International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

IIASA Interim Report IR-07-008

Comparison of the RAINS emission control cost curves for air pollutants with emission control costs computed by the GAINS model

Fabian Wagner, Wolfgang Schöpp

NOT YET Approved by:

Markus Amann
Program leader
Atmospheric Pollution and Economic Development program

(amann@iiasa.ac.at)

February 2007

Interim Reports on work of the International Institute for Applied Systems Analysis receive only limited review. Views or opinions expressed herein do not necessarily represent those of the Institute, its National Member Organizations, or other organizations supporting the work.

Abstract

This paper compares cost curves of SO_2, NO_x and PM2.5 emission controls generated with the RAINS (Regional Air Pollution Information and Simulation) model with cost estimates obtained from the GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies) model. Based on the same set of input data, results from both models are very similar, and differences are considered as insignificant.

About the authors

Fabian Wagner and Wolfgang Schöpp work at the Atmospheric Pollution and Economic Development program of the International Institute for Applied Systems Analysis (IIASA).

Table of contents

1 Introduction

The Regional Air Pollution Information and Simulation (RAINS) model, developed at the International Institute for Applied Systems Analysis (IIASA), describes the pathways of pollution from anthropogenic driving forces to the most relevant environmental impacts (Amann *et al.*, 2004). It brings together information on economic and energy development, emission control potentials and costs, atmospheric dispersion and environmental sensitivities towards air pollution (Schöpp *et al.*, 1999). The model addresses threats to human health posed by fine particulates and ground-level ozone as well as risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated levels of ozone. These air pollution-related impacts are considered in a multi-pollutant context, quantifying the contributions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of fine (PM2.5) and coarse (PM2.5-PM10) particles (**Error! Reference source not found.**). RAINS holds the essential information on all aspects listed above for 43 European countries and links this data in such a way that the environmental implications of alternative assumptions on economic development and emission control strategies can be assessed. On-line access to the model and to all input data is available at http://www.iiasa.ac.at/rains.

	PM	SO_2	NO_x	VOC	NH_3
Health impacts: PM	√	√	√	√	√
O_3			√	√	
Vegetation damage: O_3			√	√	
Acidification		√	√		√
Eutrophication			√		√

Figure 1.1: The multi-pollutant/multi-effect approach of the RAINS model

The RAINS optimization balances emission control measures across countries, pollutants and economic sectors in such a way that user-defined target levels on the various environmental impacts are met at least costs. With this feature, the RAINS model has been used earlier in the negotiations on the 'Second Sulfur Protocol' (Tuinstra *et al.*, 1999), the 'Gothenburg Multi-pollutant/Multi-effect Protocol' to the Convention on Long-range Transboundary Air Pollution, and for the Emission Ceilings Directive of the European Union (Amann and Lutz, 2000). After 2000, the RAINS model has been used as the central analytical instruments for the cost-effectiveness analysis of the Clean Air For Europe (CAFE) programme of the European Commission (CEC, 2001) that developed the Thematic Strategy on Air Pollution (CEC, 2005). The RAINS methodology was subject to a scientific peer review (CEC, 2004), and databases have been reviewed by experts from Member States and industry in two series of bilateral consultations.

In recent years, the RAINS model has been extended to capture economic interactions between the control of conventional air pollutants and greenhouse gases. This GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the three F-gases (Klaassen *et al.*, 2004). GAINS also considers structural and non-technical measures, and conducts a fuller assessment of co-benefits (Figure 1.2). Thereby, GAINS constitutes an extended version of the RAINS model that can analyze, in addition to the existing features of the RAINS model, the interplay between air pollution control and greenhouse gas mitigation strategies. The air pollution-related features of the GAINS model are now used in the cost-effectiveness analysis for the revision of national emission ceilings directive.

	PM	SO_2	NO_x	VOC	NH_3	CO_2	CH_4	N_2O	CFCs HFCs SF_6
Health impacts: PM	√	√	√	√	√				
O_3			√	√			√		
Vegetation damage: O_3			√	√			√		
Acidification		√	√		√				
Eutrophication			√		√				
Radiative forcing: - direct						√	√	√	√
- via aerosols	√	√	√	√	√				
- via OH			√	√			√		

Figure 1.2: The GAINS multi-pollutant/multi-effect framework

To establish confidence in the GAINS model and its policy conclusions, the European Commission has engaged a team of international experts to review the equivalency of the air pollution-related features of GAINS with the conventional RAINS analysis. In January 2007, the team has met at IIASA to review the new features and to examine differences between the RAINS and the GAINS models. In order to establish equivalency of the cost-effectiveness analysis between the two models, the review team has requested IIASA to conduct a country-by country comparison of the RAINS cost curves with cost estimates produced through the GAINS model.

This report presents the results of this intercomparison for SO2, NOx and PM2.5. The following sections provide a brief summary of the RAINS model methodology and describe the methodological differences of GAINS that are relevant for the cost-effectiveness analysis presented in this report.

2 Methodologies of the RAINS and the GAINS models

2.1 Emission estimates

For each of the pollutants listed in Figure 1.2, RAINS and GAINS estimate emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied:

$$E_{i,p} = \sum_{k} \sum_{m} A_{i,k} ef_{i,k,m,p} x_{i,k,m,p} \tag{1}$$

where:

i, k, m, p	Country, activity type, abatement measure, pollutant, respectively
$E_{i,p}$	Emissions of pollutant *p* (for SO_2, NO_x, VOC, NH_3, PM2.5, CO_2 , CH_4, N_2O, etc.) in country *i*
$A_{i,k}$	Activity level of type *k* (e.g., coal consumption in power plants) in country *i*
$ef_{i,k,m,p}$	Emission factor of pollutant *p* for activity *k* in country *i* after application of control measure *m*
$x_{i,k,m,p}$	Share of total activity of type *k* in country *i* to which a control measure *m* for pollutant *p* is applied.

This approach allows capturing critical differences across economic sectors and countries that could justify differentiated emission reduction requirements in a cost-effective strategy. It reflects structural differences in emission sources through country-specific activity levels. It represents major differences in emission characteristics of specific sources and fuels through source-specific emission factors, which account for the degrees at which emission control measures are applied. More detail is available in Cofala and Syri, 1998a, Cofala and Syri, 1998b, Klimont *et al.*, 2000, Klimont *et al.*, 2002, Klimont and Brink, 2006, Klaassen *et al.*, 2005, Höglund-Isaksson and Mechler, 2005, Winiwarter, 2005, Tohka, 2005. RAINS and GAINS estimate future emissions according to Equation 1 by varying the activity levels along exogenous projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures.

2.2 Emission control measures and their costs

Basically, three groups of measures to reduce emissions can be distinguished:

- *Behavioral changes* reduce anthropogenic driving forces that generate pollution. Such changes in human activities can be autonomous (e.g., changes in life styles), they could be fostered by command-and-control approaches (e.g., legal traffic restrictions), or they can be triggered by economic incentives (e.g., pollution taxes, emission trading systems, etc.). The RAINS/GAINS concept does not internalize such behavioral responses, but reflects such changes through alternative exogenous scenarios of the driving forces.

- *Structural measures* that supply the same level of (energy) services to the consumer but with less polluting activities. This group includes fuel substitution (e.g., switch from coal to natural gas) and energy conservation/energy efficiency improvements. The GAINS model introduces such structural changes as explicit control options, while the RAINS approach disregarded these measures as emission control options.
- A wide range of *technical measures* has been developed to capture emissions at their sources before they enter the atmosphere. Emission reductions achieved through these options neither modify the driving forces of emissions nor change the structural composition of energy systems or agricultural activities. RAINS and GAINS consider about 1,500 pollutant-specific end-of-pipe measures for reducing SO_2, NO_x, VOC, NH_3 and PM emissions and assess their application potentials and costs.. In addition, GAINS includes several hundred options for greenhouse gases.

Any optimal allocation of emission control measures across countries and sectors is crucially influenced by differences in emission control costs across emission sources. It is therefore of utmost importance to systematically identify the factors leading to variations in emission control costs among countries, economic sectors and pollutants. Diversity is caused, i.a., by differences in the structural composition of existing emission sources (e.g., fuel use pattern, fleet composition, etc.), the state of technological development, and the extent to which emission control measures are already applied.

Assuming a free market for emission control technologies, the same technology will be available to all countries at the same costs. However, country- and sector-specific circumstances (e.g., size distributions of plants, plant utilization, fuel quality, energy and labor costs, etc.) lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources. For each of the 1,500 emission control options, RAINS and GAINS estimate their costs of local application considering annualized investments (I^{an}), fixed (OM^{fix}) and variable (OM^{var}) operating costs, and how they depend on technology m, country i and activity type k. Unit costs of abatement (ca), related to one unit of activity (A), add up to:

$$ca_{i,k,m} = \frac{I^{an}_{i,k,m} + OM^{fix}_{i,k,m}}{A_{i,k}} + OM^{var}_{i,k,m} \,. \tag{2}$$

For the cost-effectiveness analysis, these costs can be related to the emission reductions achieved. The costs per unit of abated emissions (cn) of a pollutant p are calculated as:

$$cn_{i,k,m,p} = \frac{ca_{i,k,m}}{ef_{i,k,0,p} - ef_{i,k,m,p}} \tag{3}$$

where $ef_{i,k,0,p}$ is the uncontrolled emission factor in absence of any emission control measure (m=0).

2.2.1 RAINS cost curves for emission controls

For its optimization routine the RAINS model produces cost curves for emission control, which provide for each country a ranking of the available emission control measures according to their marginal costs. If, for a given activity *k*, more than one control option is available, marginal costs (*mc*) for control option *m* for pollutant *p* in country *i* are calculated as:

$$mc_{i,k,m,p} = \frac{cn_{i,k,m,p}ef_{i,k,m,p} - cn_{i,k,m-1,p}ef_{i,k,m-1,p}}{ef_{i,k,m,p} - ef_{i,k,m-1,p}}. \qquad (4)$$

Cost curves $f_{i,p}$ list for a country *i* for increasing levels of stringency the total costs $C_{i,p}^*$ of the least-cost combinations of the available abatement measures that reduce national total emissions of pollutant *p* to any technically feasible emission level $E_{i,p}^*$ $(E_{i,p\,min} < E_{i,p}^* < E_{i,p\,max})$:

$$C_{i,p}^* = f_{i,p}(E_{i,p}^*) = \sum_{s=1}^{S} \Delta E_{i,s,p} mc_{i,s,p} + \delta \cdot mc_{i,s+1,p} \qquad (5)$$

where $mc_{i,s,p}$ are the marginal costs defined in Equation 4 and sorted over the activities *k* and measures *m* in such a way that $mc_{i,s,p} \leq mc_{i,s+1,p}$, $\Delta E_{i,s,p}$ are the corresponding emission reductions, and *S* is such that $E_{i,pmax} - \sum_{s=1}^{S} \Delta E_{i,s,p} > E_{i,p}^*$, but $E_{i,pmax} - \sum_{s=1}^{S+1} \Delta E_{i,s,p} \leq E_{i,p}^*$ and $\delta = E_{i,pmax} - \sum_{s=1}^{S} \Delta E_{i,s,p} - E_{i,p}^*$. Details on the cost calculations are provided in Cofala and Syri, 1998a, Cofala and Syri, 1998b, Klimont *et al.*, 2000, Klimont *et al.*, 2002.

2.2.2 The use of cost data in GAINS

In contrast to the single-pollutant cost curve approach used in RAINS, the optimization module of GAINS uses an explicit representation of technologies. While in RAINS the decision variables in the cost optimization are the segments of (independent) cost curves based on a fixed energy projection, in GAINS the decision variables are the activity levels of individual technologies themselves.

