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# INTEGRATED ASSESSMENT OF AIR POLLUTION AND GREENHOUSE GASES MITIGATION IN EUROPE

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**Keywords**: Air pollution, greenhouse gases, integrated assessment, policy applications.

**Abstract**: Paper discusses integrated assessment methodology of air pollution and greenhouse gases mitigation. RAINS/GAINS model developed at the International Institute for Applied Systems Analysis (IIASA) is described. Its use in policy-relevant analysis is discussed with particular focus on studies for the development of policies of the European Union and under the UN/ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). Importance of interactions and synergies between air pollution and greenhouse gases policies is stressed. Integrated assessment has proven to be an important tool for preparation of air pollution control legislation in Europe. Although most prominent applications of integrated assessment referred to international policies, recently these methods have been applied in several national studies for in-depth analyses at sub-national regional level. It is advisable to further disseminate applications of the methodology and software tools for regional assessment.

## INTRODUCTION

Economic activities such as energy consumption, industrial production and agricultural farming cause emissions of air pollutants, which have several negative effects on ecosystems and human health. Exposure of people to fine particles increases morbidity and mortality. Elevated concentrations of ground-level ozone have impact on human health and cause damage to sensitive plants. Deposition of acidifying substances causes leaching of nutrients and releases toxic metals to the soil and waters, which in turn damages plants and fish in lakes. Excessive deposition of nitrogen (eutrophication of ecosystems) endangers bio-diversity.

There are important linkages and interactions between emissions and mitigation strategies for gases contributing to air pollution and greenhouse effect. Systematic analysis of those interactions requires an integrated approach. This paper discusses such an approach developed at IIASA. Main features of the integrated assessment model RAINS/GAINS are described. Next, applications of the model in policy-relevant studies for Europe and in particular for the revision of the EU National Emission Ceilings (NEC) Directive are discussed.

## RAINS/GAINS METHODOLOGY

Air pollution needs to be considered as a multi-pollutant, multi-effect problem. Major pollutants are particulate matter (PM), sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), ammonia ($NH_3$), non-methane organic compounds (VOC). These pollutants cause acidification and eutrophication of ecosystems, high concentrations of ground-level ozone, and have important negative health effects. Since air pollutants are transported in the atmosphere over long distances, mitigation strategies require international action. Solving such a complex problem requires an integrated approach. In 1990's IIASA has developed the RAINS model (Regional Air Pollution Information and Simulation) to study cost-efficient strategies to control air pollution in Europe [4]. Pollutants and effects covered by RAINS are shown in Table 1 (part with a grey background).

Table 1. Environmental effects of air pollutants and greenhouse gases covered by the GAINS model

| | PM | $SO_2$ | $NO_x$ | VOC | $NH_3$ | $CO_2$ | $CH_4$ | $N_2O$ | BC, OC, F-gases |
|---|---|---|---|---|---|---|---|---|---|
| Health impacts: | | | | | | | | | |
| PM | √ | √ | √ | √ | √ | | | | |
| $O_3$ | | | √ | √ | | | √ | | |
| Vegetation damage: | | | | | | | | | |
| $O_3$ | | | √ | √ | | | √ | | |
| Acidification | | √ | √ | | √ | | | | |
| Eutrophication | | | √ | | √ | | | | |
| Radiative forcing: | | | | | | | | | |
| – direct | | | | | | √ | √ | √ | √ |
| – via aerosols | √ | √ | √ | √ | √ | | | | |
| – via OH | | | √ | √ | | | √ | | |

area with grey background – pollutants and effects covered by the RAINS model; extensions to GAINS are shown in red

PM – particulate matter
$NO_x$ – nitrogen oxides
$NH_3$ – ammonia
$CH_4$ – methane
F-gases – fluorinated gases
OC – organic carbon
$O_3$ – ozone
$SO_2$ – sulfur dioxide
VOC – non-methane volatile organic compounds
$CO_2$ – carbon dioxide
$N_2O$ – nitrous oxide
BC – black carbon
OH – hydroxide

