with detailed data available.

We applied decomposition analysis combined with an analysis of the chronological development of emission factors and mandated emission limits. Our use of official emission inventory data and publicly available data on the development of SO_2 policy instruments increase the usefulness of our results to policy makers.

The results indicate that at least 26–27% (corresponding to ~35–36 ktonne annually) of the decoupling 1990–2012 was due to SO_2 policy instruments. 4–5% (~6–7 ktonne) of the decoupling was caused by one environmental permit decision and stricter sulphur emission limit for marine oils. Most of the total impact of SO_2 policy instruments could not be causally connected to an individual instrument, because many events and developments overlap in time.

The implications of the results are that: a) SO_2 policy instruments should still be important to reduce SO_2 emissions in many countries; b) a lower boundary total emission impact of SO_2 policy instruments can be estimated, but with current knowledge and data the impacts of individual instruments are rarely possible to estimate. Research on how to increase the precision in total impact estimates of SO_2 policy instruments is needed to improve future impact analyses. More detailed emission inventory data would improve impact analysis of individual instruments.

1. Introduction

Emissions of sulphur dioxide (SO_2) are known to cause acidification of ecosystems, corrosion damages, and human health problems. Large efforts have been undertaken in Europe and other regions to reduce emissions of SO_2. International agreements such as the protocols of the UNECE Air Convention and EU:s National Emissions Ceiling Directive have been important for setting ambition levels (Hordijk and Amann, 2007; European Environment Agency, 2012; Byrne, 2015). SO_2 policy instruments such as emission limit values, performance standards, environmental permit processes, and sulphur taxes have been introduced in many countries.

Sweden, a country that still suffers from SO_2-related problems, was early to introduce SO_2 policy instruments. These typically promoted cost-effective emission control measures (Lindmark and Bergquist, 2008), and emissions have been substantially reduced. Currently (represented by 2012 in this paper), Swedish SO_2 emissions are 30 ktonne annually, which can be compared to 105 ktonne in 1990 (the earliest year with comparable data) (Swedish Environmental Protection Agency, 2014a), and 930 ktonne in 1970 (Broström et al., 1994). However, emission reductions are usually also driven by factors other than SO_2 policy instruments, such as structural changes in the energy sector, other policies, and changes in industry production patterns etc. (Hoekstra and van der Bergh, 2003). While SO_2 emissions have been reduced, Swedish Gross Domestic Product (GDP) have grown from 275 to 361 billion €$_{2005}$ during 1990–2012, implying that SO_2 emissions

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http://dx.doi.org/10.1016/j.envsci.2017.07.014
Received 15 June 2017; Received in revised form 18 July 2017; Accepted 18 July 2017

were decoupled from economic growth.

Despite past SO_2 emission reductions, Sweden and other parts of northern Europe are still expected to receive too high acid deposition until at least 2030 (Amann et al., 2014; Fölster et al., 2014) and human health problems are also predicted to persist (Holmin Fridell et al., 2013; Kiesewetter et al., 2015). More (or stricter) instruments are needed if policy targets related to acidification and human health are to be reached (Rafaj et al., 2014b). However, since many cost-effective measures have already been taken, future measures are likely to be relatively expensive. The risk of high costs associated with proposals for more instruments provide motivation for analysis of which of the present SO_2 policy instruments that have been the most effective at reducing SO_2 emissions. Such an analysis needs to consider that emission reductions are driven also by other factors than SO_2 policy instruments.

Earlier studies provides insights but have focused either on estimating the relative importance of different drivers of emission reductions (Fujii et al., 2013; Liu and Wang, 2013; Rafaj et al., 2014a,b), or on estimating the importance of one individual policy instrument, or the impacts of policy instruments in one specific sector (Hammar and Löfgren, 2001; Lindmark and Bergquist, 2008; Bergquist et al., 2013). Rafaj et al. (2014b), choosing a fuel-focused decomposition analysis of emission drivers, show that for EU15 dedicated emission control was responsible for 50% of the decoupling of emissions from economic growth between 2000 and 2010, while 15% was driven by energy intensity and energy efficiency improvements and 35% by changes in fuel mix. As a contrast Bergquist et al. (2013) find that the use of performance standards with extended compliance periods in combination with extensive joint government-industry research & development activities allowed for efficient emission reduction from the Swedish iron & steel and paper & pulp industries. Comparative impact analyses of different instruments over all emitting sectors appear missing in the literature.

Our paper complements earlier studies by estimating the total impact of SO_2 policy instruments on decoupling of emissions from economic growth as well as comparing the relative impacts of individual instruments while ensuring consistency with the total impact. The analysis focuses on Sweden since the Swedish environmental policy targets require further efforts to be met and because several different types of SO_2 policy instruments have been implemented. Sweden is also a country for which we have good access to detailed emission and instrument statistics for 1990–2012. The questions asked in this paper are: *How much of the decoupling of SO_2 emissions from economic growth was due to SO_2 policy instruments? To what extent can the impact of individual SO_2 policy instruments be quantified?*

