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A Flexibility Mechanism for Complying with National Emission Ceilings for Air Pollutants

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Executive Summary

The national emission ceilings (NECs) proposed for 2030 by the European Commission in the 2013 Clean Air Policy package have been derived from a cost-effectiveness analysis of potential emission reduction measures, based on today's best available information. However, reality might develop differently from what has been foreseen in 2013, and this could increase or decrease costs for achieving the emission ceilings. Appropriate flexibility mechanisms that allow for higher emissions could potentially avoid excessive increases in emission compliance costs. At the same time, higher emissions will fail to achieve the air quality and health targets of the Clean Air Policy package, unless compensated by additional emission reductions at other locations or of other substances.

This paper introduces a pragmatic pollution compensation scheme that would allow Member States to compensate higher emissions of pollutants (exceeding the specified emission ceilings) by additional reductions of other pollutants (below the respective emission ceilings) in the same country while maintaining the improvements in premature mortality from fine particulate matter of the original NEC proposal.

Similar to the case of CO_2 equivalents in the greenhouse Kyoto mechanism, the five precursor emissions of fine particulate matter, i.e., primary PM2.5, SO_2, NO_x, NH_3 and VOC, can be converted into 'PM-equivalent' emission quantities, using the following weighting factors k_x:

Pollutant	Weight k_x
PM2.5	1.0
SO_2	0.298
NO_x	0.067
NH_3	0.194
VOC	0.009

For establishing compliance with the emission ceilings directive, the sum PM_{eq} of the actual emissions E_x, each weighted with the respective factor k_x, must then remain below the weighted sum $\overline{PM_{eq}}$ of the original emission ceilings $\overline{E_x}$ for pollutant *x:*

$$PM_{eq} = \sum_x E_x . k_x \leq \overline{PM_{eq}} = \sum_x \overline{E_x} . k_x \qquad \text{Equation 1}$$

To limit potential deviations from the health and environmental targets of the Clean Air Policy package that could result from the simplifications adopted for this system (e.g., uniform factors for all Member States), exceedances of individual emission ceilings should be limited. For instance, restricting the sum of exceedances of all NECs below 10 percentage points would keep deviations from the health targets for PM and ozone typically well below 1%, which is within the range caused by other model and data uncertainties. However, for other ecosystems effects like eutrophication and acidification the deviations from the original objectives set by the NECD the application of flexibility may be larger. For instance, an excess of the NH_3 ceiling by 6% and the SO_2 ceiling by 4% could be compensated by additional reductions of PM2.5, NO_x and/or VOC using the corresponding factors, which do not affect eutrophication. In the worst case, this could cause an up to 9% increase in excess nitrogen deposition.

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1 Background and introduction

On 18 December 2013, the European Commission adopted a clean air policy package with the principal aim to provide better protection of the health of European citizens against excessive pollution **(**EC 2013**)**. Inter alia, the package contains a proposal for a Directive on the reduction of national emissions of certain atmospheric pollutants and amending Directive 2003/35/EC ("new NEC"). The proposal contains quantitative national emission ceilings for six substances (SO_2, NO_X, PM2.5, NH_3, VOC and CH_4) that should be met by Member States in 2030.

The proposal of these quantitative emission reduction requirements was informed by an assessment of the cost-effectiveness of potential emission reduction measures, based on today's best available information, especially on historic emission inventories, projections of future energy use and agricultural activities, and application potentials and costs of further emission reduction measures in 2030 (Amann et al. 2014). However, all these factors are associated with uncertainties. While, in principle, some of them could be reduced through further work, others are intrinsically irreducible, especially those that relate to future development (e.g., economic development, energy prices, etc.). Reality might develop differently from what has been foreseen in 2013, and this could increase or decrease costs for achieving the proposed emission ceilings. Thus, the emission reductions could potentially turn out as less cost-effective than anticipated, although compliance with the ceilings would achieve the envisaged air quality improvements.

Appropriate flexibility mechanisms that allow for higher emissions could potentially avoid excessive increases in emission compliance costs. However, higher emissions will fail to achieve the air quality and health targets of the clean air package, unless compensated by additional emission reductions at other locations or of other substances. Depending on the marginal costs for reducing emissions of different source, this might result in overall cost savings.

Emission trading in which Member States could trade emission reductions with each other could potentially provide such compensation while reducing costs. This is successfully implemented for greenhouse gases in current climate regimes. However, in contrast to long-lived greenhouse gases, for which the location of emission reductions does not affect their impact on global climate, marginal damage from air pollutants is highly site-specific, depending inter alia on meteorology, population densities, sensitivities of ecosystems, etc. It has been shown that, if given targets on air quality improvements are to be met, there is only little scope for emission trading across countries (Roemer et al. 2006). Other studies explored, for the multi-pollutant/multi-effect setting of the current air quality proposal, to what extent less reductions of emissions of one pollutant could be compensated by additional cuts of another substance within the same country (Wagner et al. 2013). A mechanism for securing the original improvements in human health from fine particulate matter and ozone as well as for ecosystems from eutrophication and acidification was proposed. However, this would require rather complex rules that seem impractical to implement and to monitor[1].

This paper examines the prospects for a simplified compensation scheme which could provide flexibility while minimizing adverse consequences for the objectives as far as practicable. It presents a simple pollution compensation scheme that would allow Member States to compensate higher emissions of one pollutant (exceeding the specified emission ceiling) by additional reductions of

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[1] Rules need to include multiple, country-specific, cross-exchange rates for the different pollutants, as well as a large set of additional conditions that have to be met for a successful trade.

another pollutant (below the respective emission ceiling) while maintaining the improvements in premature mortality from fine particulate matter of the original new NEC proposal.

Section 2 of this paper introduces a simple mechanism for compensating excess of an emission ceiling by additional reductions of another pollutant in the same country, and discusses the deviations introduced by the various simplifications of the exchange mechanism. Section 3 introduces an extension that allows compensation of excess of more than one emission ceilings. Conclusions are discussed in Section 4.

2 A simple compensation scheme allowing excess of one pollutant

This paper explores a simple pollution compensation scheme that is tailored to the rationale employed for the recent Clean Air Policy package. The main concept is that a Member State would be allowed to exceed its emission ceiling for pollutant x within a certain margin a_x if it overachieves ('undershoots') the ceiling of another pollutant y by an amount b_y. Through a pollutant-specific exchange rate k_{xy}, the compensating amount $b_y = k_{xy} * a_x$ is determined in such a way that premature mortality from PM in the EU remains unaffected.

2.1 Exchange rates

Following the rationale for the chosen air quality targets, for each Member State exchange rates between the precursor emissions of PM2.5 (i.e., primary PM2.5, SO_2, NO_x, NH_3 and VOC) can be elaborated that lead to equal improvements in premature mortality from fine particulate matter at the European (EU) scale (see Annex 1).

For the five pollutants that affect ambient PM2.5 (i.e., primary PM2.5, SO_2, NO_x, NH_3, VOC), there exist 20 possible compensation options. Exchange rates for the two compensation directions are inverse, which leads to 10 unique exchange rates (Table 2.1). These exchange rates k_{xy} specify for each Member State by how much an excess of an emission ceiling of pollutant x by one unit (e.g., ton) needs to be compensated by additional emission reductions of pollutant y, so that the same overall improvement in premature mortality is achieved.