The advantages of this approach are fourfold:

- Multi-pollutant technologies are represented adequately in this approach. Multi-pollutant emission control technologies, such as those meeting the various Euro-standards for road vehicles, can be cost-effective in a multi-pollutant multi-objective regulatory framework, even though as single pollutant control technologies they may be not. Thus, while in a cost curve approach multi-pollutant technologies often do not appear to be cost effective, in the GAINS optimization these technologies are appraised on the basis their efficiency to meet (potentially) several environmental objectives simultaneously.

- GAINS allows for (limited) changes in the underlying energy system, primarily as possible measures to reduce greenhouse gas emissions. With each change in the energy system, however, the potential for air pollution control technologies may change, and thus in RAINS the individual cost curve would need to be recalculated for each change in the energy system. Using an explicit technology representation in the GAINS optimization avoids such a cumbersome procedure, as the model "sees" the available technologies and their potentials for their application *at every stage*.

- The GAINS approach fully integrates air pollution control and greenhouse gas mitigation measures so that it not only possible to address the two issues *sequentially*, as has been done in the past: with this tool both aspects of emission control can be addressed *simultaneously* to increase economic efficiency and environmental effectiveness.

- Emission control costs are directly associated with technologies, rather than with pollutants. For single pollutant technologies this difference is spurious, but both for multi-pollutant technologies and activities changes commonly considered as greenhouse gas mitigation options it is often inappropriate to attribute costs to the reduction of a single pollutant or to allocate the costs to individual pollutants. With the technology approach of GAINS no such allocation is needed, nor is it always possible.

Another important consequence of the technology representation in GAINS is the extension of the concept of maximum technically feasible reductions (MTFR). While in the RAINS approach the point of MTFR on a single pollutant cost curve was determined by the maximum application of end-of-pipe technologies, in GAINS further reductions can be achieved by changing the underlying activities, e.g., the energy mix for a given sub-sector. Thus, for example, a switch from coal to gas or to a renewable fuel will reduce emissions of particles below a level that could be achieved with filter technologies. Though a particular fuel switch may not be cost-effective as a control measure for a single air pollutant, it is important to take this additional potential for reduction into account when air pollution targets are discussed, particularly in a carbon constrained setting.

It is important to take note of the fact that the GAINS optimization module can still be used to construct single pollutant cost curves for individual countries if so desired. In this mode the GAINS model is allowed to use all add-on technologies for air pollution control like in the RAINS model, but fuel substitutions or efficiency improvement options are suppressed, i.e., are not available. Ignoring multi-pollutant technologies for the time being, the GAINS model in RAINS mode exactly reproduces the results of the original RAINS optimization approach as shown in the remainder of this paper.

In contrast, when the restrictions on fuel substitutions and efficiency improvements are lifted and the GAINS model is allowed to use all available options, the "GAINS-mode" reveals a larger potential for emission reductions. In Figure 2.1, the thin line with bullets illustrates the single pollutant cost curve that is obtained with the GAINS model in RAINS mode. The curve begins at around 108 kt PM2.5 per year and ends at around 86 kt PM2.5 per year, which represents the maximum technically feasible reductions scenario generated with the RAINS model. Results emerging from the "GAINS mode" are indicated by the thin line with squares. This curve ends at around 79 kt PM2.5 per year with costs of around 7 billion €/yr (off the diagram). This cost estimate takes into account the change in the total system costs, i.e., costs of all fuel substitution options taken to achieve an emission level of 79 kt PM2.5 per year. If, however, only those costs are taken into account that are explicitly connected with PM2.5 end-of-pipe technologies, then the resulting costs in the MTFR scenario at 79 kt PM2.5 per year is lower than 1.6 billion €/yr, which is even below the level of the MTFR calculated in the RAINS mode (more than 1.6 billion €/yr). This is easily understood if one takes into account that the energy systems in the MTFR situations of the two cost curves are different: the bulleted line is constructed from a baseline scenario, whereas the endpoint of the second and third curves result from a scenario with less use of solid fuels – which means that there is less absolute amount of capacities that need to be controlled, which in turn implies smaller amounts of money spent on control equipment (dotted line with triangles).

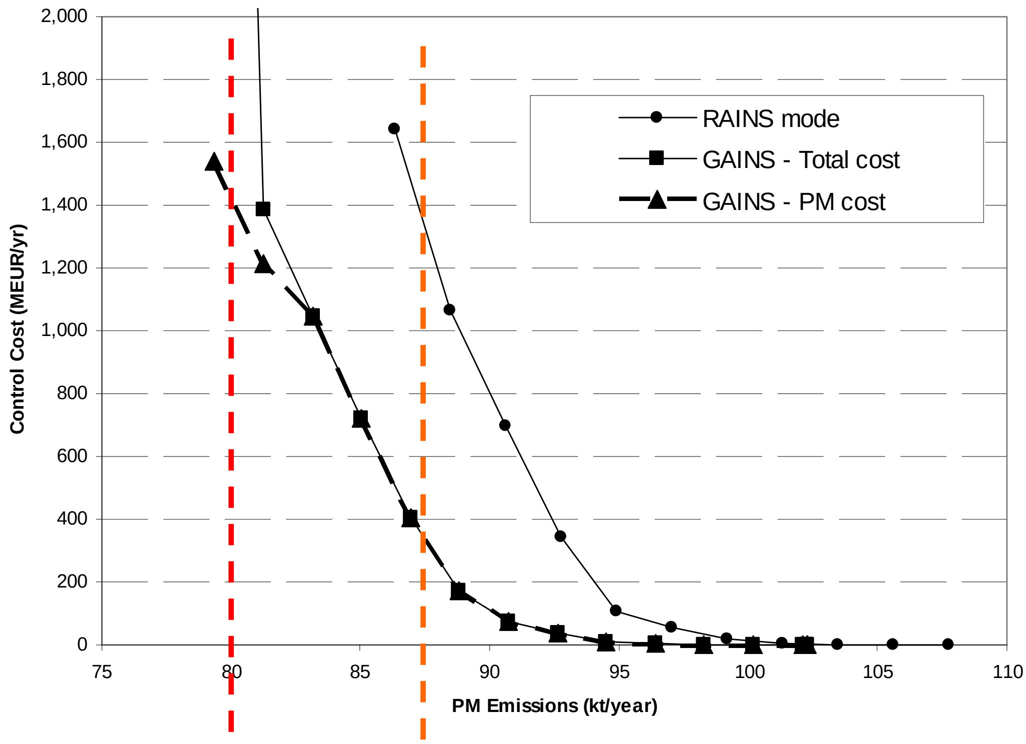


Figure 2.1: Single pollutant cost curves for PM2.5 in the year 2020. This illustrates the difference in maximum technically feasible reductions (MTFR) in the full GAINS model compared to the RAINS mode of GAINS. For details see text.

2.3 The optimization approaches

2.3.1 The RAINS optimization

As one of its most policy-relevant features, the optimization approach of the RAINS model allows a systematic search for cost-minimal combinations of emission control measures that meet user-supplied air quality targets, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. In essence, RAINS formulates an optimization problem with the objective to minimize total European control costs (for all countries *i* and pollutants *p*):

$$\sum_i \sum_p C_{i,p} \rightarrow \min . \qquad (6)$$

For each country *i* and pollutant *p*, emission control costs $C_{i,p}$ are represented in form of cost curves as described in Equation 5, i.e., as a function of national emissions $E_{i,p}$, which in turn are functions of the emission control measures $x_{i,k,m,p}$ in a country *i*:

$$C_{i,p} = f_{i,p}(E_{i,p}) = f_{i,p}(g_{i,p}(x_{i,k,m,p})) . \qquad (7)$$

Optimal emission reductions are subject to environmental constraints for the various air quality problems *q* (i.e., health impacts from PM and ozone as well as ecosystems protection against acidification and eutrophication). Numerical values for these constraints are specified by the user (i.e., policy analyst) and reflect the environmental policy targets for which a least-cost emission control strategy should be explored. In the optimization problem, these environmental constraints (targets) are linked via the source-receptor relationships $h_{l/j,q}$ with emissions strengths ($E_{i,p}$) and thus with emission controls ($x_{i,k,m,p}$) at individual emission sources *m*:

$$Targ_{l|j,q} = h_{l|j,q}(E_{i,p}) = h_{l|j,q}(g_{i,p}(x_{i,k,m,p})) \qquad (8)$$

Depending on user preferences, targets *Targ* for an effect *q* can be specified for individual grid cells *j*, countries *l*, or for the entire EU as receptor areas. To describe the relations $h_{l/j,q}$ between emission sources ($E_{i,p}$) and environmental impacts *q*, RAINS applies the source-receptor relationships and the quantifications of the various impacts as described in the preceding sections. The full mathematical formulation of the RAINS optimization approach as it was used for CAFE is provided in Wagner *et al.*, 2006.

2.3.2 The GAINS optimization

In GAINS there are two types of decision variables: (i) the activity variables $x_{i,k,m}$ for all countries *i*, activities *k*, and control technologies *m*, and (ii) the substitution variables $y_{i,k,k'}$ that represent fuel substitutions and efficiency improvements (replacing activity *k* by activity *k'*). The objective function that is minimized is the sum

$$C = \sum_{i,k} \left(\sum_m c^x_{i,k,m} \cdot x_{i,k,m} + \sum_{k'} c^y_{i,k,k'} y_{i,k,k'} \right) \qquad (9)$$

where the first term represents the total end of pipe technologies cost, and the second term represents the total substitution/energy efficiency cost term. In order to avoid double counting the substitution cost coefficients $c^{y}_{ikk'}$ in the second term are calculated for uncontrolled activities, the difference in cost for control equipment for a fuel substitution is accounted for in the first term.

It is convenient to consider the activity data $x_{i,k}$, which are obtained from the variables $x_{i,k,m}$ by performing the appropriate sum over control technologies m. Activity data as well as the substitution variables may be constrained:

$$x_{i,k,m}^{\min} \le x_{i,k,m} \le x_{i,k,m}^{\max}, \; x_{i,k}^{\min} \le x_{i,k} \le x_{i,k}^{\max}, \quad y_{i,k,k'}^{\min} \le y_{i,k,k'} \le y_{i,k,k'}^{\max} \tag{10}$$

due to limitations in applicability or availability of technologies or fuel types.

The applicability of add-on technologies may be constrained by a maximum value:

$$x_{i,k,m} \le appl_{i,k,m}^{\max} x_{i,k}, \quad appl_{i,k,m}^{CLE} \le appl_{i,k,m}^{\max} \tag{11}$$

where the maximum application rate is at least as high as the application rate in the current legislation scenario. For ammonia (NH_3), technologies in the agricultural (livestock) sector are subdivided into technologies applying to different stages of manure treatment. For these technologies, application constraints are applied at a more aggregated level.

Emissions of pollutant p are calculated from the technology-specific activity data $x_{i,k,m}$ and their associated emission factors $ef_{i,k,m,p}$:

$$E_{i,p} = \sum_k \sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \tag{12}$$

Since for no individual activity k emissions should increase above the current legislation level, it is further imposed that

$$\sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \le IEF_{i,k,p}^{CLE} \cdot x_{i,k} \tag{13}$$

where $\mathrm{ef}_{i,k,m,p}$ is the emission factor for pollutant p stemming from activity k being controlled by technology m, and $\mathrm{IEF}_{i,k,p}^{CLE}$ is the implied, i.e., average emission factor for that pollutant from activity k in country i in the current legislation scenario.

Activity variables $x_{i,k,m}$ are linked to the substitution variables $y_{i,k,k'}$ via the balance equations

$$x_{i,k} + \sum_{k'} y_{i,k,k'} - \sum_{k'} \eta_{i,k,'k} \cdot y_{i,k,'k} = x_{i,k}^{CLE} \tag{14}$$

where $x^{CLE}_{i,k}$ is the activity k in country i in the current legislation scenario and $\eta_{i,k,k'}$ is the substitution coefficient that describes the relative efficiency change in the transition from activity k' to activity k. For example, in the energy sector this last equation is balancing the energy supply before and after a fuel substitution. There are also a number of constraints which ensure consistency across various levels of aggregations of sub-sectors and sub-activities.