2. Materials and methods

2.1. Total impact of SO_2 policy instruments on SO_2 emission decoupling from economic growth

To answer the first question we applied decomposition analysis (Hoekstra and van der Bergh, 2003) based on historical data. Decomposition analysis is an appropriate way to analyse the drivers of SO_2 emission reductions (De Bruyn, 1997; Stern, 2002), and explorative decomposition analysis of historical data (counterfactual analysis) is suitable for analysing impacts of environmental policies (Ferraro, 2009). Our decomposition analysis was based on Rafaj et al. (2014a), but we disaggregated the analysis into separate calculations for the Energy & Transport (ET) and the Industrial Processes (IP) sectors. We estimated impacts of changes in the emission drivers: economic activity (Structural changes), fuel use (Fuel use changes, ET only), industrial productivity (Increased productivity, IP only), and emission factors (Emission factor changes). To do this we deconstructed calculated emission levels (*e*) for a given scenario (*sc*), sector (*s*), and year (*t*) into the sum over all sub-sectors (*ss*) and activities (*f* or *p*) of the product of the parameters: Gross Domestic Product (*GDP*), activity level (*a*) and implied emission factors (*ief*) (Eqs. (1) and (2)). The parameters *a* and *ief* were given in different units depending on sector (Table 1).

Table 1
Specification of sector-specific units of (*a*) and (*ief*) used in the decomposition analysis.

Sector (s)	Type of activity	Activity level (*a*)	Implied emission factor (*ief*)
ET	fuel (*f*)	fuel use (PJ fuel)	ktonne SO_2/PJ fuel
IP	product (*p*)	production (tonne product)	ktonne SO_2/tonne product

$$e_{sc,ET,t} = \sum_{ss,f} \left(GDP_t * \left(\frac{a}{GDP} \right)_{ss,f,t} * ief_{ss,f,t} \right) \tag{1}$$

$$e_{sc,IP,t} = \sum_{ss,p} \left(GDP_t * \left(\frac{a}{GDP} \right)_{ss,p,t} * ief_{ss,p,t} \right) \tag{2}$$

Emissions were calculated in counterfactual scenarios by holding one or several of the parameters constant at 1990 values and re-calculate the emissions for all years *t* from 1990 to 2012. The impact of a specific driver was given through the comparison of calculated emissions in a scenario in which the related parameter was fixed at 1990 values with calculated emissions in a scenario in which the related parameter was set at 2012 values, all other things equal.

Even if emission reductions started already in the 1970s, we delimited the analysis to 1990–2012 due to limitations in reliability and consistency of older emission data. Furthermore, we focused on SO_2 policy instruments although other policies and instruments also might have affected SO_2 emissions.

2.1.1. Data sources

Data on GDP development were taken from The World Bank (2015). We used energy, transport, and industry statistics from officially reported Swedish SO_2 emission inventories (Swedish Environmental Protection Agency, 2014a,b,c) and data from the industry's environmental accounts (Fig. 1). The emission inventories follow international guidelines for reporting and auditing systems, and the industry's reporting of environmental accounts (used in the Swedish emission inventory) is mandated by Swedish law. The use of officially reported emission inventory data was important since this increase our results' usefulness to policy makers as negotiation and planning support. We complemented with official Swedish statistics on heat and electricity production (Statistics Sweden, 2015) for the analysis of Fuel use changes.

2.1.2. Further details of the decomposition analysis

The ET sector includes all emissions from combustion of fuel for heat, electricity or transport purposes minus bunker fuels, and corresponds to Sector 1 minus bunker fuels in the Common Reporting Format (CRF) emission inventory classification system (UNFCCC, 2014). Bunker fuels were excluded since SO_2 emissions from these are not governed by Swedish authorities and not reported as national emissions in the SO_2 emission inventories. The data for the ET sector is grouped into 19 sub-sectors and 27 fuel categories for stationary combustion and 9 sub-sectors and 12 fuel categories for mobile combustion.

The IP sector includes Swedish emissions from raw material extraction and refinement in the sub-sectors Paper & Pulp, Iron ore extraction, Iron & Steel smelters, Cement and Other production. The IP sector corresponds to CRF Sector 2. The ET and IP sectors together generated more than 99.99% of the total Swedish SO_2 emissions in 1990–2012.

2.1.2.1. ET sector calculations. For the ET sector the data allowed for further disaggregation of *a*. We expanded *a* in Eq. (1) into the factors total final energy demand (*D*), ratio between total amount of fuel used