Table 2.1: Possible pairs of emission compensations (k_{xy} ... exchange rates)

1 ton of excess emissions of pollutant *x*	needs to be compensated by additional reductions of k_{xy} tons of pollutant *y*				
	PM2.5	SO_2	NO_x	NH_3	VOC
PM2.5 (P)	-	$k_{PS} = 1/k_{SP}$	$k_{PN} = 1/k_{NP}$	$k_{PA} = 1/k_{AP}$	$k_{PV} = 1/k_{VP}$
SO_2 (S)	k_{SP}	-	$k_{SN} = 1/k_{NS}$	$k_{SA} = 1/k_{AS}$	$k_{SV} = 1/k_{VS}$
NO_x (N)	k_{NP}	k_{NS}	-	$k_{NA} = 1/ k_{AN}$	$k_{NV} = 1/k_{VN}$
NH_3 (A)	k_{AP}	k_{AS}	k_{AN}	-	$k_{AV} = 1/k_{VA}$
VOC (V)	k_{VP}	k_{VS}	k_{VN}	k_{VA}	-

2.2 Establishing compliance with emission ceilings

For establishing compliance with a national emission ceiling, a country that exceeds the ceiling of pollutant x by a_x tons would need to demonstrate that their emissions of pollutant y are $b_y = a_x * k_{xy}$ tons below the ceiling.

2.3 Simplifying assumptions

With properly calculated exchange rates (see Annex 1) any compensation will achieve the same improvement in overall premature mortality of the EU population that is aimed for with the proposed national emission ceilings. However, as compensations will alter national emissions of the various pollutants, and thereby lead to slight deviations from the originally implied local health and environmental impacts. While these differences might be acceptable, especially in view of the simplicity of the resulting rule set, they should not be ignored when deciding about an appropriate margin for adjustments of emission ceilings.

As atmospheric lifetimes and transport distances of the involved pollutants differ, there might be implications on the spatial pattern of health improvements, with potential (positive or negative) impacts on neighboring countries that are not involved in the compensation.

Similarly, while all five pollutants act as precursor emissions of PM2.5, not all of them affect the other air quality endpoints that are addressed in the Clean Air Policy package, such as ground-level ozone, eutrophication and acidification. Thus a compensation, while neutral for overall premature mortality in the EU, might alter the co-benefits on other effects that would be achieved by the original emission ceilings.

An earlier analysis (Wagner et al. 2013) established concise constraints for compensations that would avoid negative side-effects on neighboring countries and on other air quality impacts. However, safeguarding these aspects requires a rather complex rule set that seems impractical to implement in a legal framework.

In principle, exchange rates k_{xy} are country-specific, reflecting regional differences in meteorology and population densities. Thus, an exact system would need to establish for each Member State 20 exchange rates, resulting in 560 figures for the 28 Member States. However, with a few exceptions for remotely located Member States (e.g., Cyprus, Malta), conditions are reasonably similar for across Member States. With a view to obtain a simple rule set, as a first approximation the analysis is carried out using the median exchange rates as a uniform set for all countries.

Aiming at a practical compensation system, this paper follows a pragmatic approach. It quantifies deviations from the originally envisaged air quality improvements caused by the simplifications as a function of the excess of an emission ceiling. This could provide useful information for decisions about limits on allowed compensation quantities that would avoid unacceptable dilution of the health and environmental targets established in the Clean Air Policy package.

2.4 Exchange rates for the TSAP analysis

In the compensation scheme presented above, exchange rates quantify the relative impacts of two pollutants in a given country on premature mortality from exposure to PM2.5. Thus, exchange rates consider differences between pollutants and countries in chemical transformation processes (e.g., formation of secondary aerosols), transport patterns in the atmosphere (due to emission heights and meteorological conditions) as well as their impact on population exposure (e.g., population densities). All these factors are quantified in the GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model (Amann et al. 2011) developed by the International Institute for Applied Systems Analysis (IIASA). The emission ceilings proposed in the Clean Air Policy package have been derived from a cost-effectiveness analysis with the GAINS model.

Following the methodology described in Annex 1, exchange rates have been computed for the 28 Member States. For reasons described above, the median exchange rates have been adopted as a common set for the further analysis (Table 2.2).

Table 2.2: Exchange rates derived for the TSAP cost effectiveness analysis

1 ton of excess emissions of pollutant x	needs to be compensated by additional reductions of k_{xy} tons of pollutant y				
	PM2.5	SO_2	NO_x	NH_3	VOC
PM2.5		3.356	14.925	5.155	111.111
SO_2	0.298		5.814	1.319	23.256
NO_x	0.067	0.172		0.254	5.848
NH_3	0.194	0.758	3.939		19.608
VOC	0.009	0.043	0.171	0.051	

These figures are computed from the GAINS model database, which has been used to identify the cost-optimal set of emission ceilings that is proposed by the Clean Air Policy package (Amann et al. 2014). Thus, the analysis in this paper is fully coherent with the final policy scenario.

The figures attribute largest relative weight to primary PM2.5 emissions compared to the other pollutants. On average, 1 ton of primary PM2.5 emissions cause the same premature mortality as 3.36 tons of SO_2, or 14.9 tons of NO_x, or 5.15 tons of NH_3, or 111 tons of VOC.

The high potency of primary particulate matter on premature mortality (per ton of emissions) is related to two factors: First, in the EU-28 primary PM2.5 emissions in terms of total mass were significantly lower than those of the other substances, although their contribution to PM2.5 in ambient air was of comparable magnitude. For instance, in 2005 SO_2 emissions were more than five times higher than those of PM2.5, and emissions of NO_x or VOC more than seven times. Furthermore, the majority of primary PM2.5 emissions emerges from low-level sources (domestic heating and transport) that have a much larger intake fraction for humans, so that they result in higher population exposure than the precursor emissions of secondary aerosols (e.g., SO_2, NO_x), which originate more from high-level sources.

The comparably low weight of VOC versus PM reflects the minor contribution of secondary organic aerosols, which is formed from VOC emissions, to total PM2.5 in ambient air. However, as VOC is important for meeting ozone targets, the low weight illustrates one potential short-comings of the simplified system that is primarily geared towards PM2.5 impacts. This is further discussed in Section 3.

To allow meaningful compensations, it is important that national emission inventories and emission ceilings are expressed and reported to at least three (better four) significant digits (of kilotons). The analysis in this paper employs emission estimates produced by GAINS with full precision (> eight digits). Emission ceilings are computed from the full precision base year inventory figure by applying the emission reduction requirement of the proposed NEC directive as integer percentage figures. Numerical precision is relevant for determining the compensation quantities, especially for small countries, for which emissions are often single digit integer numbers, in order to avoid potential artifacts introduced by rounding errors.

2.5 Deviations introduced by the simplifications

As explained above, a number of pragmatic simplifications have been adopted in the interest of a simple rule set for compensating emissions. Inevitably, such simplifications could lead to positive or negative deviations from the health and environmental impacts of the original set of emission ceilings. It has been shown before that a rigorous, possibly spatially explicit constraint on the original impacts would require a much more complex rule set.

To facilitate discussion of the pros and cons of such a simplified approach, this paper quantifies the deviations introduced by these simplifications as a function of the deviation from the emission ceiling. This could inform a policy decision about margins for compensation that would avoid significant and thus unacceptable dilutions of the environmental ambition level that has been agreed upon in the Clean Air Policy package.

2.5.1 EU-wide uniform exchange rates

Owing to differences in meteorology, atmospheric chemistry, topographic situations and population distributions, exchange rates vary greatly over the 28 EU Member States (see Annex 2). Extreme values occur for Member States with large spatial gradients in population densities between the emission centers and the surrounding areas (e.g., Cyprus, Malta, Finland, etc.). In these cases, formation of secondary aerosols from SO_2, NO_x, NH_3 and VOC emissions (which takes some time) occurs mainly in unpopulated areas (e.g., over the Sea), so that these precursor emissions cause much less health damage compared to emissions of primary PM2.5, which has immediate effects on population.