The full mathematical formulation of the RAINS optimization approach as it was used for CAFE is provided in Wagner *et al.*, 2007.

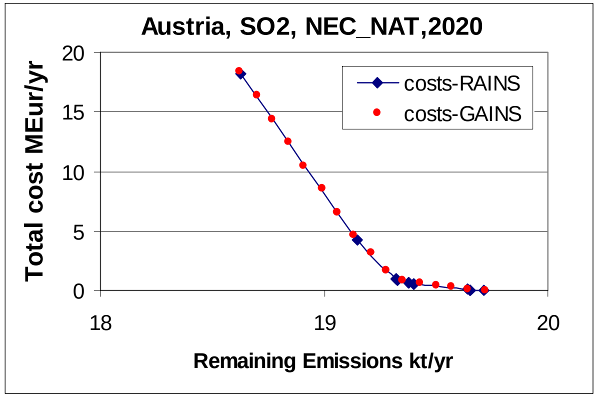
3 Comparison of cost curves

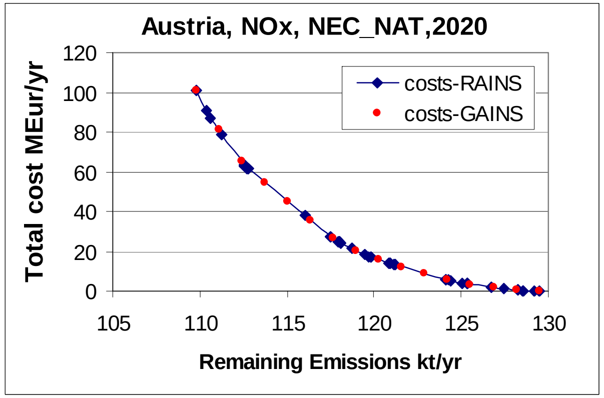
This section compares cost curves derived with the RAINS model with emission control costs calculated with GAINS. While RAINS constructs cost curves through a ranking of the available emission control measures according to their marginal costs, the GAINS model computes least-cost combinations of emission control measures for discrete emission levels given as an exogenous input. Thus, in order to compare with the RAINS cost curves, the GAINS optimization has been run for each country and pollutant for a series of 15 equidistant emission targets between the emissions of the “Current legislation” (CLE) and the “Maximum RAINS reductions” (MRR) cases.

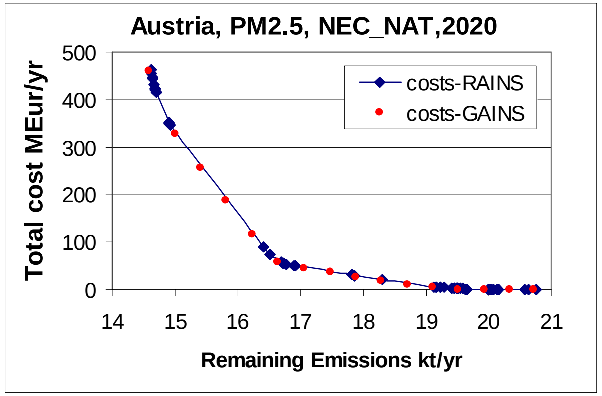
The following graphs compare cost curves for SO_2, NO_x and PM2.5, for the year 2020 and for the activity levels of the national energy projections as they are used for the revision of the emission ceilings directive. Input data reflect the state of February 2007. Due to changes in the database structures, comparisons of VOC and NH_3 cost curves could not be easily produced in time for this report.

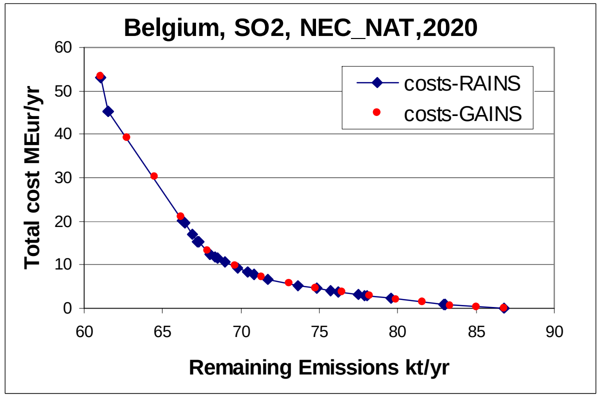
The starting point of each cost curve relates to the cost-optimal interpretation of the current legislation case. There are small differences between GAINS and RAINS in the interpretation of the cost-optimal starting point, which however is only noticeable in the SO_2 cost curve in Sweden.

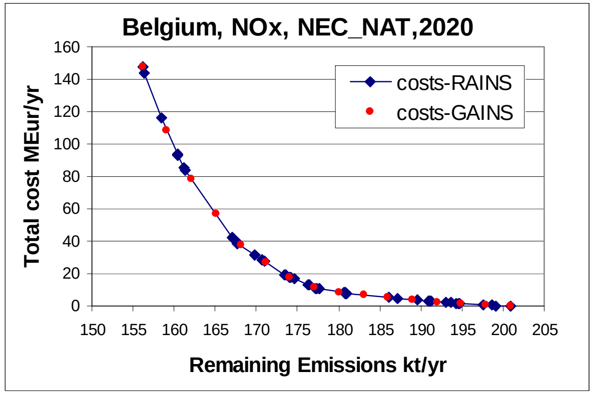
Furthermore, the comparison shows minor differences for small countries (i.e., Cyprus, Luxembourg, Malta) between RAINS and GAINS due to a limited numerical precision of the exported emission data that have been used for the graphs. However, the internal calculation in GAINS is carried out with full precision (15 digits).