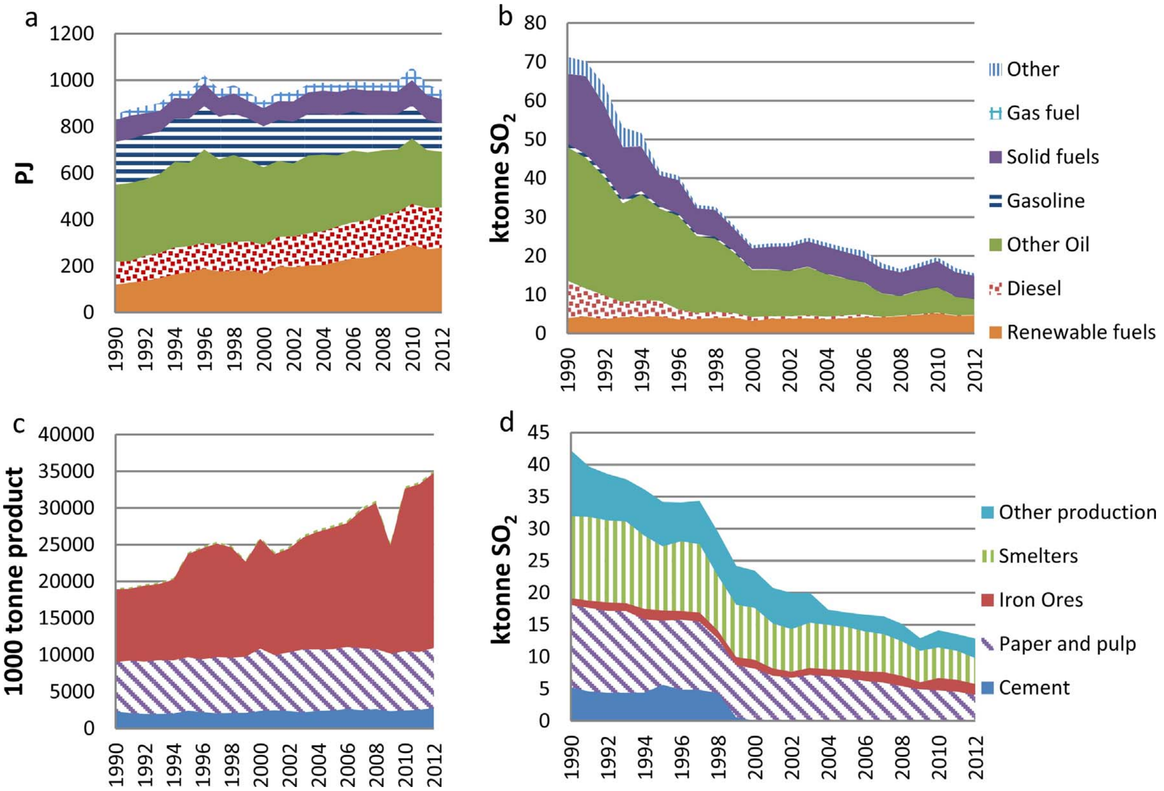

Fig. 1. Swedish fuel use 1990–2012 aggregated into major fuel categories (a), and corresponding SO_2 emissions (b), production in Swedish base industry 1990–2012 (c), and corresponding SO_2 emissions (d) (Swedish Environmental Protection Agency, 2014a,b,c). The increased fuel use in 1996 and 2010 was due to cold winters. The financial crisis of 2008 had the largest impact on production of iron. The production in Smelters and Other production is barely visible in (c) compared to the other sub-sectors, but have high SO_2 implied emission factors. Biofuels includes solid, liquid, and gaseous fuels from primarily wood-based resources. Waste fuels are included in Solid fuels. ET sector emissions from oil refineries etc. are included in category Other in 1b.The emissions from Other production are estimated based on a relative share of emissions from other sectors.

and total final energy demand D (*Fs*), and share of each fuel category in the fuel mix (*Fm*). Hence Eq. (1) could be rewritten as:

$$e_{sc,ET,t} = \sum_{ss,f} \left(GDP_{t_1} * \frac{D_{ss,t_2} * Fs_{ss,t_3} * Fm_{ss,f,t_4}}{GDP_{t_2}} * ief_{ss,f,t_5} \right) \tag{3}$$

where:

ss = ET sub-sector

D = total final energy used to generate electricity, heat, and transport services (PJ);

Fs = ratio between total amount of fuel used and D (*i.e.*, excluding hydro, nuclear, solar and wind energy) (ratio)

Fm = share of fuel category in the fuel mix (ratio)

For the ET sector we calculated four counterfactual emission scenarios for *t:* 1990–2012 and one factual emission scenario that followed statistics (*Reported ET Emissions*) (Table 2):

By comparing the resulting emissions we estimated how the ET sector decoupling of SO_2 emissions from economic growth was composed of:

i) Structural changes in the ET sector:

$$\Delta e(Structural\ changes)_t = e_{Const\,ET\,SO2/GDP,t} - e_{Const\,SO2/PJ,t} \tag{4}$$

ii) Fuel use changes:

$$\Delta e(Fuel\ use\ changes)_t = e_{Const\,SO2/PJ,t} - e_{Constant\ ET\ Emission\ factor,t} \tag{5}$$

iii) Emission factor changes in the ET sector:

$$\Delta e(Emission\ factor\ changes)_t = e_{Constant\ ET\ Emission\ factor,t} - e_{Reported\ ET\ emissions,t} \tag{6}$$

The impact of different drivers depend on the order in which the parameters in Eq. (3) are decomposed but the order we used most closely mimics the real world situation according to Rafaj et al. (2014b).

We analysed the effect of the ordering in a sensitivity analysis in which we kept *Fm* constant at 1990 levels but allowed *ief* to develop as according to emission inventory statistics, and then calculated impact on 2012 emissions. The sensitivity analysis excluded fuels not used in 2012. The impact of changing the parameter *Fs* separately was also analysed in a separate sensitivity analysis.

Since data on ET sector emissions from coke production, coke oven

Table 2
ET sector emission scenarios in the decomposition analysis.