There are important linkages between emissions of air pollutants and climate-relevant gases. These linkages exist because: (i) air pollutants have a radiative forcing too, (ii) air pollutants and greenhouse gases have common sources, (iii) controls of air pollutants and greenhouse gases result in joint benefits. Thus, over the last few years, the RAINS model has been extended to capture (economic) interactions between the control of conventional air pollutants and climate-relevant gases [12, 13]. Additional gases/pollutants and their effects covered are shown in Table 1 in red. Extended model is called GAINS (Greenhouse gas – Air pollution Interactions and Synergies) and covers – in addition to air pollutants – greenhouse gases (GHGs): carbon dioxide – $CO_2$ [13], methane

– $CH_4$ [11], nitrous oxide – $N_2O$ [24], the F-gases [20] as well as black and organic carbon (BC and OC). The model analyzes cost-efficiency of policies and measures in medium-term (10–30 years) for air pollutants and climate relevant gases. The model covers all European countries as individual emission sources.

For each of the pollutants listed in Table 1, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied. This approach allows for 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. GAINS estimates future emissions by varying the activity levels along exogenous projections of anthropogenic driving forces and by taking into account the implementation rates of emission control measures.

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

- *Behavioral changes* that reduce anthropogenic driving forces generating 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.
- A wide range of *technical measures* that 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. GAINS considers about 1500 activity- and pollutant-specific end-of-pipe measures for reducing $SO_2$, $NO_x$, VOC, $NH_3$ and PM emissions and several hundred options for greenhouse gases and assesses their application potentials and costs.

GAINS assumes a free market for emission control technologies. Thus, the same technology is 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 control options, GAINS estimates their costs of local application considering annualized investments, as well as fixed and variable operating costs. Next, these costs are used in the optimization routine.

An integrated assessment needs to link changes in the precursor emissions at various sources to responses in impact-relevant air quality indicators. GAINS analysis relies on source-receptor relationships developed from the Unified EMEP Eulerian Model [18]. In GAINS, the regional-scale assessment is performed for whole Europe with a spatial resolution of 50 km × 50 km. Health impacts are, however, most pertinent to urban areas where pollution levels are higher and where a major part of the European population lives. Thus GAINS uses the so-called urban increments, derived from the City-delta model intercomparison [19]. They reflect the local increase in PM concentration due to emissions in the city itself. Next, GAINS quantifies premature mortality that can be attributed to a long-term exposure to fine particles ($PM_{2.5}$) using dose-response functions as suggested by the World Health Organization (WHO) [23]. To identify ecosystems risks from acidification and eutrophication, GAINS uses (ecosystem-specific) annual mean deposition of acidifying compounds and compares them with critical loads compiled by the Coordination Centre for Effects (CCE) of the United Nations Economic Commission for Europe (UN/ECE) Working Group on Effects [10]. For ozone, the SOMO35 indicator is used [21] to quantify premature mortality.

As one of its most policy-relevant features, the optimization approach of the GAINS model allows a systematic search for cost-minimal combinations of emission control measures that meet user-supplied air quality and greenhouse gases emission targets. Optimization takes into account regional differences in emission control costs and atmospheric dispersion characteristics. A detailed mathematical description of the GAINS optimization model is provided in [22]. RAINS/GAINS model as well as corresponding databases are available on the Internet (http://www.iiasa.ac.at/web-apps/apd/gains).

## POLICY APPLICATIONS OF RAINS/GAINS

RAINS was used as a modeling tool for preparation of the protocols to the UN/ECE Convention on Long-range Transboundary Air Pollution (CLRTAP): the Second Sulfur Protocol (1994) and the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (1999) as well as for the EU National Emission Ceilings Directive (NEC) – 2001. It has been demonstrated that effect-oriented international pollution control strategies are much more efficient than strategies based on other principles. As an example, Figure 1 demonstrates cost-efficiency of reducing population exposure to ozone using RAINS optimization routine. The data originate from studies used in connection with the preparation of the Gothenburg Protocol to the CLRTAP. The red line, stretching from the reference (REF) case through three optimal scenarios for different ambition levels (G5/1 to G5/3) shows the changes in costs for different values of impact indicator. Next, the cost-optimal solutions are compared to scenarios based on uniform percentage reduction in each country or uniform per capita emissions. Costs for the later scenarios are up to a factor of five higher than for the effect-oriented cases with the same reduction of exposure index.