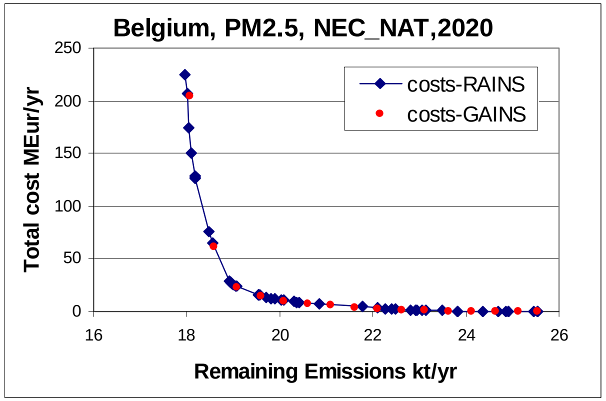

Austria, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

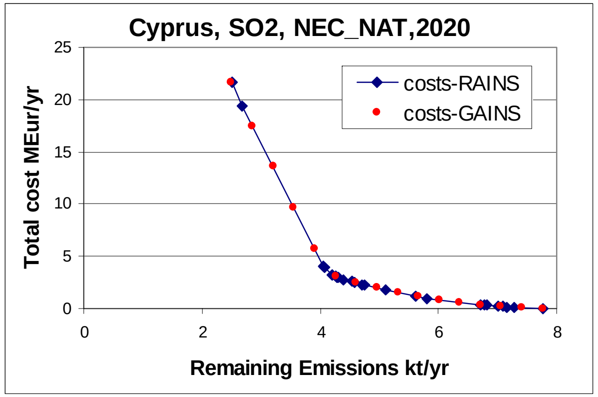

Austria, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

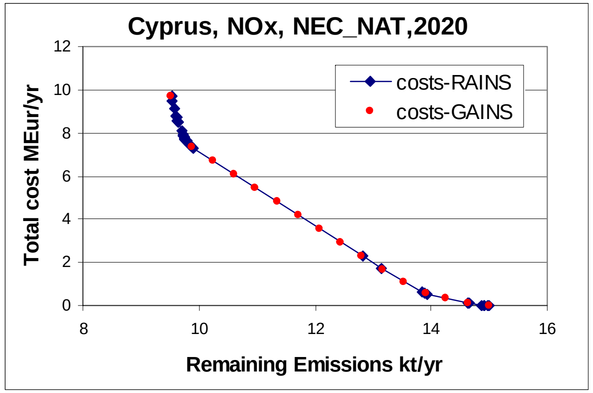

Austria, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

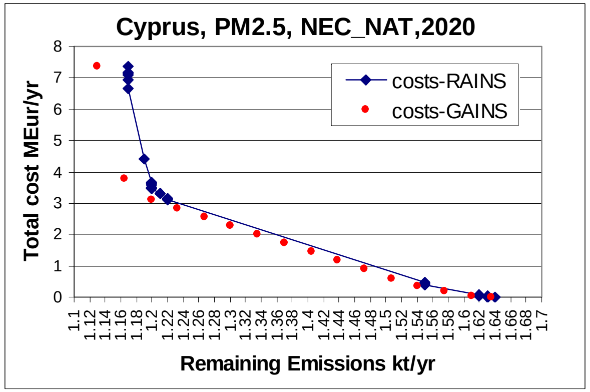

Belgium, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

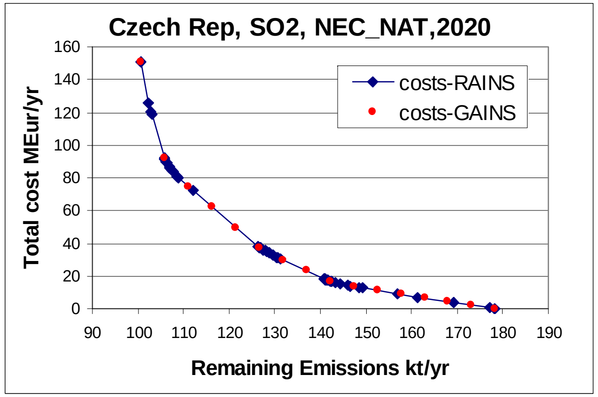

Belgium, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

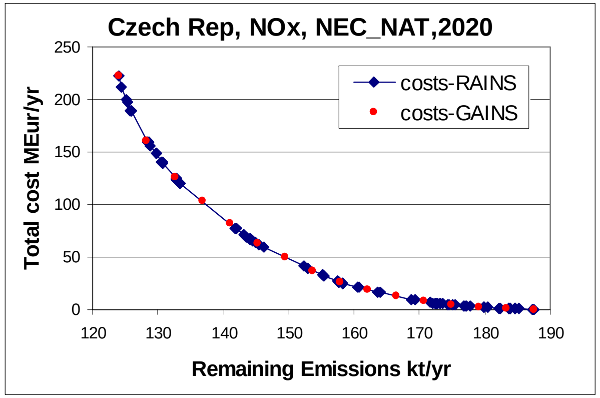

Belgium, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

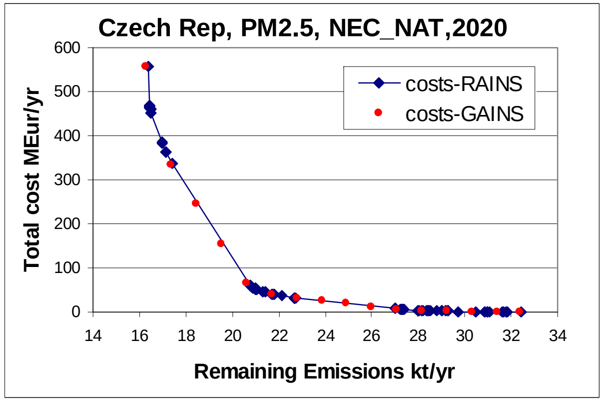

Cyprus, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

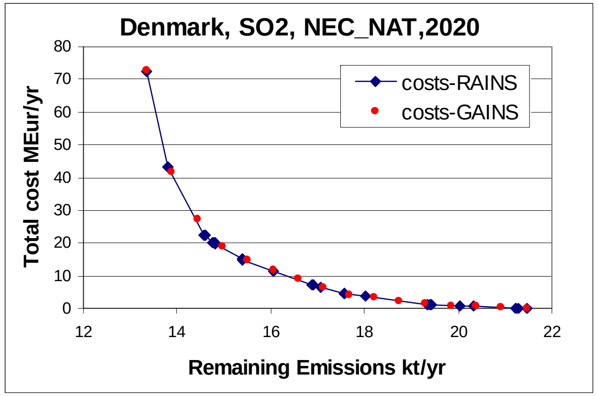

Cyprus, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

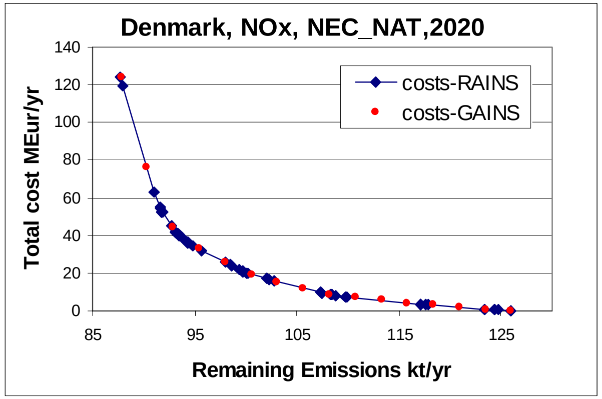

Cyprus, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

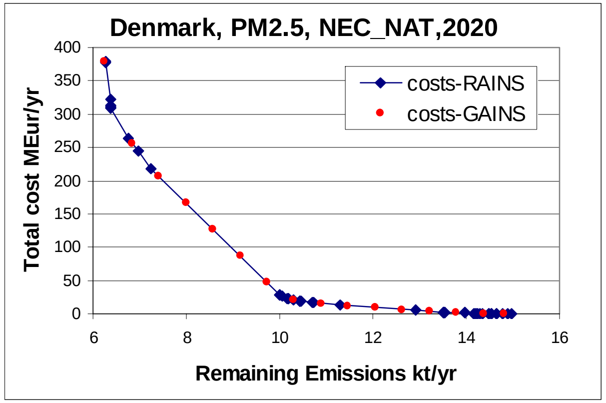

Czech Rep, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

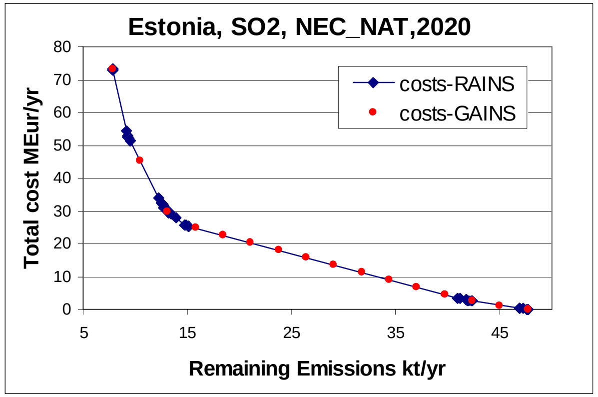

Czech Rep, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

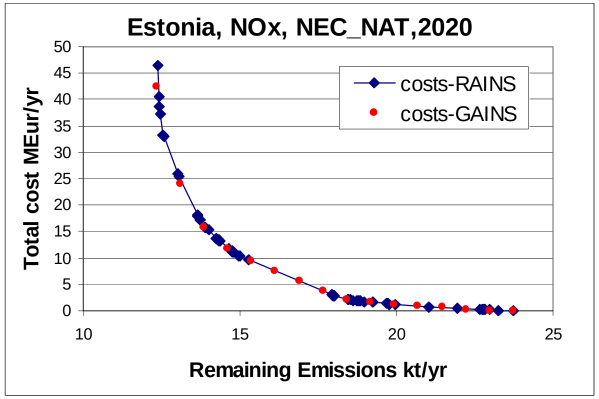

Czech Rep, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

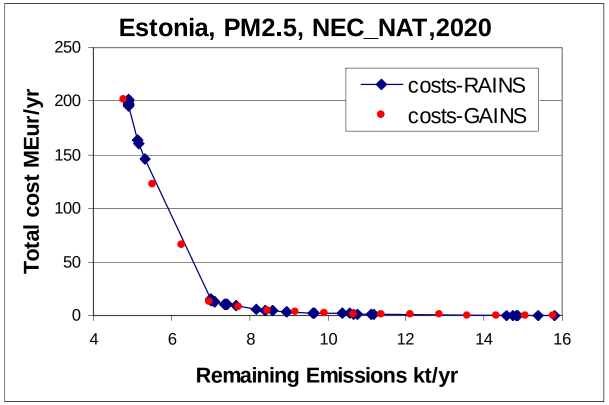

Denmark, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

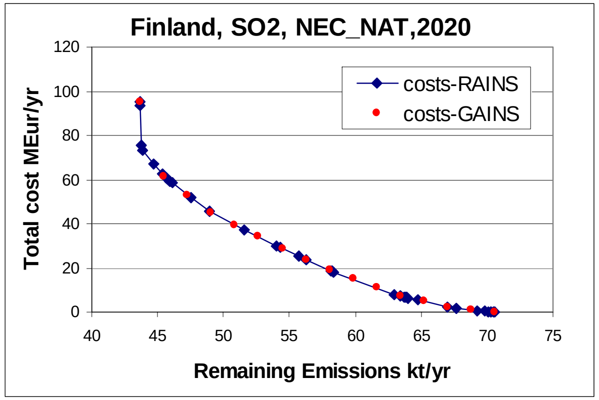

Denmark, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

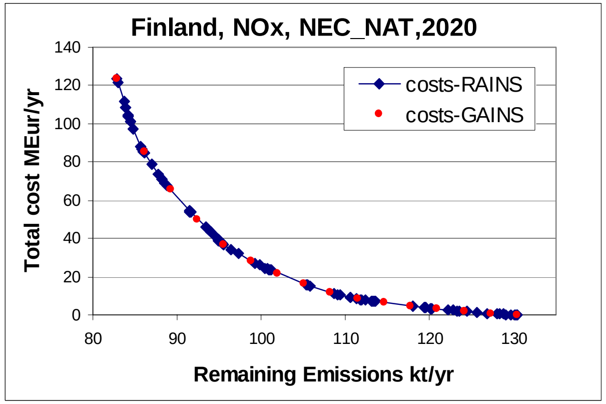

Denmark, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

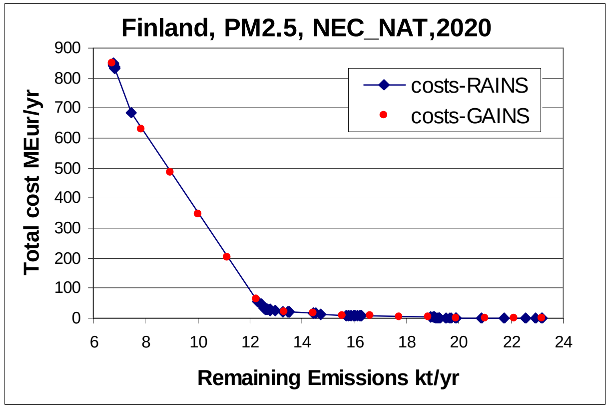

Estonia, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

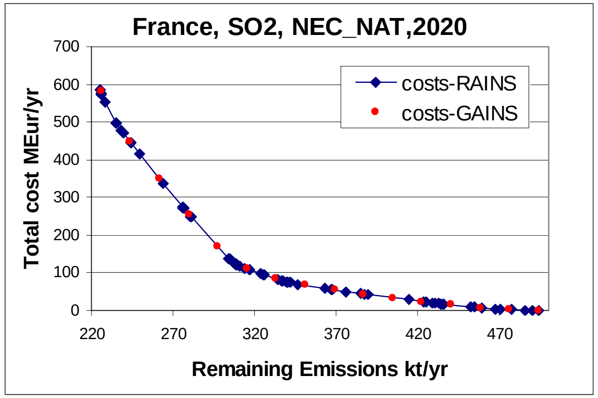

Estonia, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

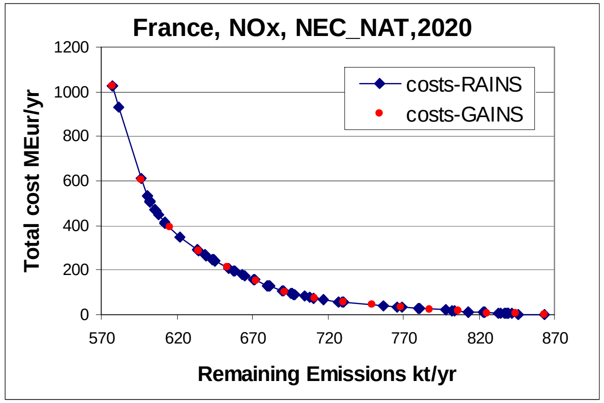

Estonia, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

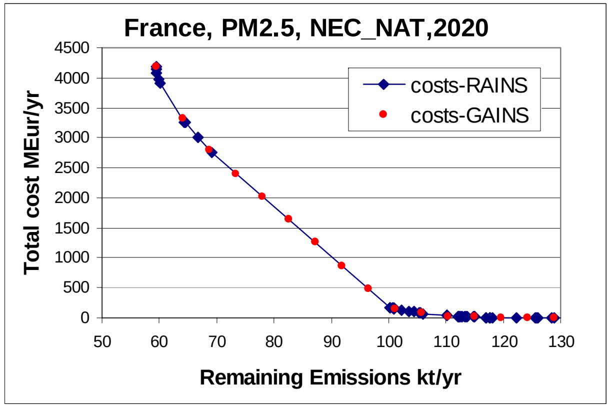

Finland, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
20
40
60
80
100
120
40
45
50
55
60
65
70
75

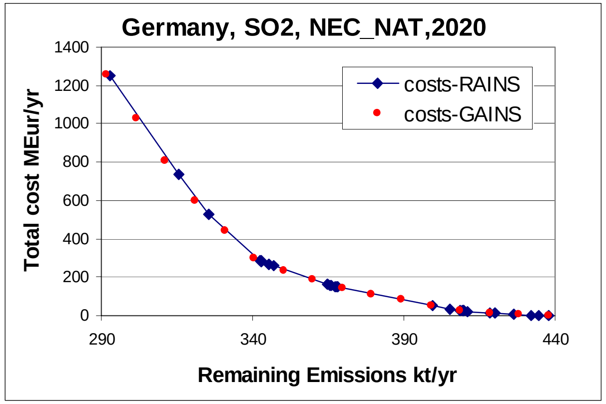

Finland, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
20
40
60
80
100
120
140
80
90
100
110
120
130

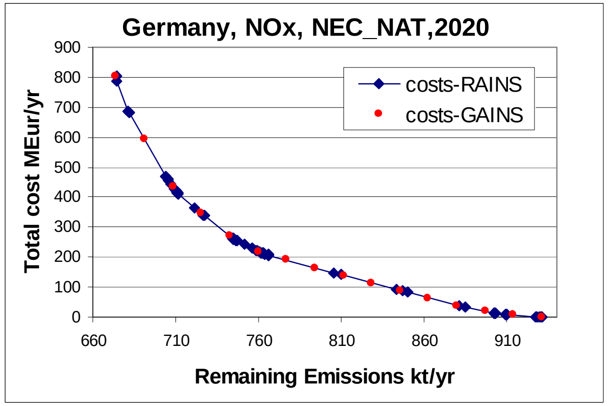

Finland, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
100
200
300
400
500
600
700
800
900
6
8
10
12
14
16
18
20
22
24