Scenario (*sc*)	Description
Constant ET emission intensity of the economy (Const_ET_SO_2/ GDP)	t_1 = t and $t_2 = t_3 = t_4 = t_5$ = 1990, making the activity per GDP ratio and *ief* fixed at 1990 values while GDP grows according to statistics.
Constant emission intensity of energy use (Const_SO_2/PJ)	$t_1 = t_2 = t$ and $t_3 = t_4 = t_5$ = 1990 so that *GDP* and *D* develop according to statistics.
Constant Fuel mix	$t_1 = t_2 = t_3 = t$ and $t_4 = t_5$ = 1990. *GDP, D* and *Fs* develop according to statistics.
Constant ET Emission factor	$t_1 = t_2 = t_3 = t_4 = t$ and t_5 = 1990. *GDP, D, Fs* and *Fm* develop according to statistics.
Reported ET emissions	All factors develop according to statistics.

gas, catalytic cracking and sulphur recovery were too aggregated to allow for any decomposition we kept emissions from these sources identical in the *Const_SO2/PJ, Constant Fuel mix, Constant ET Emission factor*, and *Reported ET emissions* scenarios. The total reported emissions from these sources were 4.3 ktonne SO_2 in 1990 and 0.6 ktonne in 2012.

2.1.2.2. IP sector calculations. The scenario calculations for the IP sector were in most aspects analogous to the calculations for the ET sector. However, instead of estimating impacts of Fuel use changes we estimated the impacts of Increased productivity, which had impact on implied emission factors in the IP sector. Increased productivity includes impacts on emissions of production process improvements and economies of scale. Over the years 1990–2012 the Swedish industry experienced changes in these and industrial productivity increased. To capture the impact of Increased productivity we expanded *ief* in Eq. (2) with a productivity increase factor *eff* (Eq. (7)):

$$e_{sc,IP,t} = \sum_{ss,p} \left(GDP_{t_6} * \left(\frac{a}{GDP} \right)_{ss,p,t_7} * (1 - eff_{ss})^{(t_8 - 1990)} * ief_{ss,p,t_9} \right) \tag{7}$$

where:

ss = IP sub-sector

eff = annual productivity increase (ratio)

For the iron mining industry (iron ores) we had data on both tonne input material and tonne products and calculated *eff* as the annual increase in product/input-ratio per year ($eff = 0.004$, which mean a 0.4% increase in product per input per year). For the other subsectors (smelters, cement, & paper and pulp) of the IP sector we used a literature value of $eff = 0.017$ per year as published by Commonwealth of Australia (2008). The four scenarios calculated for the IP sector are presented in Table 3.

The drivers' impact on decoupling of IP sector SO_2 emissions from economic growth were calculated through:

i) Structural changes in the IP sector:

$$\Delta e(Structural\ changes)_t = e_{Const\,IP\,SO2/GDP,t} - e_{Const\,SO2/tonne,t} \tag{8}$$

ii) Increased productivity:

$$\Delta e(Increased\ productivity)_t = e_{Const\,SO2/tonne,t} - e_{Constant\ IP\ Emission\ factor,t} \tag{9}$$

iii) Emission factor changes in the IP sector:

$$\Delta e(Emission\ factor\ changes)_t = e_{Constant\ IP\ Emission\ factor,t} - e_{Reported\ IP\ emissions,t} \tag{10}$$

Emissions from Other production were kept identical in the scenarios *Const_SO2/tonne* and *Constant IP Emission factor* because only very aggregated data was available for this sub-sector. Emissions from Other production were 10 ktonne SO_2 in 1990 and 3 ktonne in 2012, which is a significant share of the total emissions from the Swedish IP sector. This means that the impacts of Increased productivity and Emission factor changes in the IP sector are somewhat underestimated in the decomposition analysis.

2.2. The causality between SO_2 policy instruments and reduced SO_2 emissions

The decomposition analysis described above results in estimates of how much the change over time in each driver contributes to the decoupling of emissions from economic growth. To estimate the total impact of SO_2 policy instruments on emissions, we also need to find which drivers that are affected by SO_2 policy instruments. This part of the analysis was based on a literature review and complementary mass balance analysis of oil imports (see the Supplementary material). It showed that Emission factor changes in the ET sector is the only driver that is directly (and only) affected by SO_2 policy instruments. SO_2 policy instruments can affect also other drivers in the ET and IP sectors; however, these impacts could not be quantified because the drivers can also be affected by other policies or external events. We therefore considered ET sector Emission factor changes as a lower bound of the impacts of SO_2 policy instruments.

2.3. The impacts of individual SO_2 policy instruments

To answer the second research question we analysed the impact on emissions of individual SO_2 policy instruments by observing the chronological correlations between changes in the emission requirements of the instruments and changes in implied SO_2 emission factors. All SO_2 policy instruments implemented during the period in the ET sector, with the exception of the sulphur tax on emissions from coal combustion, specify requirements on allowed maximum sulphur contents or emission limit values (ELV). The ELV:s restricted sulphur in fuel or allowed for corresponding implied emission factors (IEF) by the use of emission control technology. For coal, the sulphur tax applied to the entire sulphur content of the fuel. The requirements in the IP sector were plant and/or technology-specific. We quantified the requirements as instrument-specific ELV pathways. For the regulated activity and/or sub-sector an individual SO_2 policy instrument causes a change over time in the values of the corresponding ELV pathway. The pathways were then compared to the development of IEF pathways for the same activity and/or sub-sector. We controlled for confounding impacts of SO_2 instruments by excluding situations where several ELV pathways affected one IEF pathway from further analysis.