Such differences must be taken into account if the original health impacts were to be precisely maintained after a compensation. This would require for each Member State 20 specific exchange rates, resulting in 560 figures for the 28 Member States (with compensations prohibited for zero or infinite values of the exchange rates).

As a pragmatic simplification, this paper examines the use of the median exchange rate emerging for the 28 countries to be uniformly applied to all Member States. Thereby, instead of 560 exchange rates, a rule set specifies 20 rates (e.g., those presented in Table 2.2) that apply to all countries.

Obviously, the use of median exchange rates leads to deviation from the original health improvements for the EU-28. However, as shown in Figure 2.1, assuming a limit on emission increases of 10% of the national emission ceiling, differences from individual trades remain, in the worst case, below 0.11% of total health impacts. For 97% of the compensation options, increases in total European health effects remain below 0.05%. These differences scale with the assumed limit on the excess of the emission ceiling, i.e., they would be half for a 5% emission increase, and double for a 20% increase. Furthermore, there is no statistical bias in the differences, as the number of deteriorations equals the number of improvements for the 560 compensation options in the EU-28. In the worst but extremely unlikely case, i.e., if all countries applied the compensation that results in the largest deterioration, total health impacts in the EU-28 would increase by 0.76%.

In the context of other uncertainties in the modelling of atmospheric dispersion and health impacts, the deviations from a 10% increase in emissions do not appear as significant.

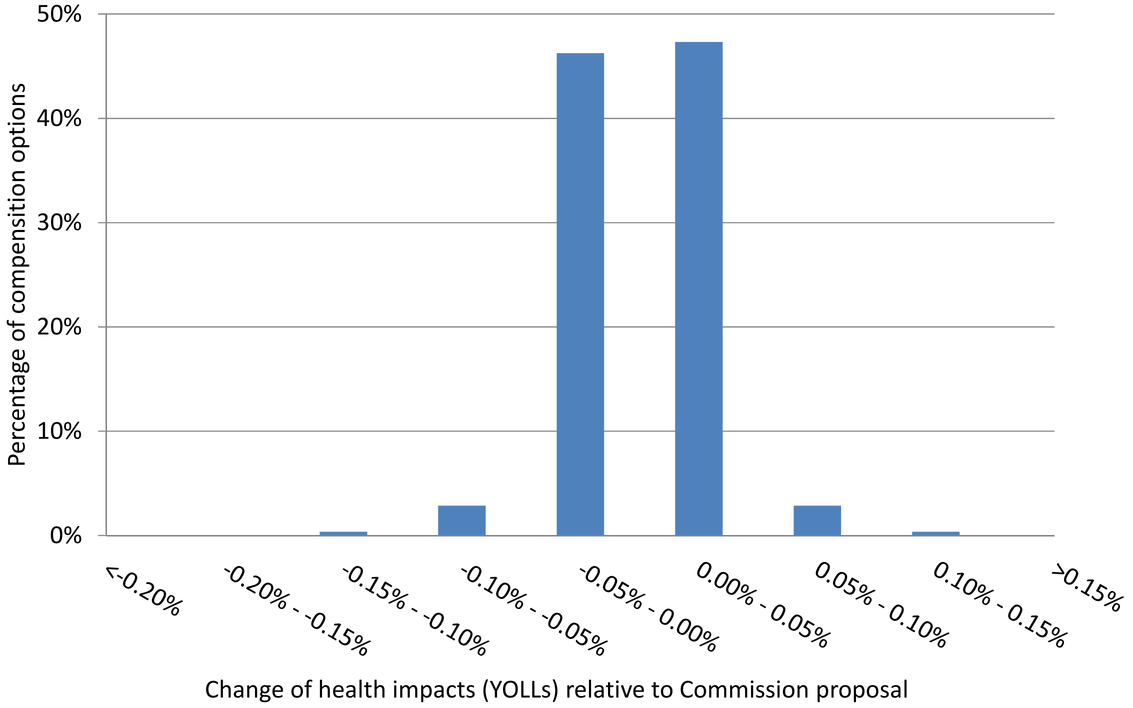

Figure 2.1: Differences in total health impacts (years of life lost) in the EU-28 from using a uniform set of exchange rates (median rates) for all Member States, compared to health impacts resulting from the Commission proposal

2.5.2 Changes in the spatial pattern of health improvements

As an important feature, the rule set presented in this paper refers to the health target set for the cost-effectiveness analysis in the Commission impact assessment, i.e., for 2030 an overall reduction of the number of lost life years in the EU by 52% compared to 2005 (or, in an alternative but equivalent formulation, a 67% gap closure between the current legislation (CLE) and maximum technically feasible reduction (MTFR) cases in 2030). In the policy discussions on the proposed set of emission ceilings the focus has been on achieving the overall EU wide target, rather than preserving the particular pattern of impact reduction Member State by Member State.

Following this logic, the compensation mechanism discussed in this paper maintains the target at the EU-level (with the simplification of median exchange rates as discussed above), while accepting possible re-arrangements of health improvements among Member States.

Although, per design, all pollution compensations will occur within the same country, the spatial consequences on health impacts could potentially differ. Slightly different transport characteristics of primary and secondary formed aerosols could shift the spatial impacts on ambient PM2.5 concentrations away from or closer to the country, depending on which pollutants are involved. While a compensating country could balance potentially higher health impacts against resulting savings in emission control costs, down-wind countries do not reap potential economic savings from the flexibility mechanism and could potentially suffer from compensations in third-party countries.

The magnitudes of the impacts of a 10% violation of an emission ceiling on health impacts in the same country as well as in down-wind countries are shown in Figure 2.2.