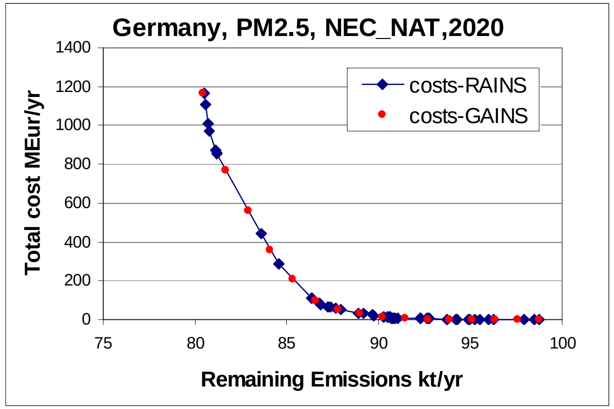

France, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
100
200
300
400
500
600
700
220
270
320
370
420
470

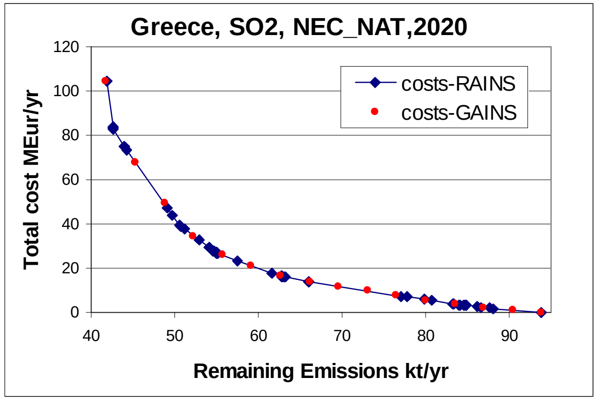

France, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
200
400
600
800
1000
1200
570
620
670
720
770
820
870

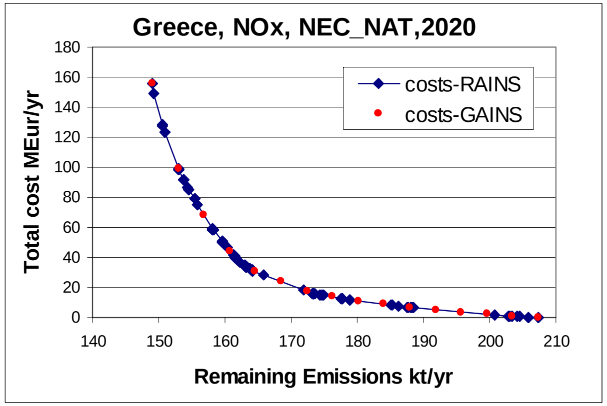

France, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
500
1000
1500
2000
2500
3000
3500
4000
4500
50
60
70
80
90
100
110
120
130

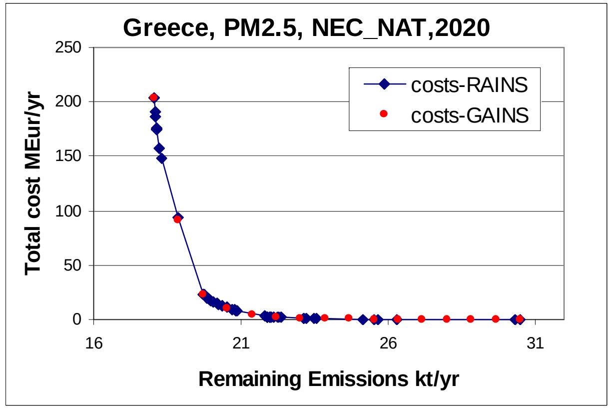

Germany, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
200
400
600
800
1000
1200
1400
290
340
390
440

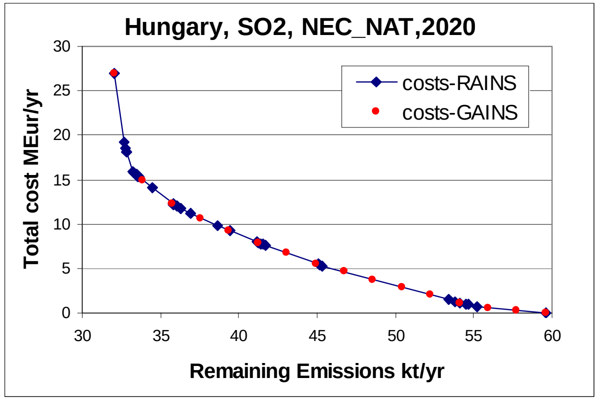

Germany, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
100
200
300
400
500
600
700
800
900
660
710
760
810
860
910

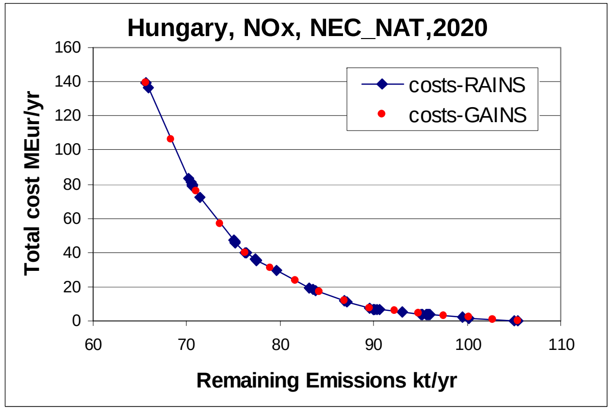

Germany, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
200
400
600
800
1000
1200
1400
75
80
85
90
95
100

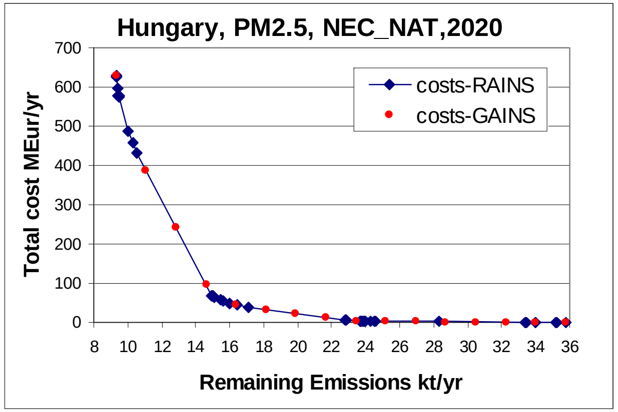

Greece, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
20
40
60
80
100
120
40
50
60
70
80
90

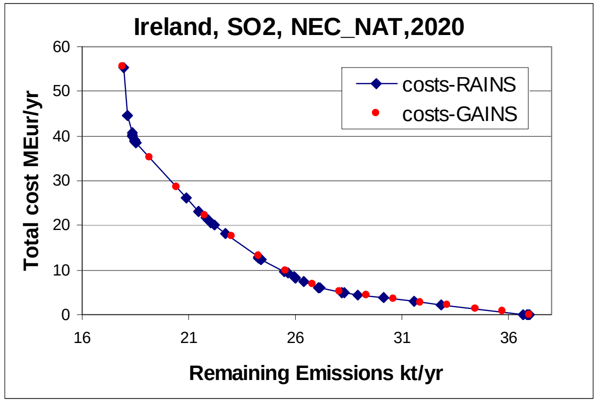

Greece, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
20
40
60
80
100
120
140
160
180
140
150
160
170
180
190
200
210

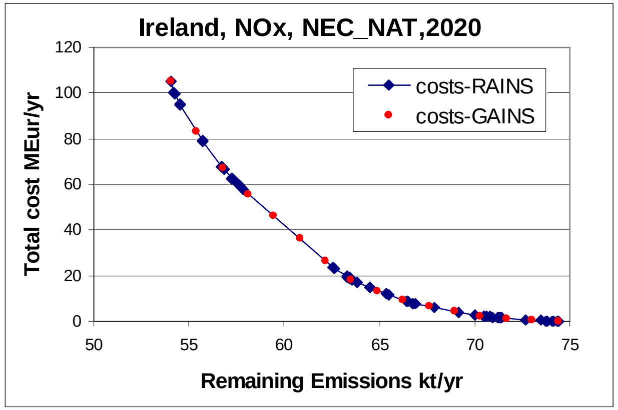

Greece, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
0
50
100
150
200
250
16
21
26
31