The sector and activity aggregation level of the ELV and the IEF pathways was determined by the specification of the associated individual SO_2 instrument. If correlations could be established between changes in ELV and IEF pathways we calculated factual and counterfactual 2012 SO_2 emissions for the individual SO_2 policy instrument associated with the IEF pathway. When calculating counterfactual 2012 emissions, the *ief* value was kept constant at the pre-SO_2 instrument implementation value. We considered potential announcement effects (Agnolucci et al., 2009) by varying the year used to select the pre-instrument *ief* value. The difference between the factual and counterfactual 2012 SO_2 emissions was considered as the individual SO_2 policy instruments' lower bound impact on SO_2 emission decoupling.

2.3.1. Data sources

We used data on the Swedish Sulphur law and other regulations (Swedish Environmental Protection Agency, 1997; Regeringskansliet,

Table 3
IP sector emission scenarios in decomposition analysis.

Scenario (*sc*)	Description
Constant IP emission intensity of the economy (Const_IP_SO_2/GDP)	$t_6 = t$ and $t_7 = t_8 = t_9 = 1990$ so that the activity per GDP ratio and *ief* are fixed at $t = 1990$ values while GDP grows according to statistics.
Constant emission intensity of production (Const_SO_2/tonne)	$t_6 = t_7 = t$ and $t_8 = t_9 = 1990$. GDP and activity per GDP grows according to statistics.
Constant IP Emission factor	$t_6 = t_7 = t_8 = t$ and $t_9 = 1990$. GDP and activity per GDP grows according to statistics and annual productivity increases each year.
Reported IP emissions	All factors develop according to statistics and assumed productivity increases.

Table 4
ET sector SO_2 ELV values as mandated by the Sulphur Law, lower ELV for the sulphur tax, and upper range for waterway fee discount for the period 1984–2010. When no sub-sector is specified, the ELV apply to the entire ET-sector.

Year	Sectors and fuels	ELV [ktonne SO_2/ PJ fuel]
1984	stationary all fuels small plants (for plants with emissions <400 ton SO_2/year)	0.3
1984	stationary all fuels large plants (for plants with emissions >400 ton SO_2/year)	0.2
1984	all oils for non-industrial use	0.5
1987	fuel oil class 1 (annual average)	0.09
1988	stationary coal new plants	0.1
1991	*sulphur tax limit (oil)*	0.05
1991	mobile diesel – MK1 (environmental class 1)	0.0005
1991	mobile diesel – MK2 (environmental class 2)	0.002
1991	mobile diesel – MK3 (environmental class 3)	0.09
1993	all oil use	0.4
1993	stationary coal existing small plants	0.2
1993	stationary coal existing large plants	0.1
1993	stationary all fuels small plants	0.2
1993	stationary all fuels large plants	0.1
1994	mobile gasoline MK2 with catalytic equipment	0.005
1994	mobile gasoline MK2 – no catalytic equipment	0.01
1995	stationary fuel oil class 1 & diesel	0.09
1998	mobile gasoline MK1	0.005
1998	environmentally diversified harbour and waterway fees	0.5
2000	marine diesel, marine fuel oil	0.09
2002	*sulphur tax limit (oil)*	0.02
2002	mobile gasoline – MK1	0.002
2002	mobile gasoline – MK2	0.007
2002	mobile diesel – MK1	0.0000
2002	mobile diesel – MK2	0.000
2002	mobile diesel – MK3	0.00
2005	mobile gasoline – MK1	0.0005
2007	marine oil	0.7
2008	diesel fuel oil, fuel oil class 1	0.05
2008	marine diesel fuel oil, and fuel oil	0.05
2008	environmentally diversified harbour and waterway fees	0.2
2009	mobile gasoline – MK2	0.0005
2009	mobile diesel – MK2	0.0005
2009	mobile diesel – MK3	0.0005
2010	marine fuel ELV at berth	0.05
2010	marine fuel	0.5

2015; Rättsnätet, 2015; SPBI, 2015) (Table 4) to obtain ELV pathways. In addition to general regulations we also gathered information about the environmental permit processes and decisions made in concession boards or in environmental courts from Svensson (2003) and Gillberg (2015).

3. Results and analysis

3.1. The total impact of SO_2 policy instruments

3.1.1. Decoupling of emissions from economic growth in the ET sector

For the ET sector the decomposition analysis showed that by 2012 43% of the SO_2 decoupling from 1990 was due to Structural changes, 25% due to Fuel use changes, and 32% due to Emission factor changes (Fig. 2).

Based on Section 2.2, we consider the impact of Emission factor changes (32% (~30.5 ktonne) of the ET sector decoupling) to be a lower bound of the total SO_2 policy instrument impact on SO_2 emissions in the ET sector.