Recently RAINS was applied as a basic tool for the assessment within the EU Clean Air for Europe (CAFE) Program. CAFE results have been used for preparation of the EU Thematic Strategy on Air Pollution [7]. The Strategy proposed the following targets regarding improvement of air pollution indicators in 2020 compared with the situation in 2000:

- decrease of life years lost caused by anthropogenic emissions of fine particles by 47%,
- decrease of area of forest and freshwater ecosystem with acid deposition above critical loads for acidification by 74 and 39% respectively,

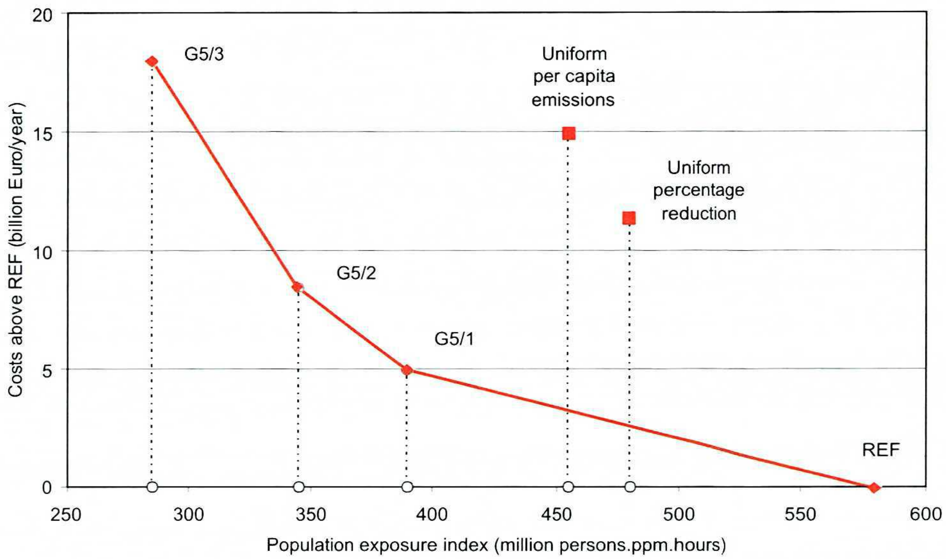

Fig. 1. Costs of reducing population exposure index to ground-level ozone using effect-oriented approach vs. uniform reductions cases

- decrease of ecosystem area where nitrogen deposition exceeds critical loads for eutrophication by 43%,
- decrease of premature mortality from ozone by 10%.

Currently revision of the NEC Directive is underway. The aim of this revision is to modify the emission ceilings for each Member State (EU-27) so that Thematic Strategy targets are met at least cost. Feasibility and costs of the ceilings for air pollution depend on policies with regard to greenhouse gases. Thus, GAINS is being applied for various sets of activity scenarios, including different assumptions on reducing the greenhouse gases. Figure 2 shows co-benefits (in terms of pollution reduction) of scenarios assuming various levels of $CO_2$ emissions. These scenarios have been developed with the use of the European energy model PRIMES [17] under different assumptions about carbon price (from 0 €/Mg $CO_2$ to 90 €/Mg $CO_2$). For comparison, points corresponding to the emissions for the CAFE baseline scenario and the national energy projections used for NEC are also shown. Within the range of carbon prices studied, a 1% reduction of $CO_2$ emissions causes approximately 1.5% reductions in $SO_2$ emissions. Co-benefits for $NO_x$ and $PM_{2.5}$ are also substantial.

As said above, GAINS also includes options for reduction of non-$CO_2$ greenhouse gases – $CH_4$, $N_2O$, and F-gases. As an example, Figure 3 demonstrates the emission reduction potential and marginal cost of reducing methane emissions from agriculture in the EU-15 and in the "New" Member States (NMS-10) as estimated in [11]. Data for more recent scenarios by country are available from GAINS on-line.