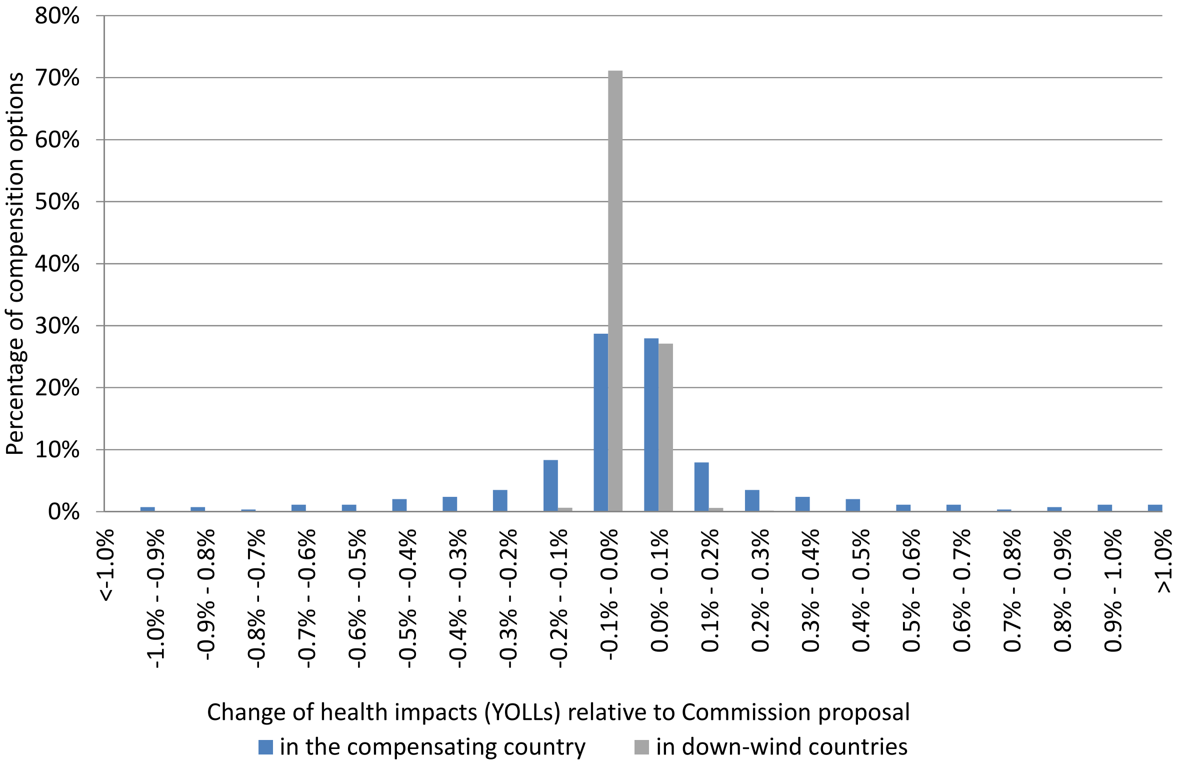

Figure 2.2: Frequency distributions of the differences in PM health impacts from all possible compensation options to compensate a 10% increase of one pollutant. a) Health impact within the compensating country, b) health impacts in down-wind countries. Negative numbers indicate lower health impacts than in the original proposal.

For all possible options for compensating a 10% violation of an emission ceiling, differences in health impacts remain below ±1.8% within the compensating country, and below ±0.7% in down-wind countries. In 95% of the possible options, the deterioration in health impacts is below 0.6% in the compensating country, and below 0.08% in downwind countries. In down-wind countries the distribution is biased, with 72% of the possible options resulting in additional health benefits compared to the original situation. While the modified emission patterns lead to better health protection in these countries, overall emission control costs would be higher than in the original proposal if the same cost data for measures were used.

2.5.3 Implications on other air pollution effects

Following the rationale for the emission ceilings proposed by the European Commission, the exchange rates in this paper are derived with a sole focus on PM health impacts. As such, they do not consider other health and vegetation impacts from reduced ground-level ozone, eutrophication and acidification.

The following sections explore the magnitude and significance of the side-effects of possible compensations on these impacts.

Ground-level ozone

Ground-level ozone is formed from pre-cursor emissions of NO_x and VOC, while the other pollutants considered in the compensation scheme (i.e., SO_2, NH_3 and primary PM2.5) do not affect ozone levels. As such, compensations will lead to additional health and vegetation benefits from lower ozone, if NO_x or VOC would be reduced in order to compensate for an excess of one of the other three substances. However, ozone will increase if an excess of a NO_x or VOC ceiling is compensated by additional SO_2, NH_3 or PM2.5 reductions.

For the worst cases, i.e., if a 10% increase in NO_x or VOC is not compensated by another ozone precursor substance, the resulting differences in premature mortality are presented in Figure 2.3. As in the Commission impact assessment, the number of premature deaths from ozone in the EU-28 is chosen as the metric for measuring ozone health impacts.

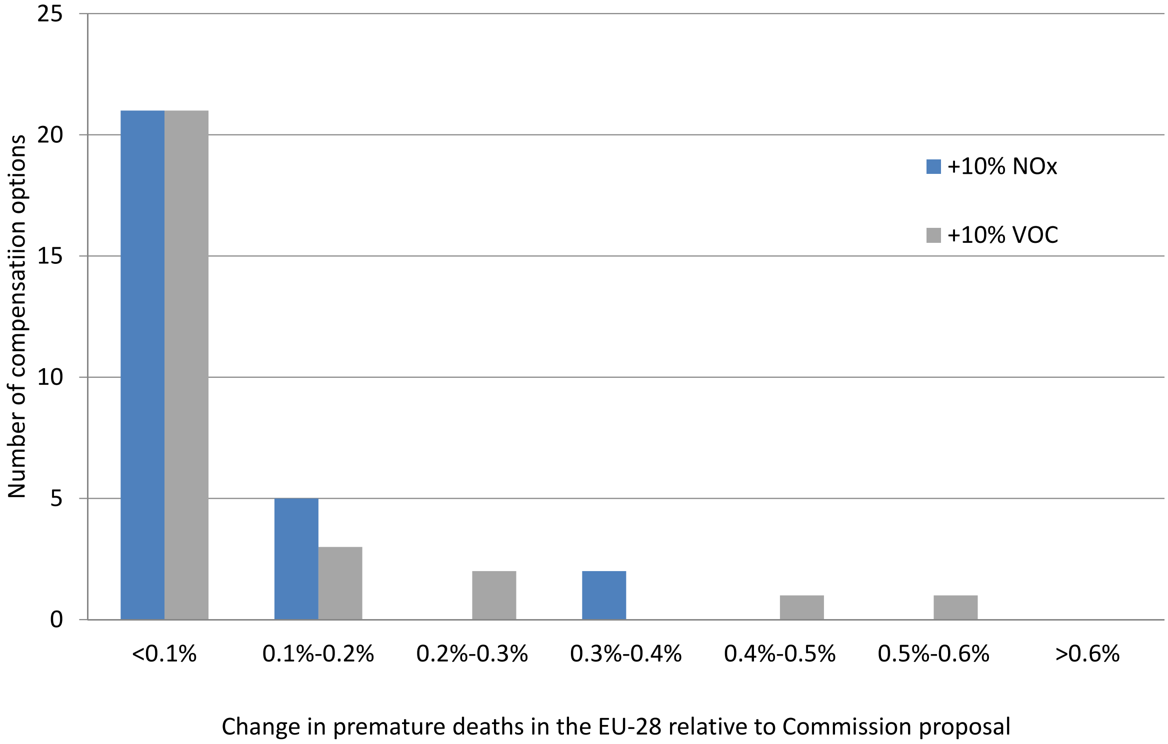

Figure 2.3: Frequency distributions of the differences in EU-wide ozone health impacts for compensating a) a 10% increase in NO_x emissions by PM, SO_2 or NH_3 reductions, b) a 10% increase in VOC emissions by PM, SO_2 or NH_3 reductions

In the worst case, for a 10% violation of the VOC emission ceiling the number of premature deaths in the EU-28 from a single compensation could increase by 0.56%, and for a 10% violation of a NO_x ceiling by 0.35%. If all countries opted for these most unfavorable compensations, premature deaths from ozone in the EU-28 would increase by 2% for NO_x and by 2.3% for VOC. Obviously, these are extreme cases, and more likely combinations in which not all countries will apply the same compensation will result in significantly lower numbers. Especially, as mentioned above, there are many cases conceivable where ozone precursor emissions would be reduced in order to compensate for higher PM, SO_2 or NH_3 emissions.

Eutrophication

Eutrophication, i.e., excess nitrogen deposition, is another air pollution effect to which not all of the pollutants of the compensation scheme contribute. Thus, if an excess of NO_x or NH_3 ceilings would be compensated by additional PM2.5, SO_2 or VOC reductions, eutrophication will increase.

Figure 2.4 explores the eutrophication impacts of a 10% excess of NO_x and NH_3 ceilings, if they are not compensated by the other eutrophication precursors. For the proposed set of emission ceilings, increases in NH_3 emissions will have significantly larger impacts than increases in NO_x. Compensation of NH_3 in one country could increase excess nitrogen deposition (i.e, nitrogen deposition exceeding the critical loads for eutrophication) in the EU-28 by up to 1%, compared to 0.22% as the largest rise resulting from a 10% increase in NO_x. In the unlikely case where all 28 Member States would increase their NH_3 emissions by 10% above the ceilings without compensating by additional NO_x reductions, excess nitrogen deposition in the EU-28 would increase by 9%, compared to 1.5% for a 10% increase in NO_x emissions.