The sensitivity analysis showed that by calculating impacts of Emission factor changes (Eq. (6)) before Fuel use changes (Eq. (5)) the relative importance of Emission factor changes would increase. Instead of causing ~30.5 ktonne of the decoupling, Emission factor changes were associated with at least 45.4 ktonne due to the larger use of sulphur-containing fossil fuels. The sensitivity analysis also showed that the impact on emissions of separately keeping the parameter *Fs* constant was insignificant.

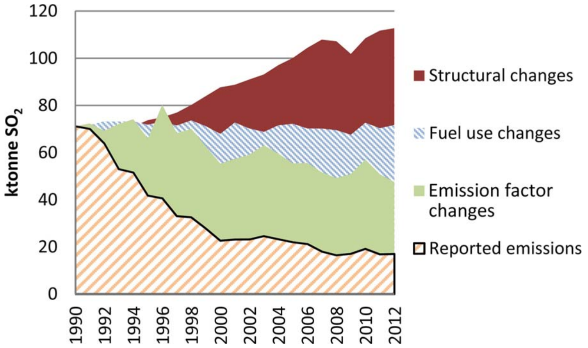

Fig. 2. Factual and counterfactual Swedish ET sector SO_2 emissions 1990–2012. The lower bound impact of SO_2 policy instruments corresponds to Emission factor changes in the figure. The peak in the 1996 and 2010 emissions in the Emission factor changes area is due to a cold winter (inducing increased fuel use) in combination with 1990 implied emission factors.

3.1.2. Decoupling of emissions from economic growth in the IP sector

For the IP sector the decomposition analysis indicated that 45% of the SO_2 decoupling was due to Structural changes, 24% due to Increased productivity, and 31% due to Emission factor changes (Fig. 3).

As presented in Section 2.2, there was a confounding mix of emission reduction drivers in the IP sector so we could not quantify the total SO_2 policy instrument impact on SO_2 emissions from the IP sector based on the decomposition analysis. The analysis of individual policy instruments gave a small contribution to this estimate, however (see next section).

3.2. Estimating the SO_2 instrument with highest impact

For three SO_2 policy instruments, the ELV and IEF pathways correlate well over time and there was no data indicating confounding impacts from other SO_2 instruments, other types of policies, or external events. There was however qualitative indications of confounding for one of the three instruments. In this section we present the results for the three instruments, starting with the highest impact. To simplify the reading we have in this paper harmonized the terminology used in the legal and emission inventory texts.

The SO_2 policy instrument with highest impact on 2012 emissions was the 1996 environmental permit decision to mandate the use of a scrubber by October 1998 in the cement production plant with a large majority of the sub-sectors' SO_2 emissions. In 1998, the average implied emission factor was 2 tonne SO_2/ktonne cement produced (2.3 in

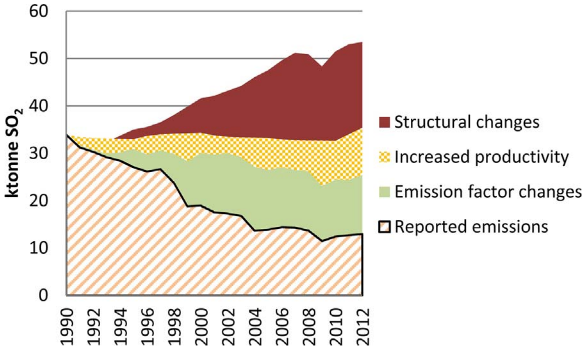

Fig. 3. Factual and counterfactual Swedish IP sector SO_2 emissions 1990–2012. The impact of SO_2 policy could not be estimated on this level of aggregation due to too many confounding factors.

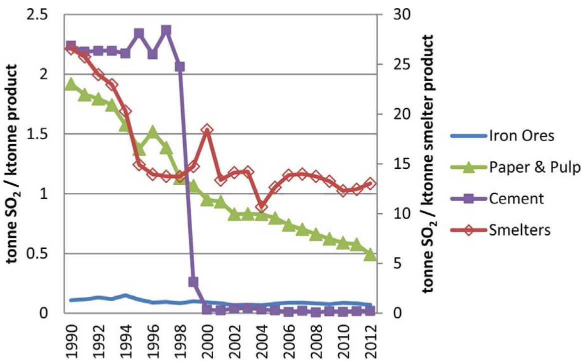

Fig. 4. IEF pathways for cement production in Sweden 1990–2012, including the less distinct IEF pathways for iron ore, paper & pulp and smelters as comparison. The right hand axis shows implied emission factor units for smelters.

1997), and in 2000 it was < 0.1 tonne/ktonne cement product (Fig. 4). This reduction in implied emission factors caused by the environmental permit decision decoupled Swedish SO_2 emissions from economic growth with 5.0–5.8 ktonne SO_2 by 2012 (12.3–14.4% of IP sector decoupling, 3.7–4.3% of total decoupling).