Table 2 presents the emissions of air pollutants for the EU Member States (EU-27) in 2000 and for two "Baseline" projections in 2020 as used in the NEC analysis [2]. The "National" scenario reflects national expectations of economic, energy, and agricultural developments in each Member State. The "Coherent" scenario was created with the EU-wide models (PRIMES for energy [17], CAPRI and FAO for agriculture [5, 8]). The co-

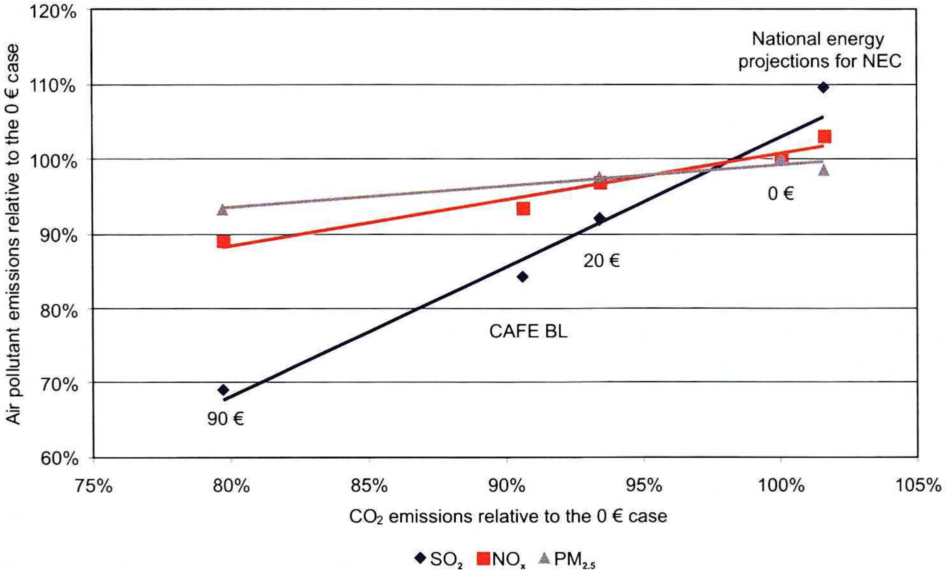

Fig. 2. Air pollutant emissions as a function of GHG mitigation; energy projections for EU-15 from the PRIMES model

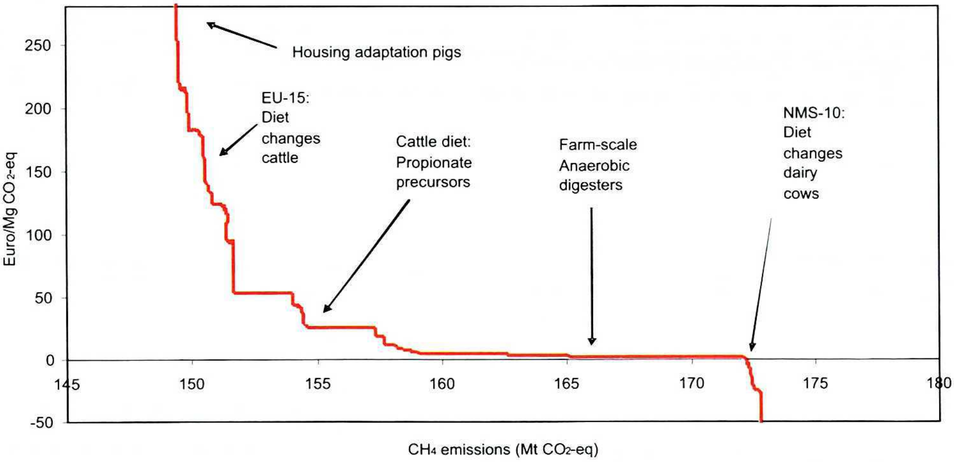

Fig. 3. Cost curve for methane reduction from the agricultural sector in countries of the European Union (an example)

herent scenario assumes meeting the recently adopted objectives of the European Union's energy policy: minus 20% reduction of greenhouse gases and 20% share of renewable energy by 2020. Each scenario assumes penetration of emission control measures according to the current international and national emission and fuel standards (the "Current legislation" case). Because of stringent standards already in force in the EU, emissions of all air pollutants decrease. In the national scenario, this decrease is 61% for $SO_2$, 43% for $NO_x$ and VOC, and about 10% for ammonia. In the "Coherent" scenario, the emission reductions are even higher.