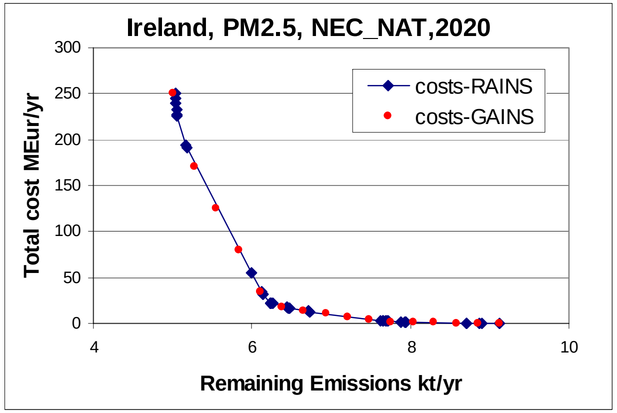

Hungary, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

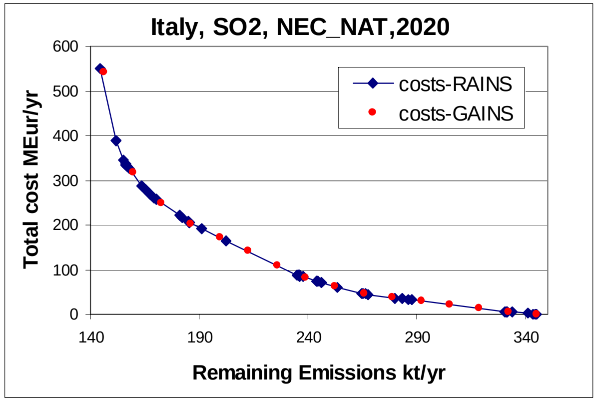

Hungary, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

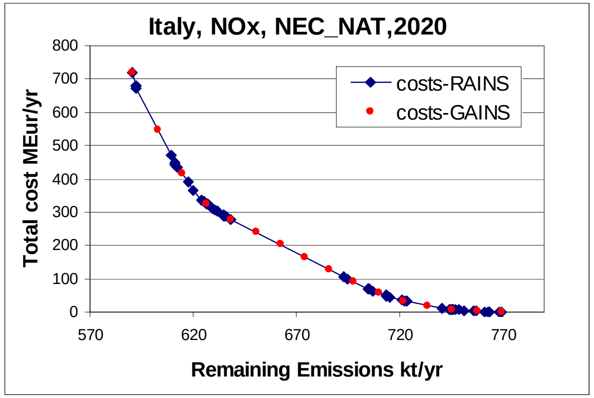

Hungary, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

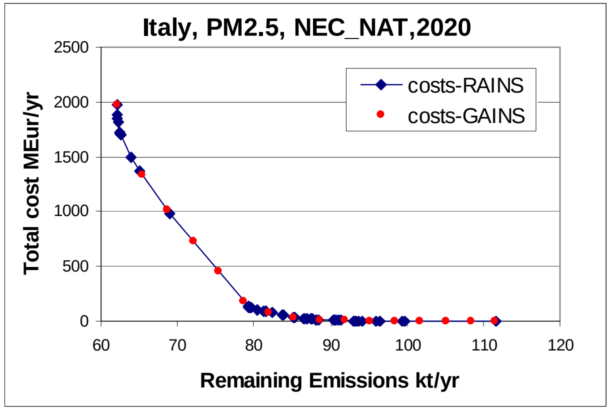

Ireland, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

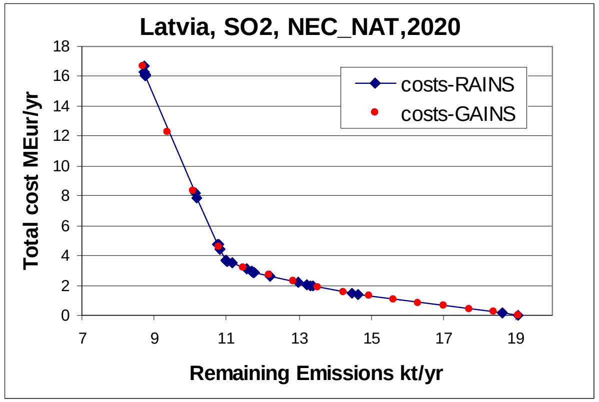

Ireland, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

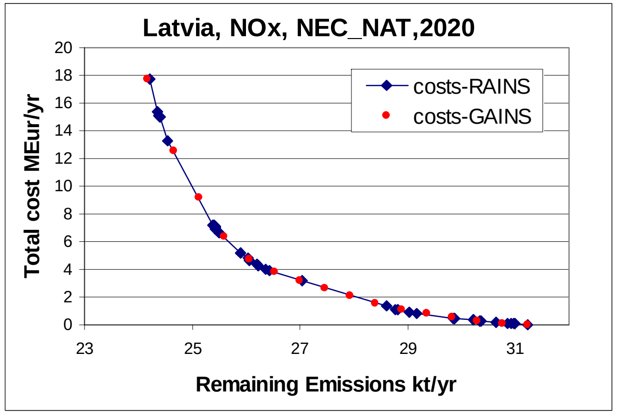

Ireland, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

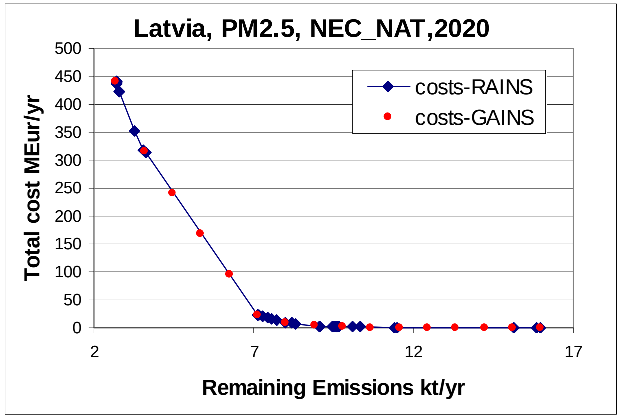

Italy, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

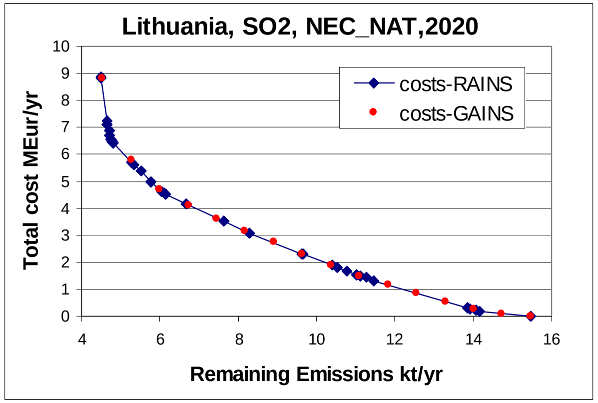

Italy, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

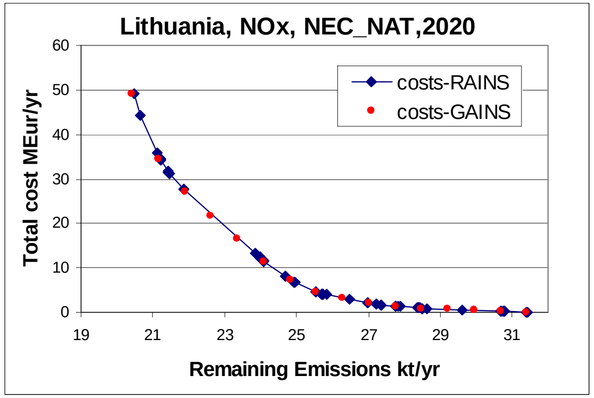

Italy, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

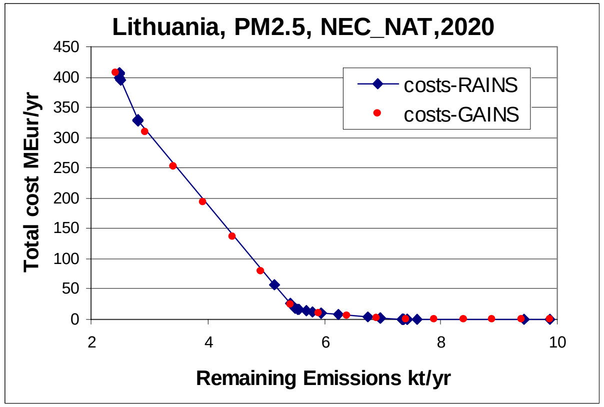

Latvia, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

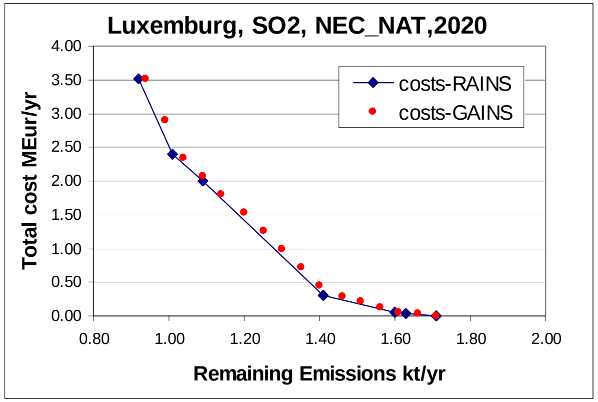

Latvia, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

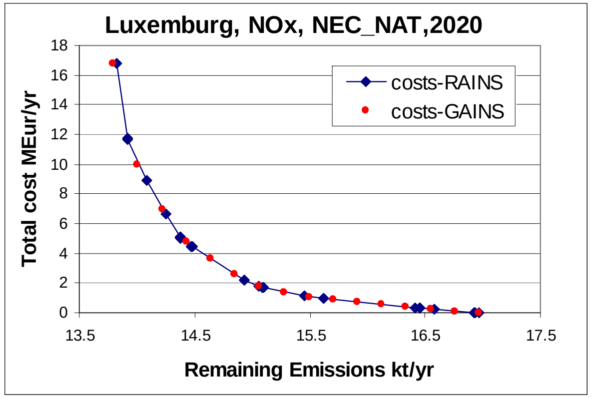

Latvia, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS

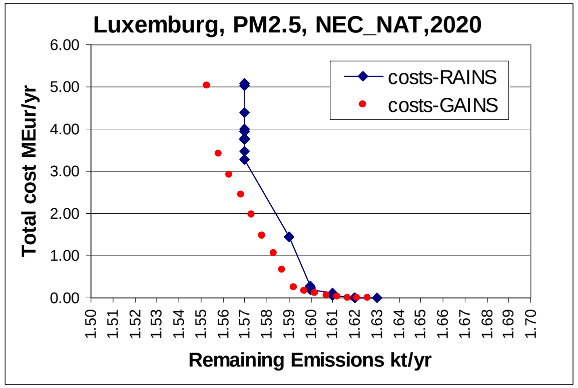

Lithuania, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

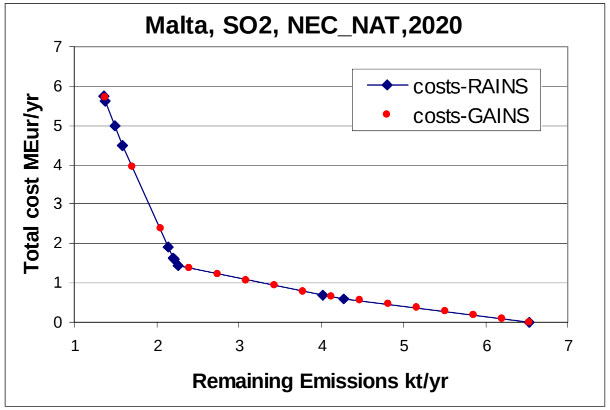

Lithuania, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

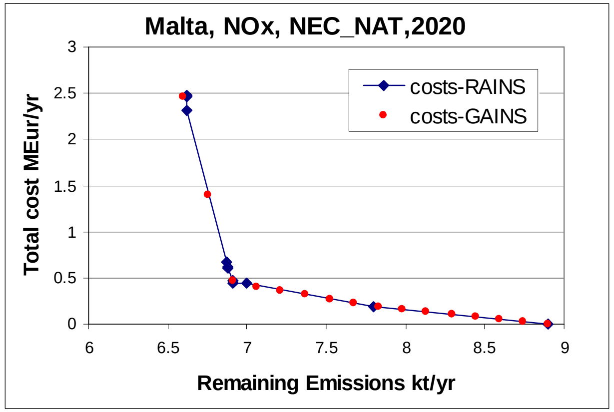

Lithuania, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

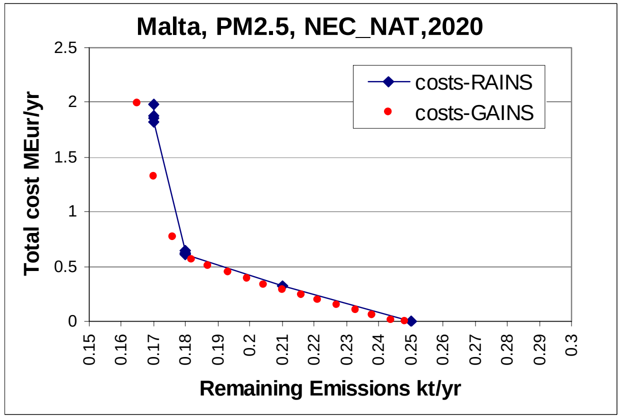

Luxemburg, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

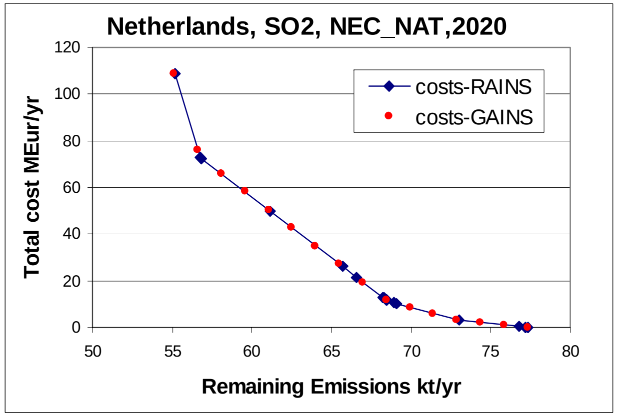

Luxemburg, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

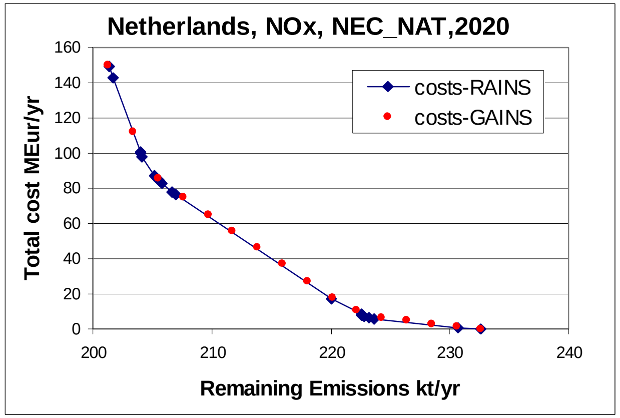

Luxemburg, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

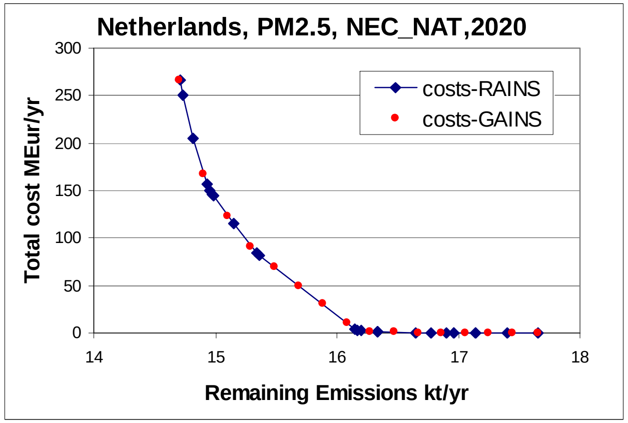

Malta, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

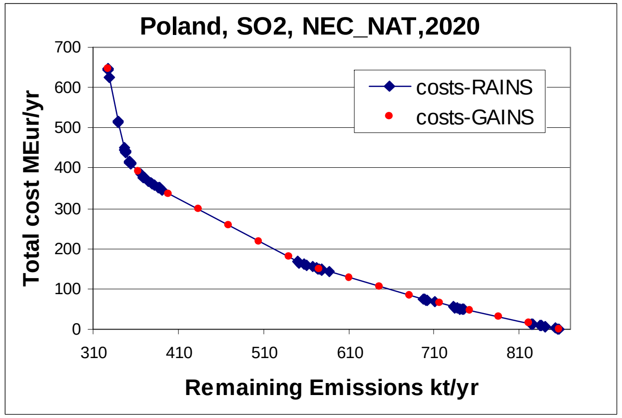

Malta, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

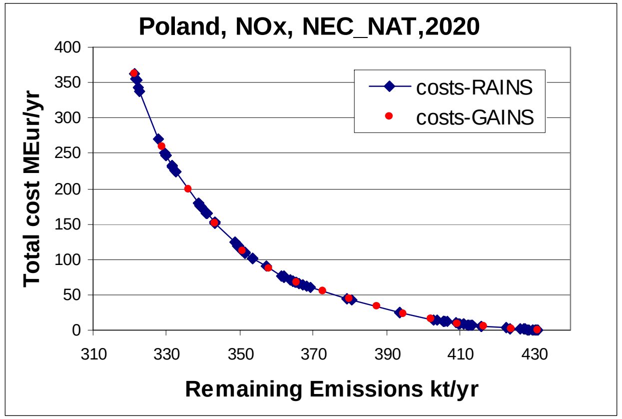

Malta, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

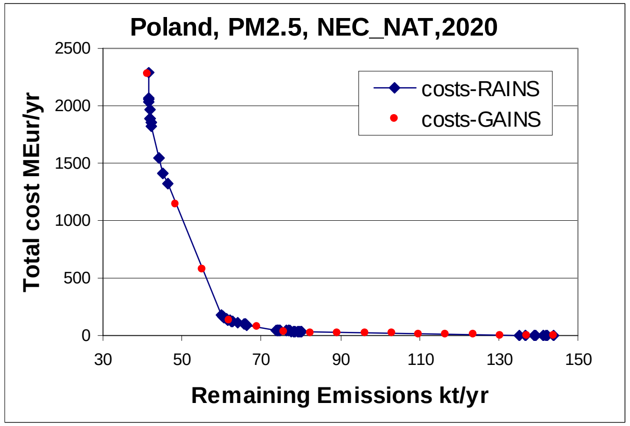

Netherlands, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

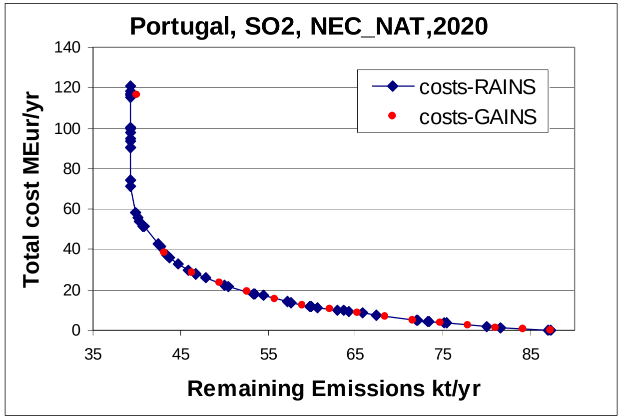

Netherlands, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

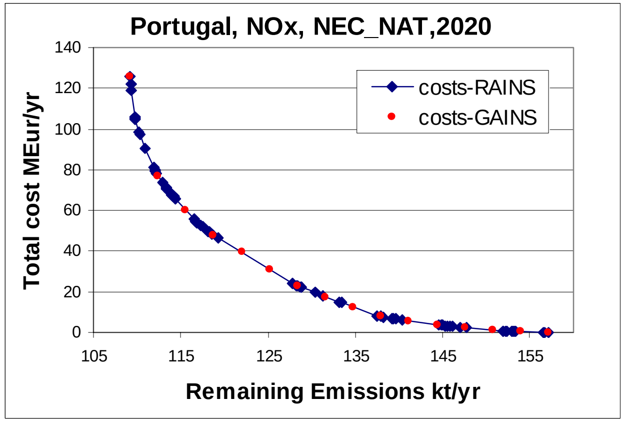

Netherlands, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

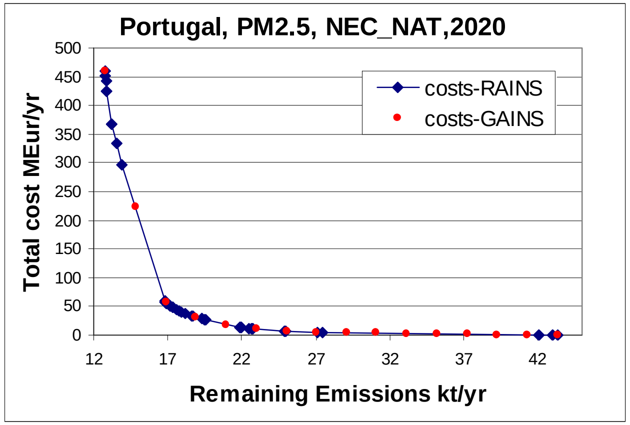

Poland, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

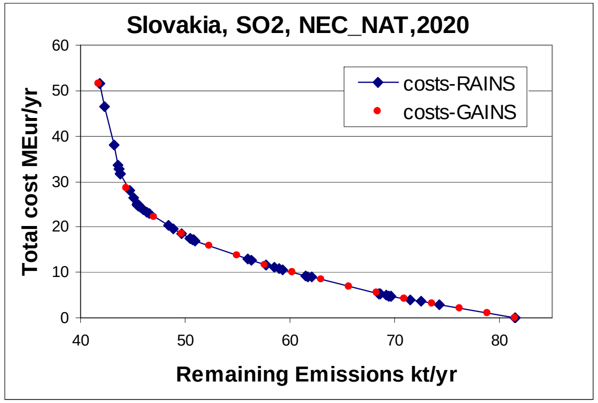

Poland, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

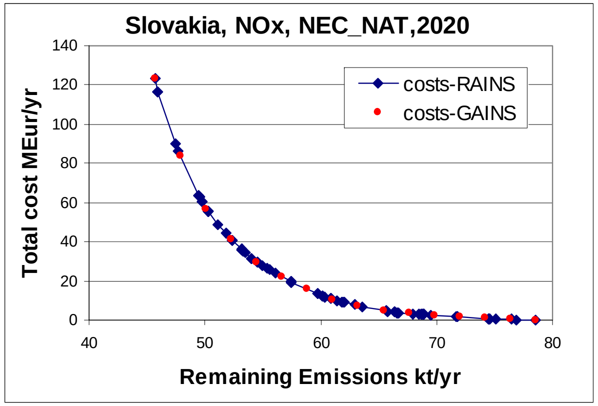

Poland, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

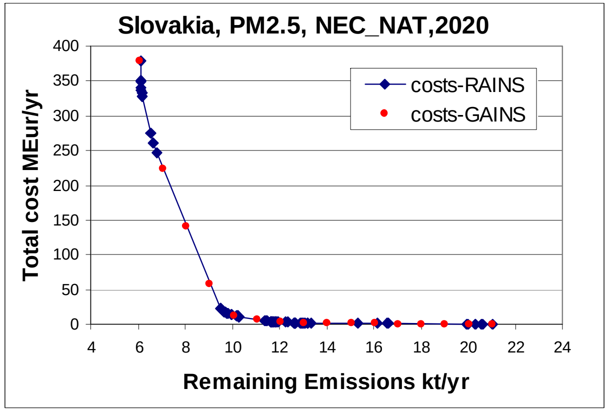