SO_2 emissions from marine oil was over the period controlled by two SO_2 policy instruments, the limitation of sulphur content in marine oils (implemented 2007 and 2010), and the 1998 environmentally differentiated waterway fee. The 2007 and 2010 limitation was estimated to be the only SO_2 policy instrument with impacts on SO_2 emissions from marine oil. The environmentally differentiated waterway fee included a discount on the waterway fee given for ships that used fuels with sulphur content corresponding to emissions below 0.5 ktonne SO_2/PJ 1998–2007 and below 0.25 ktonne SO_2/PJ 2008–2012. However, the sulphur content of marine oil was always higher than the upper limit for the environmentally differentiated waterway fee, implying that the maximum SO_2-related fee was always paid by the ships using marine oil. Hence the differentiated waterway fee failed to have any impact on the IEF marine oil pathway (which is not to say that the instrument didn't have impact on emissions from other fuels). In 2007 the EU and Swedish law limited the sulphur content in all marine oils sold in the EU and Sweden to 1.5% (0.7 ktonne SO_2/PJ fuel) and in 2010 the limit was lowered to 1%. These limitations affected the IEF pathway of marine oil (Fig. 5). The limitation of sulphur content in marine oils resulted in a decoupling of 1.4 ktonne SO_2 by 2012 when compared to 2005 (one year announcement effect). If assuming no announcement effect (using 2006 as pre-ELV year), the decoupling by 2012 would have been 0.9 ktonne.

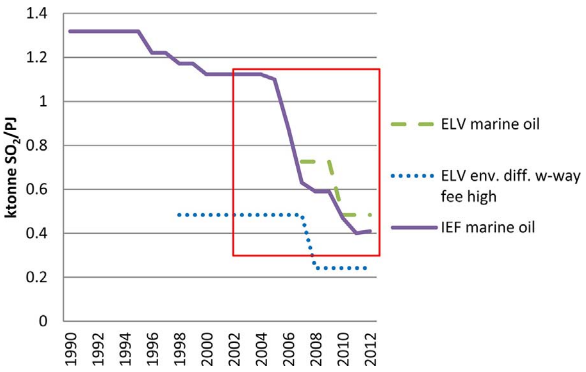

Fig. 5. The IEF pathway for marine oil and corresponding ELV marine oil pathway in Sweden in 1990–2012. The ELV pathway for the environmentally differentiated waterway fees is included for comparison (ELV env. diff. w-way fee high). The box shows a decline in implied emission factors that well corresponds to the 2007 implementation of ELV for marine oils. The IEF for marine oil is always higher than the upper boundary for environmentally differentiated waterway fees, implying maximum fee to be paid and no impact of waterway fees on the sulphur content of marine oil.

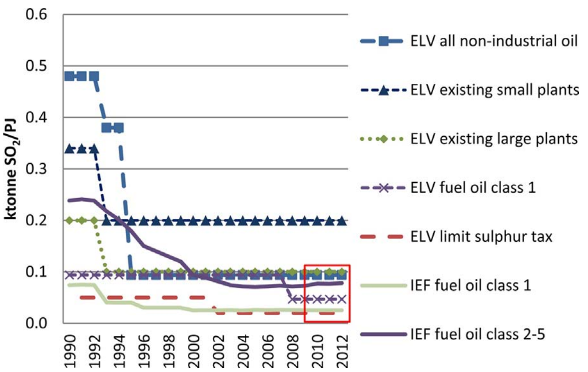

Fig. 6. Implied emission factors for fuel oil class 1 and fuel oil class 2–5 and the ELV pathways representing the control of emissions from stationary oil combustion in Sweden 1990–2012. The IEF for fuel oil class 1 is by 2012 in line with the limit for paying sulphur tax and lower than the ELV for fuel oil class 1. The IEF for fuel oil class 2–5 is lower than the corresponding ELV for oil used in non-industrial activities (ELV all non-industrial oil).

Available emission data suggests that the sulphur tax had an impact on the 2012 emissions from fuel oil class 1 & 2–5 (Fig. 6). By 2012 the implied emission factor for fuel oil class 1 is below the ELV for fuel oil class 1 and in line with the tax limit for all oils, and the implied emission factor for fuel oil class 2–5 is below the ELV for all non-industrial oil and the ELV for existing large plants (box in Fig. 6). However, the impact of the sulphur tax is at risk of being confounded by other simultaneous events and overlapping policies: technology spill over, environmental permits and local initiatives (known to us by personal communication with anonymous experts, but not documented) have contributed to reducing the fuel oil class 1 & 2–5 implied emission factors below the ELV for fuel oil Class 1 and ELV for all non-industrial oils respectively. The total impact on decoupling by 2012 was 0.5 ktonne SO_2 for fuel oil class 1 and 0.4 ktonne for fuel oil class 2–5. How much of this impact that can be allocated to the sulphur tax is unclear. Announcement effects were irrelevant due to the many confounding impacts during earlier years.

4. Discussion and implications

In total, our results show that Swedish SO_2 policy instruments caused at least 26.0–26.7% (35.5–36.3 ktonne) of the total decoupling of SO_2 emissions from economic growth, a number that includes the impacts from ET sector Emission factor changes (30.5 ktonne) and the impact of the scrubber installation in one cement plant in the IP sector (5.0–5.8 ktonne). 29.1–29.6 ktonne of the decoupling caused by SO_2 policy instruments could not be connected to any individual instrument. Causal connections could only be established for one environmental permit decision (the cement plant scrubber) and stricter ELV on marine oils, which together caused at least 4.3–5.3% (5.9–7.2 ktonne) of the total decoupling. If the sulphur tax would be considered solely responsible for the differences between ELV and IEF pathways of fuel oil class 1 & 2–5 use in stationary combustion in 2012, the instrument would have contributed with another 0.6% (0.9 ktonne) of the total decoupling.