Whether a 9% increase in excess nitrogen deposition is deemed acceptable remains a political choice. Negative side effects could be reduced by a lower margin within compensation of NH_3 emissions would be allowed.

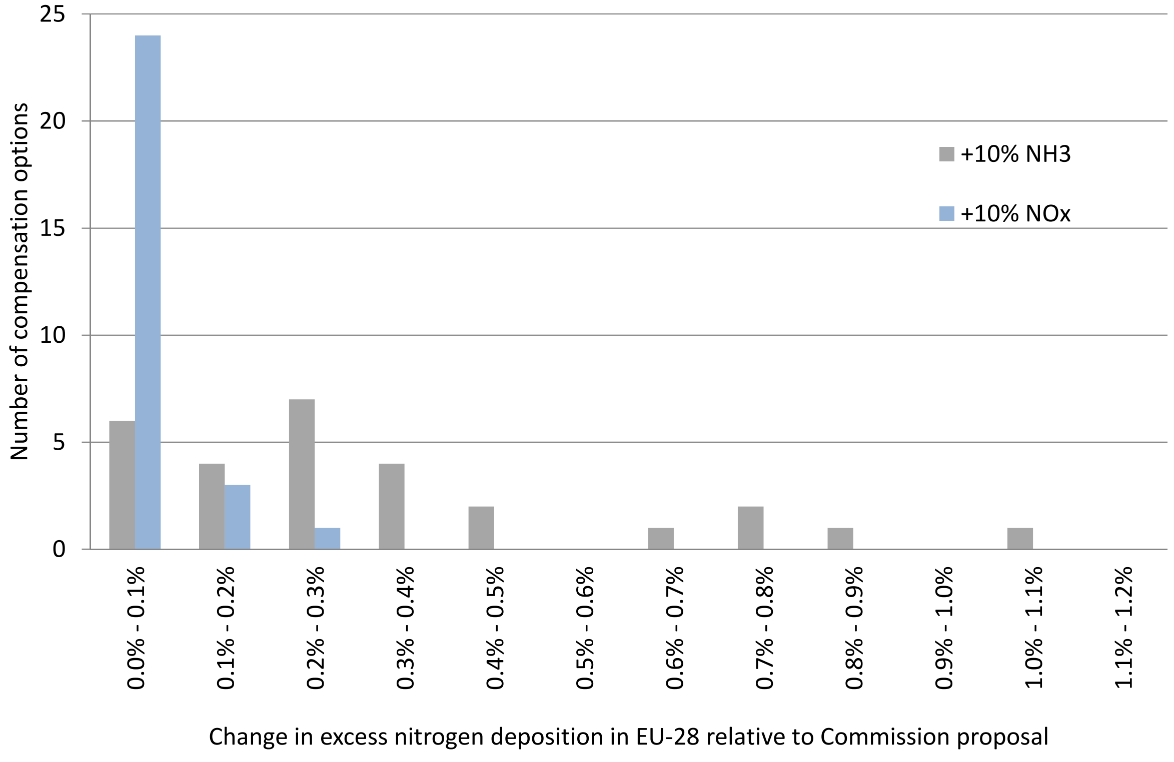

Figure 2.4: Frequency distributions of the differences in EU-wide excess nitrogen deposition for compensating a) a 10% increase in NO_x emissions by PM, SO_2 or VOC reductions, b) a 10% increase in NH_3 emissions by PM, SO_2 or VOC reductions

Acidification

In a similar vein, acidification will suffer if additional PM or VOC reductions will be used for compensating higher acidification precursor emissions of SO_2, NO_x and NH_3. Again, increases in NH_3 emissions will have the largest impacts, unless compensated by additional reductions in SO_2 or NO_x. In the worst case, EU-wide acidifying deposition in excess of the critical loads for acidification could increase by 3.4% (for a 10% increase of NH_3 emissions in the Netherlands), and by 11.3% if all Members States would act in the same way (Figure 2.5). An EU-wide increase of SO_2 by 10% would increase excess deposition by 2.2%, and of NO_x by 1.4%.

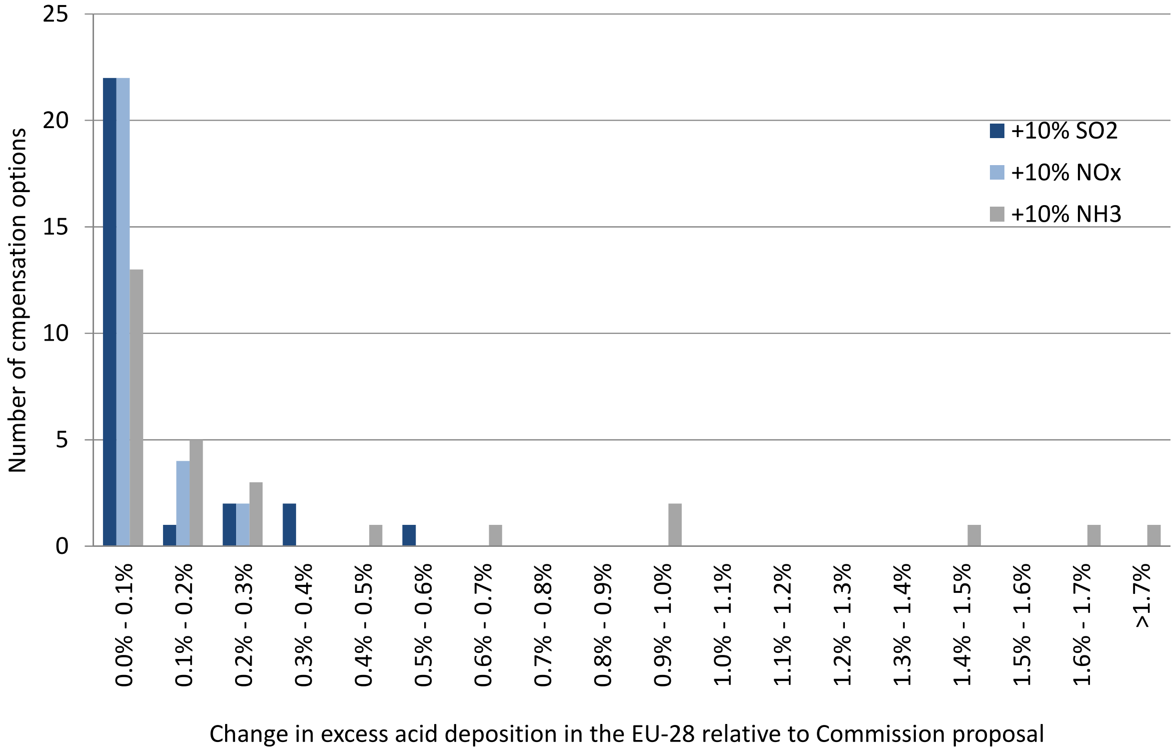

Figure 2.5: Frequency distributions of the differences in EU-wide acid deposition in excess of critical loads for compensating a 10% increase in SO_2, NO_x or NH_3 emissions by additional PM or VOC reductions

3 Compensations involving multiple pollutants

The analysis presented above explores the scope for compensating excess of an emission ceiling of one pollutant by additional reductions of another pollutant. However, flexibility could be enhanced by allowing multiple pollutants to be involved in the compensation.

Without changing the rationale and assumptions of the preceding analysis, the compensation rules could convert emissions of all pollutants into one ‘air pollution equivalent’, e.g., a PM equivalent (similar to a CO_2 equivalent in the Kyoto greenhouse gas mechanisms).