Portugal, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

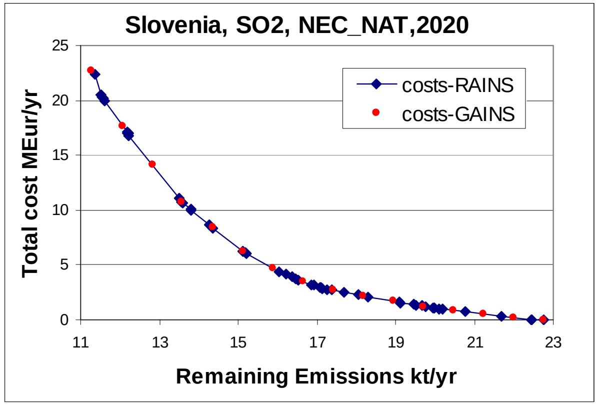

Portugal, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

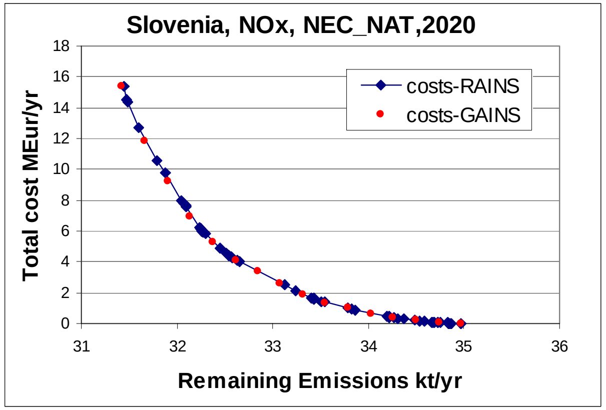

Portugal, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

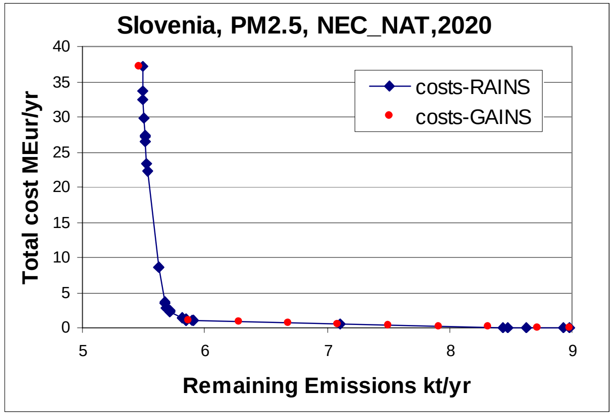

Slovakia, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

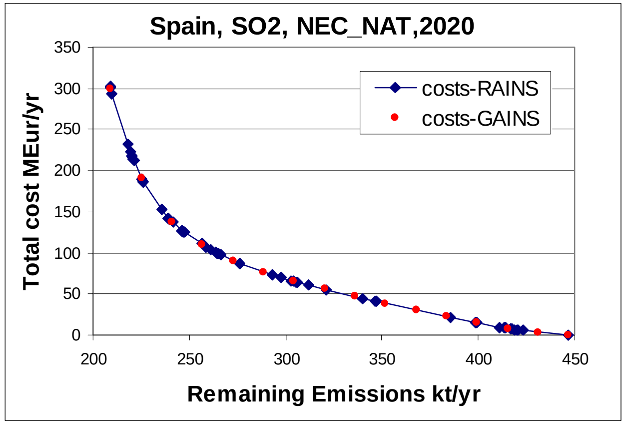

Slovakia, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

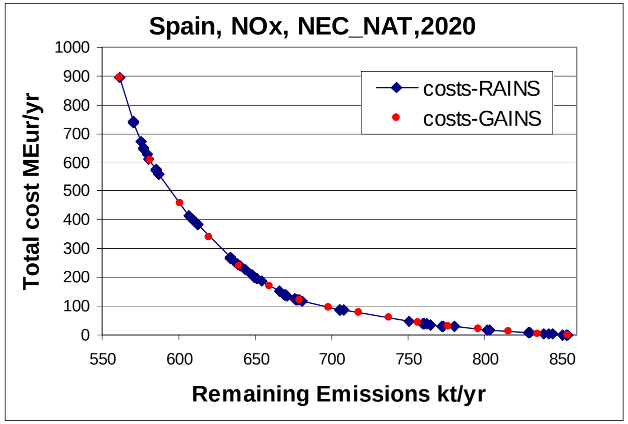

Slovakia, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

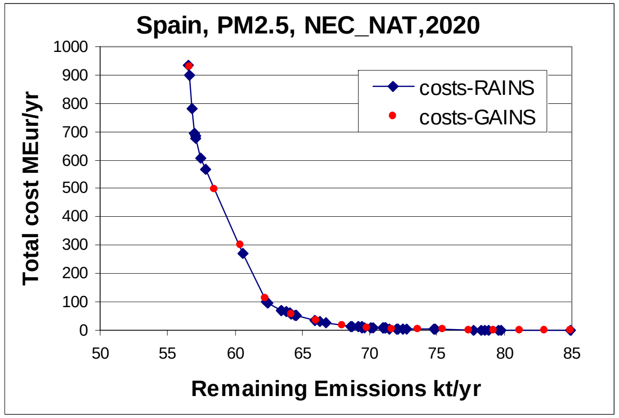

Slovenia, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

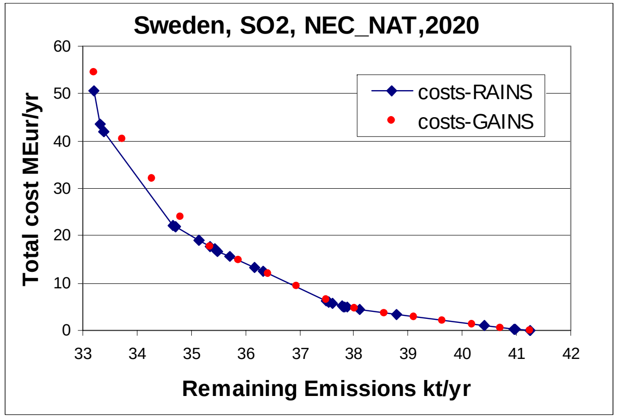

Slovenia, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

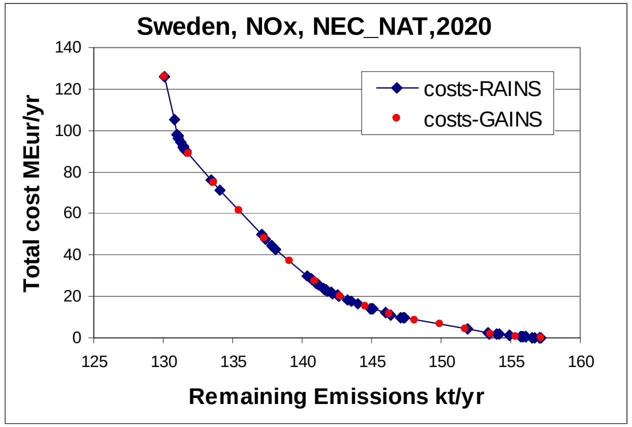

Slovenia, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

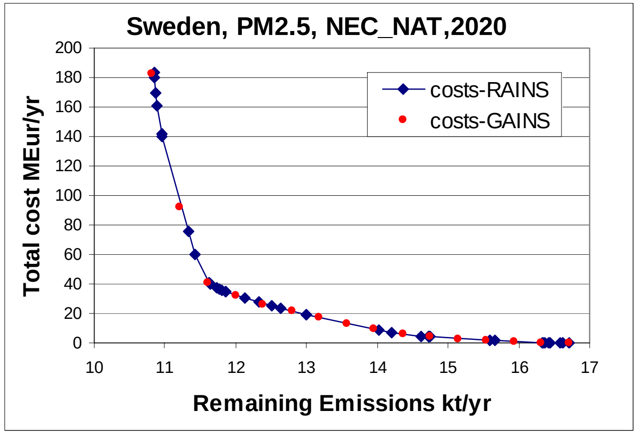

Spain, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

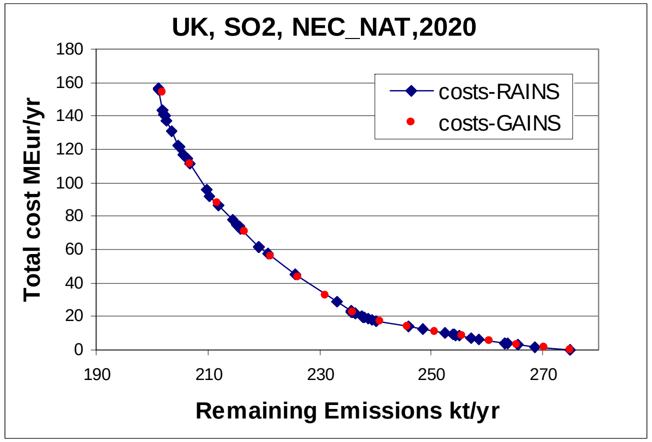

Spain, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

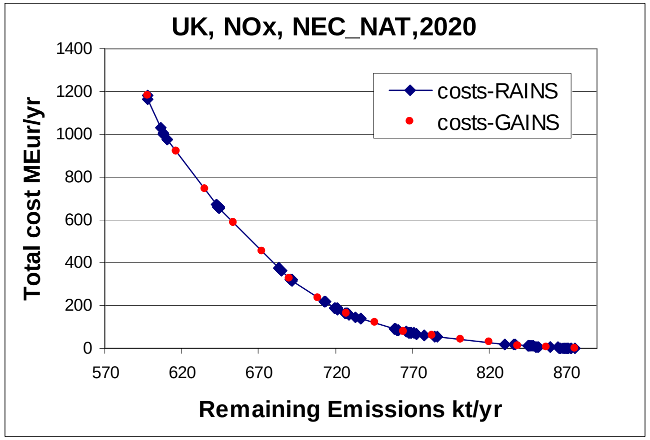

Spain, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr

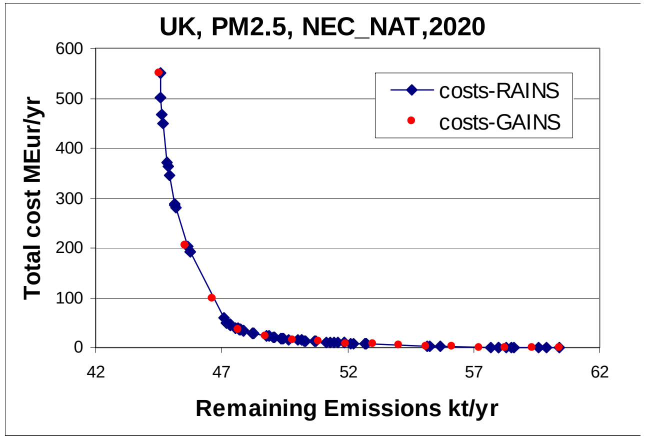

Sweden, SO2, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr


Sweden, NOx, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr


Sweden, PM2.5, NEC_NAT,2020
costs-RAINS
costs-GAINS
Total cost MEur/yr
Remaining Emissions kt/yr


UK, SO2, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
180
160
140
120
100
80
60
40
20
0
190
210
230
250
270


UK, NOx, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
1400
1200
1000
800
600
400
200
0
570
620
670
720
770
820
870


UK, PM2.5, NEC_NAT,2020
Total cost MEur/yr
Remaining Emissions kt/yr
costs-RAINS
costs-GAINS
600
500
400
300
200
100
0
42
47
52
57
62

References

Amann, M. and Lutz, M. (2000). The revision of the air quality legislation in the European Union related to ground-level ozone. Journal of Hazardous Materials 78, 41-62.

Amann, M., Cofala, J., Heyes, C., Klimont, Z., Mechler, R., Posch, M. and Schöpp, W. (2004). The RAINS model. Documentation of the model approach prepared for the RAINS review. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

CEC (2001). The Clean Air for Europe (CAFE) Programme: Towards a Thematic Strategy for Air Quality. Communication from the Commission. COM(2001)245 final. Commission of the European Communities, Brussels, Belgium.

CEC (2004). Service contract for Review of the RAINS Integrated Assessment Model. ENV.C1/SER/2003/0079. Commission of the European Communities, Brussels.

CEC (2005). Communication from the Commission to the Council and the European Parliament on a Thematic Strategy on Air Pollution. SEC(2005) 1132. Commission of the European Communities, Brussels, http://eur-lex.europa.eu/LexUriServ/site/en/com/2005/com2005_0446en01.pdf.