Our results from the decomposition analysis are in line with previous studies. Rafaj et al. (2014a) show that dedicated end-of-pipe emission controls (corresponding to our Emission factor changes) were responsible for ~22% of the decoupling of SO_2 emissions from economic growth in Western Europe during 1960–2010. Rafaj et al. (2014b) show that end-of-pipe emission controls were responsible for ~30% of the decoupling of SO_2 emissions from growth in EU-15 countries during 2000–2010.

We could clearly associate the impact of SO_2 policy instruments on Emission factor changes in the ET sector but we could not quantify the impacts of the instruments on Fuel use changes, Increased productivity,

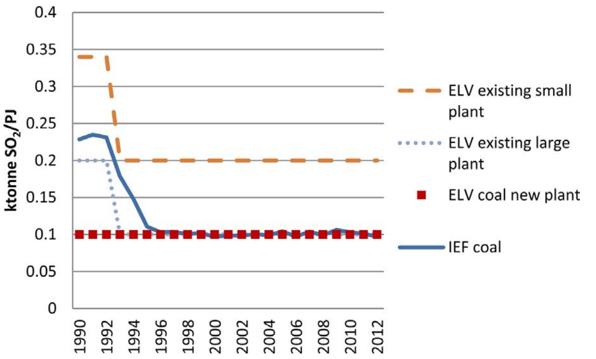

Fig. 7. ELV and IEF pathways for coal 1990–2012. For coal there was no lower sulphur content limit for paying the sulphur tax, so this tax could not be visualised in the figure. In addition to the ELV pathways in the figure, the IEF pathway for coal can during earlier years also have been affected by a tax that was levied on all sulphur in the fuel.

and IP sector Emission factor changes. This limitation was partly due to the lack of scientific consensus on which drivers that are affected by the instruments. To more precisely estimate the total impact of SO_2 policy instruments, we would need more statistical data and further research on the different ways that the instruments lead to emission reductions.

We could only quantify the impact of a few individual SO_2 policy instruments, representing a minor share of total decoupling. For most individual instruments quantification was not feasible, partly because their impacts often overlap in time. The type and level of aggregation of data collected in the emission inventories was another barrier in the analysis. As an example, the IEF pathway from coal use developed from ~ 0.23 ktonne SO_2/PJ in 1990 and levelled off at 0.1 ktonne SO_2/PJ around 1997 (Fig. 7). However, four different SO_2 policy instruments potentially affected this reduction in implied emission factors: an ELV on existing small plants, an ELV on existing large plants, an ELV on new plants (commissioned after 1988), and a sulphur tax. The emission inventory data do not specify any separation between coal used in small and large plants or between old and new plants. Neither is there any estimate of the average age of the plants. So in this example (and several others) the individual impact of each of the instruments could not be estimated while still being consistent with official emission inventories.

Ideally, our type of analysis would benefit from SO_2 emission inventories being expanded to also include data aggregated into emission inventory categories on for example: number, ages, and sizes of fuel combustion plants and industrial facilities; installation years of emission abatement technology; fuel price developments; information on raw material use and production of final products; as well as information on when in time that any given policy was announced. Future analysis would also benefit from a common classification of fuels and sectors in the emission inventories and in the policy and legislative documents. Furthermore, it is necessary to develop methods and collect data to improve the possibility to separate impacts of overlapping policies. However, due to the existence of many real-life confounding factors we presume that it will still be impossible to estimate impacts of all individual SO_2 policy instruments. Furthermore, to extend this analysis to estimate impacts on for example acidification and human health one would first have to use chemical transport models to estimate impacts on emission dispersion. If doing so one would have to consider the fact that some of the instruments' emission impacts are relatively small. It should therefore be anticipated that the modelled impact on emission dispersion, acidification, and human health from most of the instruments might render insignificant results.

Our results have a couple of implications of relevance for SO_2 policy in particular and potentially also for environmental policy in general. First of all, our results illustrate that additional SO_2 policy instruments can be important even in a country that has already sharply reduced SO_2 emissions and simultaneously implements CO_2 policies. This indicates that SO_2 policy instruments should have impacts in countries that started reducing SO_2 emissions later than Sweden and are implementing CO_2 policies. Second, the method used in this paper allowed for a limited impact analysis of SO_2 policy instruments based on emission inventory data. Since standardized emission inventories are mandatory for all partners of the UNECE Air Convention and within the European Union it should be possible to perform similar analyses in other countries and also for other pollutants. Third, to assess the impacts of a greater number of individual SO_2 policy instruments, collection of more detailed data in SO_2 emission inventories and research on how emission drivers are affected by instruments are needed.

Acknowledgements

This work was financially supported by the Swedish Environmental Protection Agency through the research programs CLEO and SCAC, and through contract numberNV-08840-13. The funding sources had no involvement in any part of the analysis or writing of this paper. We would like to thank five anonymous industrial experts for assistance in interpreting the results.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2017.07.014.

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