Table 2. Scenarios of baseline emissions of air pollutants in the EU Member States (EU-27) as calculated by GAINS for NEC analysis

| | | 2020 | | | |
|---|---|---|---|---|---|
| | 2000 | National | | Coherent | |
| | $10^{12}$ g | $10^{12}$ g | Reduction from 2000 | $10^{12}$ g | Reduction from 2000 |
| $SO_2$ | 10.3 | 4.1 | -61% | 2.4 | -77% |
| $NO_x$ | 12.3 | 7.0 | -43% | 5.9 | -52% |
| VOC | 11.0 | 6.3 | -43% | 6.3 | -43% |
| $PM_{2.5}$ | 1.8 | 1.2 | -35% | 1.0 | -42% |
| $NH_3$ | 4.0 | 3.6 | -10% | 3.6 | -10% |

However, the Baseline reductions are not high enough to achieve the air quality targets from the Thematic Strategy [7]. Further, cost- optimized emission reductions by country necessary to achieve the targets are shown in Figure 4 for $NO_x$ and Figure 5 for $PM_{2.5}$. The vertical lines for each country show a difference between the Baseline emissions in 2020 and the maximum reductions as calculated by GAINS relative to the 2000 emissions. Markers (diamonds or squares) show the cost-optimal values. Details are available in [3].

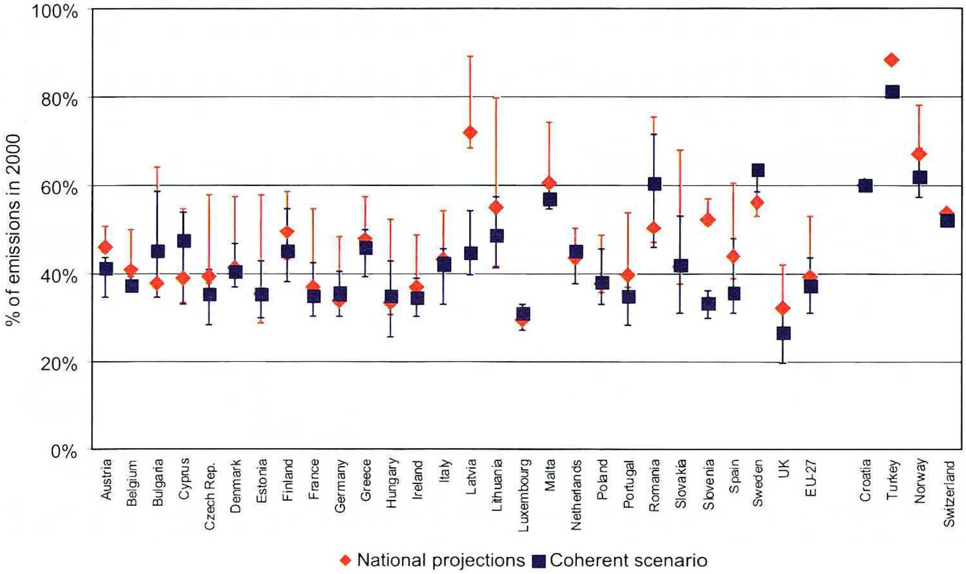

Fig. 4. Optimized emissions of $NO_x$ – reductions from the baseline level in 2020

Figure 6 shows the spatial distribution of the loss of life expectancy due to anthropogenic sources of $PM_{2.5}$ in the base year (2000) and compares it with the situation after achieving Thematic Strategy targets in a cost-optimal way. In 2000, the average loss of life expectancy in the European Union (EU-27) was more than eight months. On large areas in the Benelux countries, Poland, northern Italy and Hungary the loss was higher than 12 moths with peak values higher than 30 months. Reduction of emissions required to achieve the Thematic Strategy targets causes' important improvement of that indicator.