Cofala, J. and Syri, S. (1998a). Sulfur emissions, abatement technologies and related costs for Europe in the RAINS model database. IR-98-035. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Cofala, J. and Syri, S. (1998b). Nitrogen oxides emissions, abatement technologies and related costs for Europe in the RAINS model database. IR-98-88. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Höglund-Isaksson, L. and Mechler, R. (2005). The GAINS Model for Greenhouse Gases - Version 1.0: Methane (CH_4). IIASA IR-05-54. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Klaassen, G., Amann, M., Berglund, C., Cofala, J., Höglund-Isaksson, L., Heyes, C., Mechler, R., Tohka, A., Schöpp, W. and Winiwarter, W. (2004). The Extension of the RAINS Model to Greenhouse Gases. IR-04-015. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Klaassen, G., Berglund, C. and Wagner, F. (2005). The GAINS Model for Greenhouse Gases - Version 1.0: Carbon Dioxide (CO_2). IIASA Interim Report IR-05-53. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Klimont, Z., Amann, M. and Cofala, J. (2000). Estimating Costs for Controlling Emissions of Volatile Organic Compounds from Stationary Sources in Europe. IR-00-51. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Klimont, Z., Cofala, J., Bertok, I., Amann, M., Heyes, C. and Gyarfas, F. (2002). Modelling Particulate Emissions in Europe: A Framework to Estimate Reduction Potential and Control Costs. IR-02-076. International Institute for Applied Systems Analysis (IIASA), Laxenburg.

Klimont, Z. and Brink, C. (2006). Modelling of Emissions of Air Pollutants and Greenhouse Gases from Agricultural Sources in Europe. IR-04-048. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Schöpp, W., Amann, M., Cofala, J., Heyes, C. and Klimont, Z. (1999). Integrated Assessment of European Air Pollution Emission Control Strategies. Environmental Modeling and Software 14(1), 1-9.

Tohka, A. (2005). The GAINS Model for Greenhouse Gases –Version 1.0: HFC, PFC and SF6. Interim Report IR-05-56. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Tuinstra, W., Hordijk, L. and Amann, M. (1999). Using computer models in international negotiations. The case of acidification in Europe. Environment 41(9), 33-42.

Wagner, F., Schöpp, W. and Heyes, C. (2006). The RAINS optimization module for the Clean Air For Europe (CAFE) Programme. IR-06-29. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Wagner, F., Amann, M. and Schoepp, W. (2007). The GAINS optimization module as of 1 February 2007. Interim Report IR-07-004. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Winiwarter, W. (2005). The GAINS Model for Greenhouse Gases - Version 1.0: Nitrous Oxide (N_2O). Interim Report IR-05-55. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.