The PM equivalent of a non-PM precursor *x* can be computed with a PM equivalent weight k_x, which reflects the respective PM exchange rate k_{xy} (i.e., k_{SP}, k_{NP}, k_{AP}, k_{VP}) in Table 2.2.

For establishing compliance with the emission ceilings directive, the sum PM_{eq} of the actual emissions E_x, each weighted with the respective factor k_x, must then remain below the weighted sum of the original emission ceilings $\overline{PM_{eq}}$:

$$PM_{eq} = \sum_x E_x.k_x \leq \overline{PM_{eq}} = \sum_x \overline{E_x}.k_x \qquad \text{Equation 1}$$

For the TSAP analysis, the following ‘PM equivalent’ factors k_x emerge from Table 3.1:

Table 3.1: PM equivalent factors for the TSAP analysis

Pollutant	Weight k_x
PM2.5	1.0
SO_2	0.298
NO_x	0.067
NH_3	0.194
VOC	0.009

3.1 Limiting the deviations resulting from the simplifications

This formulation would allow for all pollutants deviations from the specified emission ceilings, as long as the total PM_{eq} quantity is maintained. Although this might increase economic efficiency, it should be noted that resulting deviations from the original health and environmental targets are, roughly speaking, additive for each trade. Allowing mission ceilings , e.g., of three pollutants, to be exceeded by 10% each and substituted by corresponding additional reductions of the two other pollutants, this might result in three times larger differences in health and environmental effects than from a 10% excess of a single emission ceiling. Obviously, such negative environmental consequences could be restricted by lower margins for exceedances.

A pragmatic multi-pollutant system could restrict the sum of the exceedances of emission ceilings of all pollutants (e.g., in percentage points) to a certain limit. For instance, keeping the sum of exceedances below 10 percentage points would keep the differences from the original health and environmental impacts within the margins that have been discussed above in Section xx. Such a system would allow, e.g., an excess of the NH_3 ceiling by 6% and the SO_2 ceiling by 4%, to be compensated by additional reductions of PM2.5, NO_x and/or VOC using the corresponding factors. Thus, in addition to Equation 1, the condition of Equation 2 would need to be fulfilled in each country:

$$\sum_x \left(1 - \frac{E_x}{\overline{E_x}}\right) < m \qquad \text{Equation 2}$$

with E_x denoting emissions of exceeding pollutant x, $\overline{E_x}$ the emission ceiling (the expression being calculated only for those pollutant exceeding the ceilings) and m the total limit to the deviations (in percent).

3.2 Other considerations

The comparably low PM equivalent factors of non-PM emissions in Table 3.1 highlight the potent role of primary PM2.5 for health effects (on a mass basis), and allow compensation of relatively large volumes of exceedances of non-PM emissions by comparably small amounts of additional reductions of PM2.5. While this is plausible reflecting the relative ratios of the mass of emissions as well as the larger intake fraction of low-level emissions of PM, the potentially small improvements in PM appear as problematic given (a) the current uncertainties in PM inventories, and (b) potential rounding errors if reporting and compensation is done on a kiloton basis. Potentially, these issues could be addressed by two mechanisms:

a) applying an off-set to compensation that accounts for uncertainties by introducing a bias towards larger health improvements. In such a case, a compensation requires, e.g., 50% larger emission reductions than would result from the exchange rates in Table 2.2, which reduces the chances that a compensation would compromise the health targets of the Clean Air Policy package,

b) a requirement that calculations are done with full precision, and rounding performed only at the last step.

3.3 Formulation of rules for compensations

For a multi-pollutant compensation schemes, rules could then be expressed as follows:

> *A Member State is allowed to exceed national emissions ceilings of pollutants, provided that:*

1. *The accumulated exceedances of the emission ceilings of the five pollutants (in percentage points relative to the emission ceiling) remains below, e.g., ten percent; and*
2. *the excess of emission ceilings (in tons) is compensated by additional reductions of other pollutants below the respective emission ceilings using the exchange rates in Table 3.2.*

Table 3.2: Exchange rates

1 ton of excess emissions of pollutant $_x$	needs to be compensated by additional reductions of k_{xy} tons of pollutant y				
	PM2.5	SO_2	NO_x	NH_3	VOC
PM2.5		3.356	14.925	5.155	111.111
SO_2	0.298		5.814	1.319	23.256
NO_x	0.067	0.172		0.254	5.848
NH_3	0.194	0.758	3.939		19.608
VOC	0.009	0.043	0.171	0.051	

An alternative formulation could use the 'PM equivalent' concept:

> *A Member State is allowed to exceed national emissions ceilings of pollutants, provided that :*

1. *The accumulated exceedances of the emission ceilings of the five pollutants (in percentage points relative to the emission ceiling) remains below, e.g., ten percent; and*
2. *the sum of the emissions of the five pollutants, each weighted by the respective PM equivalent factors, remains below the sum of the five NECs, weighted by the same PM equivalent factors given in Table 3.3).*

Table 3.3: PM equivalent factors

Pollutant	Weight k_x
PM2.5	1.0
SO_2	0.298
NO_x	0.067
NH_3	0.194
VOC	0.009

4 Conclusions

Appropriate flexibility mechanisms that allow for (limited) excess of a national emission ceiling could potentially avoid excessive increases in emission compliance costs, if future will develop differently from today's expectations. However, higher emissions will fail to achieve the air quality and health targets of the Clean Air Policy package, unless compensated by additional emission reductions at other locations or of other substances.

This paper analyzes a pragmatic scheme that would allow a Member State to exceed the emission ceiling of one pollutant and compensate it by additional reductions of another substance below the respective emission ceiling (within the same country). To maintain the environmental ambition level that has been established by the European Commission in its Clean Air Policy package, exchange rates define the required amount of substituting emissions so that the originally established target for premature mortality from fine particles in the EU-28 will remain unaffected.

Earlier analysis has shown that maintaining the exact level and spatial pattern of the multiple air quality benefits on human health and vegetation would require a complex rule set, with 560 country- and pollutant specific exchange rates for 28 Member States and a large set of additional constraints and conditions. Such complexities are impractical for policy applications, where rules for compensation need to be laid down in sufficiently simple legal text.

This paper discusses a system with a number of pragmatic simplifications that would maintain compliance with the original spirit and ambition level of the environmental targets of the Clean Air Policy package, while requiring only a minimum set of rules. In particular, the paper develops a set of 20 exchange rates between pollutants that could be universally applied to all Member States. With such exchange rates, compensations would, on average, maintain the improvements in premature mortality from fine particulate matter, and not increase it by more than 0.76% in the worst but rather unlikely case if all countries exceeded their most health-relevant ceiling by 10%.

Employing the same models, data and assumptions that have been used for the final policy scenario (Amann et al. 2014) of the Clean Air Policy package, excess of the emission ceiling of primary PM2.5 by one ton could be compensated by additional emission reductions SO_2 by 3.36 tons, or of NO_x by 14.9 tons, or of NH_3 by 5.15 tons, or of VOC by 111 tons. The exchange rates between the other pollutants can be directly computed from these figures.

As the exchange rates are derived from a sole focus on PM health effects, co-benefits of the proposed emission ceilings on other air quality effects could deteriorate if compensations do not involve the relevant precursor emissions. However, it is found that, if compensations are limited to a 10% excess of an emission ceiling, in the most unfavorable and rather unlikely constellation premature deaths from ozone in the EU-28 would increase by a maximum of 2.3% compared to the proposed set of ceilings.

Larger deviations could potentially occur for eutrophication, where 10% higher NH_3 emissions would increase excess nitrogen deposition in the EU-28 by 9% in the worst case (and 10% higher NO_x emissions by 1.5%).