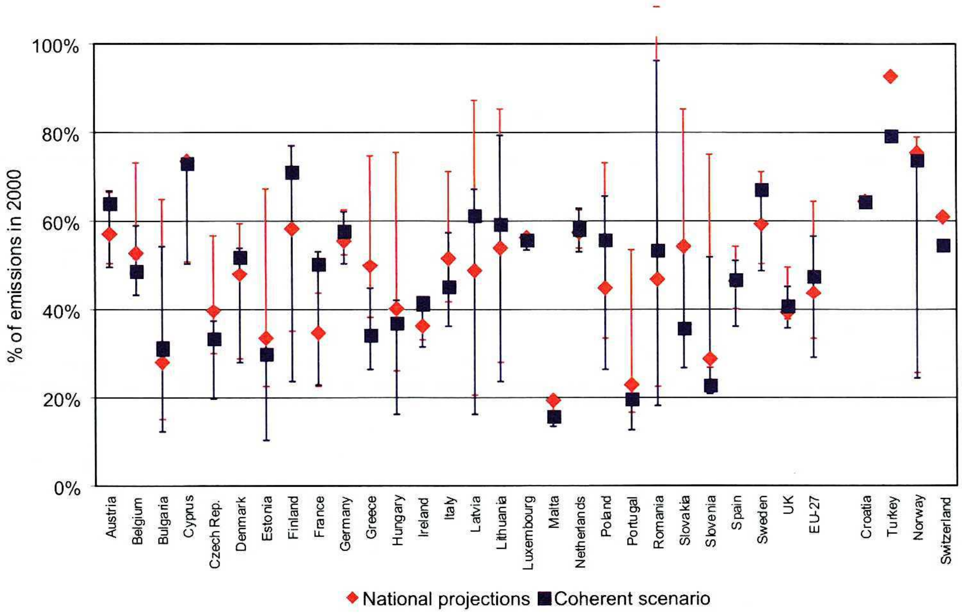

Fig. 5. Optimized emissions of $PM_{2.5}$ – reductions from the baseline level in 2020

Figure 7 presents the corresponding change in acidification indicator for forests. In 2000 about 260 000 km$^2$ of forest area were endangered by acidification. For the optimal case, endangered area is reduced to about 50 000 km$^2$.

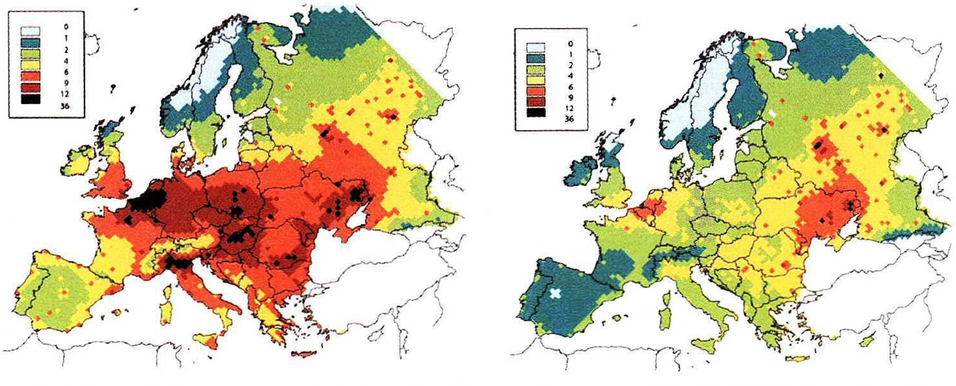

Fig. 6. Loss of life expectancy (months) due to anthropogenic sources of $PM_{2.5}$ in 2000 (left panel) and in 2020 for the scenario meeting the Thematic Strategy targets (right panel)

Currently new scenarios are under development. They take into account changes in structures of national energy systems implied by the proposal for "burden sharing" agreement with regard to the reduction of greenhouse gases. Finalization of the work on the revision of the NEC Directive is expected in spring 2010. Review of the Gothenburg Protocol to CLRTAP, which commenced in 2007 [14], is planned for 2010. Also in this review GAINS model plays a major role as a national scenarios generating tool and is used for checking the compliance with agreed targets.

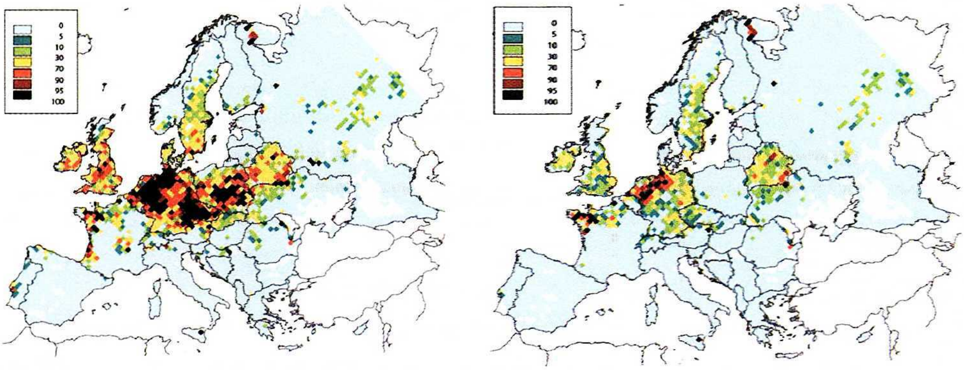

Fig. 7. Percentage of forest area with acid deposition above critical loads in 2000 (left panel) and in 2020 for the scenario meeting the Thematic Strategy targets (right panel)

Integrated assessment approach as used by RAINS/GAINS can also be applied to analyze national emission control policies, including zooming-in to sub-national regions or large emission sources. This is necessary in order to address the best ways of complying with international ceilings and targets as well as for development of tailored policies for heavily polluted regions. In late 1990's scientists from Poland worked on the development of RAINS-Poland model. The model was then applied for the analysis of environmental problems caused by emissions of $SO_2$ and $NO_x$ [15, 16]. It is recommended that Poland continues work on integrated assessment capabilities to find the best ways of implementation of the upcoming revised NEC Directive as well as to address pollution problems in many of Polish cities caused, inter alia, by the use of low-quality coal as household fuel. Recently, the Netherlands and Italy implemented RAINS as a support tool for analyzing their national air pollution problems – compare [1, 9] and [6]. Sweden and Ireland are working on national implementations.

## SUMMARY AND CONCLUSIONS

Experience with RAINS/GAINS clearly indicates that integrated models enable comprehensive, policy-relevant assessment of air pollution control strategies. They help to explore a wide range of activity scenarios and air quality/greenhouse gases emissions targets. Thanks to the optimization capability, the models allow for achieving environmental targets at least cost. Thus the models have been widely used in exploring all-European air pollution control policies and served for preparation of air pollution control legislation in Europe. Also national implementations of that approach are getting momentum and deliver results that support international efforts to reduce air pollution as well as demonstrate synergistic effects of strategies to reduce emissions of gases contributing to climate change. Recently GAINS has been applied for China and India. Work on a global version of the model, which will include remaining major emitters of air pollutants and greenhouse gases in the world, is under way.

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## ZINTEGROWANE OCENY REDUKCJI ZANIECZYSZCZEŃ POWIETRZA I EMISJI GAZÓW CIEPLARNIANYCH W EUROPIE

Artykuł omawia metodologię zintegrowanych ocen redukcji zanieczyszczeń powietrza oraz redukcji emisji gazów cieplarnianych. Opisano model RAINS/GAINS opracowany w Międzynarodowym Instytucie Stosowanej Analizy Systemowej (IIASA). Omówiono zastosowanie modelu w studiach mających znaczenie dla kształtowania europejskiej polityki środowiskowej, ze szczególnym uwzględnieniem polityki Unii Europejskiej oraz prac w ramach Konwencji EKG ONZ w sprawie transgranicznego zanieczyszczenia powietrza na dalekie odległości. Podkreślono znacznie interakcji i synergii między strategiami kontroli zanieczyszczenia powietrza i redukcji emisji gazów cieplarnianych. Zintegrowane oceny są ważnym elementem działań na rzecz poprawy jakości środowiska w Europie. Dotychczas metody te były stosowane przede wszystkim do badań na poziomie międzynarodowym. Ostatnio znajdują one coraz szersze zastosowanie w badaniach krajowych do szczegółowych analiz na poziomie regionalnym. Celowe jest dalsze rozpowszechnianie zastosowań tej metodologii oraz narzędzi do ocen regionalnych.