Higher NH_3 emissions will also make the largest difference for acidification, with up to 11% more excess deposition if all Member States increased their NH_3 emissions by 10%. This would reduce the 'gap closure' from the proposed ceilings to about 30%. In contrast, an EU-wide increase of SO_2 by 10% would increase excess deposition by 2.2%, and of NO_x by 1.4%. As mentioned above, these numbers have to be seen as extreme cases, and differences will be significantly lower in more likely situations when not all Member States opt for the same pollutant without involving other relevant precursor emissions in the compensation. As these numbers are computed for a 10% increase of an emission ceiling, negative side effects could be restricted through a smaller margin of compensation.

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Annex 1: Derivation of the formula for the exchange rates

For the following it is useful to recall that in the GAINS model the EU28-wide YOLL function is calculated as:

$$\text{YOLL} = \sum_r k_r \left[\sum_p \left(\sum_s T_{s,r}(p) \cdot E_s(p) \right) + c_r + \sum_\sigma T^{UI}_{r,\sigma} \cdot E_{r,\sigma}(PPM2.5) \right] \tag{1}$$

where, in the first term, the $T_{s,r}(p)$ represent the source-receptor matrices for pollutant p in the population-weighted PM2.5 concentration calculation, and $E_s(p)$ are the national emissions. The index s runs over all source regions (including sea regions), r runs over all receptor regions (28 MSs), and p runs over the relevant pollutants (primary PM2.5, SO_2, NO_X, NH_3, VOC). The last term in the square brackets represents the urban increment in PM2.5 concentrations, i.e. contributions from low-level sources that characterize urban PM2.5 concentrations above the regional background, and the sum runs over all relevant SNAP1 sectors σ (i.e. 2, 7 and 8). The constants c_r represent the EMEP boundary conditions, so that the expression in square brackets represents the population-weighted PM2.5 concentration in receptor region r. The constants k_r convert population-weighted PM2.5 concentrations into YOLLs in receptor region r and reflect life table and relative risk information.

The increase in EU28-wide YOLL (ΔYOLL) from an increase of the emissions E pollutant A by a small amount $\delta E_s(A)$ over the NEC of Member State *s* can be expressed as:

$$\Delta\text{YOLL} = \left(\frac{\partial \text{YOLL}}{\partial E_s(A)} \right) \cdot \delta E_s(A) \tag{2}$$

Equation (2) answers the first question above: for $\delta E_s(A)$ = 1 kiloton, the change in YOLL can be calculated. Similarly, Equation (2) can be used to calculate the *reduction* in YOLL if another pollutant B is reduced below the NEC by the amount $\delta E_s(B)$:

$$\Delta\text{YOLL} = \left(\frac{\partial \text{YOLL}}{\partial E_s(B)} \right) \cdot \delta E_s(B) \tag{3}$$

The conditions that must hold so that an exceedance of pollutant A is indeed compensated by an additional reduction can be expressed mathematically by combining Equations (2) and (3) and requiring that the YOLL value does not increase:

$$\Delta\text{YOLL} = \left(\frac{\partial \text{YOLL}}{\partial E_s(A)} \right) \cdot \delta E_s(A) + \left(\frac{\partial \text{YOLL}}{\partial E_s(B)} \right) \cdot \delta E_s(B) \leq 0 \tag{4}$$

from which it is straightforward to derive:

$$\delta E_s(B) \geq - \left[\frac{\left(\frac{\partial \text{YOLL}}{\partial E_s(A)} \right)}{\left(\frac{\partial \text{YOLL}}{\partial E_s(B)} \right)} \right] \cdot \delta E_s(A) = - R_s(A,B) \cdot \delta E_s(A) \tag{5}$$

This defines the exchange rate $R_s(A,B)$ for the compensation of an A-exceedance with an additional B-reduction. For the equality the compensation is exact; the inequality indicates that higher (but not lower) values for the exchange rate could be chosen too without violating the environmental target.

Without urban increment

In this section the last term in the bracket in Equation (1)is ignored. Then the marginal changes in Equation (2) can be written explicitly as:

$$\left(\frac{\partial \mathrm{YOLL}}{\partial E_s(A)}\right) = \sum_r k_r \cdot T_{s,r}(A) \tag{6}$$

The left hand side is the derivate of the YOLL value with respect to the emissions of pollutant A in the source region s, $E_s(A)$, (i.e. by how much the YOLL value changes if the emissions of A in s change by one unit. The sum over r ensures that if the emissions in one MS (the source region s) change, then the changes in YOLL in all receptor regions r are taken into account, both in the source region as well as all 'downwind' regions.

Thus the lowest (and therefore most economical) exchange rate can be calculated from the GAINS source receptor matrices and YOLL conversion constants k_r as:

$$R_s(A,B) = \left[\frac{\sum_r k_r \cdot T_{s,r}(A)}{\sum_r k_r \cdot T_{s,r}(B)}\right] \tag{7}$$

It is worth re-emphasizing that the derivation of the formula for the exchange rate (Equation (7)) is only valid for small $\delta E_s(A)$ in Equation (2). Thus it is not only legitimate, but absolutely necessary to restrict the amounts of allowed exceedances, thereby limiting the scope of this flexible mechanism.

With urban increment

The above does not explicitly take into account the urban increment in the calculation of PM2.5 concentrations, thus the positive effects of reducing primary PM2.5 are underestimated. The challenge is that only the emissions of certain sectors contribute to the urban increment, while Equation (7) is based on national emissions and the NECs are also imposed – by definition – at the national level and not at the sectoral level.

In view of this difficulty a pragmatic approach is taken and it is assumed that the shares of emissions of relevant SNAP1 sectors σ in the national total are constant in policy scenarios, in particular those in which the flexible mechanism can be applied. It is therefore assumed that the sectoral primary PM2.5 emissions can be expressed as a share of the national total.

$$E_{r,\sigma}(PPM2.5) \;=\; u_{s,\sigma}(PPM2.5) \cdot E_s(PPM2.5) \tag{8}$$

With this the following modification of Equation (7) can be derived:

$$R_s^{UI}(A,B) = \left[\frac{\sum_r k_r \cdot \;(T_{s,r}(A) + \delta_{A,PPM2.5} \cdot \delta_{s,r} \cdot \;\sum_\sigma T_{s,\sigma}^{UI} \cdot u_{s,\sigma}(A))}{\sum_r k_r \cdot \;(T_{s,r}(B) + \delta_{B,PPM2.5} \cdot \delta_{s,r} \cdot \;\sum_\sigma T_{s,\sigma}^{UI} \cdot u_{s,\sigma}(B))}\right] \tag{9}$$

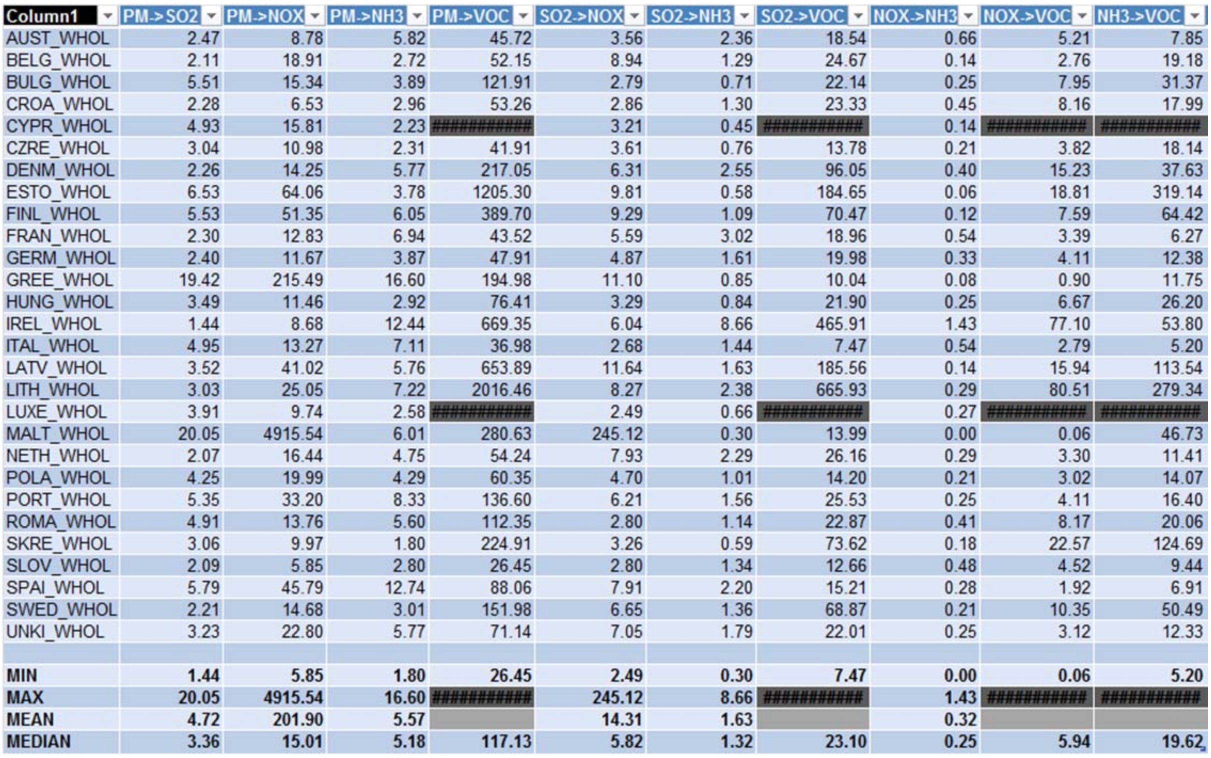
The extension has two main components: the $T_{s,\sigma}^{UI}$ is the urban increment source-receptor matrix for SNAP1 sector σ the source region s, which has an influence on the PM2.5 concentration in the source region itself (the condition r=s for this term is ensured by the Kronecker delta $\delta_{s,r}$). The factor $u_{s,\sigma}(A)$ in the numerator represents the share of the emissions of the urban increment-relevant sector σ in the total emissions of A (the factor $\delta_{A,PPM2.5}$ ensures that there is only a contribution if A represents primary PM2.5).

Thus, if neither A or B represent primary PM2.5, then Equation (9) is identical to Equation (7), as required. If A represents primary PM2.5 (but B not, because A and B represent different pollutants) then in addition to the numerator of Equation (7), the additional term in numerator of Equation (9) represents the urban increment, and it only is non-zero in the sum over *r* when source and receptor region are the same.

In the present context it is useful to determine the shares $u_{s,\sigma}(PPM2.5)$ from the scenario that represented the Commission Proposal (Scenario *B7* in (Amann et al. 2014)), because all offsets will be calculated relative to this scenario.

Annex 2: Country-specific exchange rates

Country-specific exchange rates. Cells shaded in dark grey take infinite values due to zero elements in the corresponding source-receptor matrices. As a result, mean values for these columns cannot be calculated (cells shaded in light grey). Here only 10 combinations are shown, the inverses can be calculated accordingly and are exact [except for the medians – see text].



Column1	PM->SO2	PM->NOX	PM->NH3	PM->VOC	SO2->NOX	SO2->NH3	SO2->VOC	NOX->NH3	NOX->VOC	NH3->VOC
AUST_WHOL	2.47	8.78	5.82	45.72	3.56	2.36	18.54	0.66	5.21	7.85
BELG_WHOL	2.11	18.91	2.72	52.15	8.94	1.29	24.67	0.14	2.76	19.18
BULG_WHOL	5.51	15.34	3.89	121.91	2.79	0.71	22.14	0.25	7.95	31.37
CROA_WHOL	2.28	6.53	2.96	53.26	2.86	1.30	23.33	0.45	8.16	17.99
CYPR_WHOL	4.93	15.81	2.23	###########	3.21	0.45	###########	0.14	###########	###########
CZRE_WHOL	3.04	10.98	2.31	41.91	3.61	0.76	13.78	0.21	3.82	18.14
DENM_WHOL	2.26	14.25	5.77	217.05	6.31	2.55	96.05	0.40	15.23	37.63
ESTO_WHOL	6.53	64.06	3.78	1205.30	9.81	0.58	184.65	0.06	18.81	319.14
FINL_WHOL	5.53	51.35	6.05	389.70	9.29	1.09	70.47	0.12	7.59	64.42
FRAN_WHOL	2.30	12.83	6.94	43.52	5.59	3.02	18.96	0.54	3.39	6.27
GERM_WHOL	2.40	11.67	3.87	47.91	4.87	1.61	19.98	0.33	4.11	12.38
GREE_WHOL	19.42	215.49	16.60	194.98	11.10	0.85	10.04	0.08	0.90	11.75
HUNG_WHOL	3.49	11.46	2.92	76.41	3.29	0.84	21.90	0.25	6.67	26.20
IREL_WHOL	1.44	8.68	12.44	669.35	6.04	8.66	465.91	1.43	77.10	53.80
ITAL_WHOL	4.95	13.27	7.11	36.98	2.68	1.44	7.47	0.54	2.79	5.20
LATV_WHOL	3.52	41.02	5.76	653.89	11.64	1.63	185.56	0.14	15.94	113.54
LITH_WHOL	3.03	25.05	7.22	2016.46	8.27	2.38	665.93	0.29	80.51	279.34
LUXE_WHOL	3.91	9.74	2.58	###########	2.49	0.66	###########	0.27	###########	###########
MALT_WHOL	20.05	4915.54	6.01	280.63	245.12	0.30	13.99	0.00	0.06	46.73
NETH_WHOL	2.07	16.44	4.75	54.24	7.93	2.29	26.16	0.29	3.30	11.41
POLA_WHOL	4.25	19.99	4.29	60.35	4.70	1.01	14.20	0.21	3.02	14.07
PORT_WHOL	5.35	33.20	8.33	136.60	6.21	1.56	25.53	0.25	4.11	16.40
ROMA_WHOL	4.91	13.76	5.60	112.35	2.80	1.14	22.87	0.41	8.17	20.06
SKRE_WHOL	3.06	9.97	1.80	224.91	3.26	0.59	73.62	0.18	22.57	124.69
SLOV_WHOL	2.09	5.85	2.80	26.45	2.80	1.34	12.66	0.48	4.52	9.44
SPAI_WHOL	5.79	45.79	12.74	88.06	7.91	2.20	15.21	0.28	1.92	6.91
SWED_WHOL	2.21	14.68	3.01	151.98	6.65	1.36	68.87	0.21	10.35	50.49
UNKI_WHOL	3.23	22.80	5.77	71.14	7.05	1.79	22.01	0.25	3.12	12.33
MIN	**1.44**	**5.85**	**1.80**	**26.45**	**2.49**	**0.30**	**7.47**	**0.00**	**0.06**	**5.20**
MAX	**20.05**	**4915.54**	**16.60**	###########	**245.12**	**8.66**	###########	**1.43**	###########	###########
MEAN	**4.72**	**201.90**	**5.57**		**14.31**	**1.63**		**0.32**		
MEDIAN	**3.36**	**15.01**	**5.18**	**117.13**	**5.82**	**1.32**	**23.10**	**0.25**	**5.94**	**19.62**