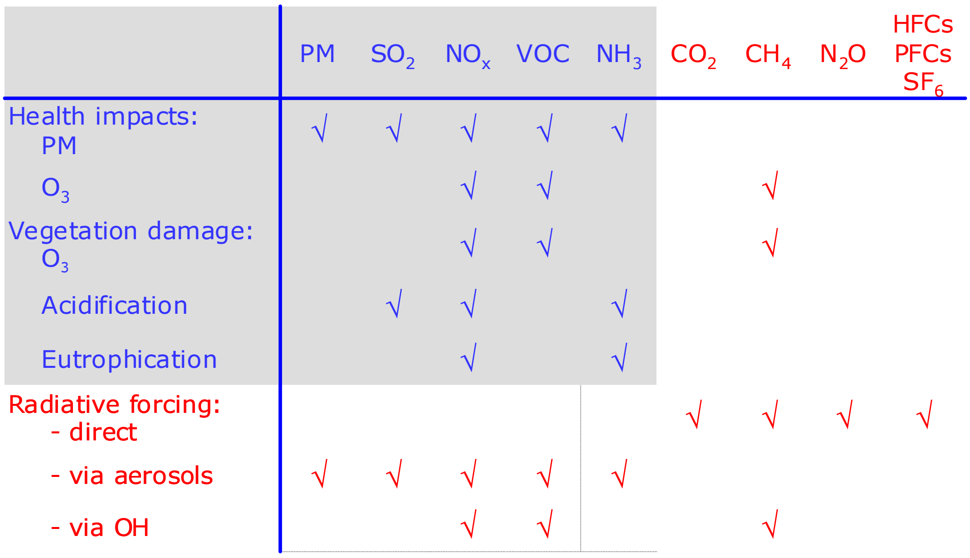
The GAINS model

1 Introduction

The Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model (http://gains.iiasa.ac.at/) has been developed at the International Institute for Applied Systems Analysis (IIASA) and provides an integrated assessment framework describing the pathways of atmospheric pollution from anthropogenic driving forces to relevant health and environmental impacts. It brings together information on future economic, energy and agricultural development, emission abatement potentials and costs, atmospheric dispersion and environmental sensitivities towards air pollution. The model addresses threats to human health posed by fine particles and ground-level ozone, and the risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated levels of ozone. These impacts are considered in a multi-pollutant context, quantifying the contributions of all major air pollutants as well as the six greenhouse gases considered in the Kyoto protocol (Figure 1).



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

Figure 1: The GAINS multi-pollutant/multi-effect framework.

The model can explore cost-effective strategies to reduce emissions of air pollutants in order to meet specified environmental targets. It also assesses how specific control measures simultaneously influence different pollutants, permitting a combined analysis of air pollution and climate change mitigation strategies, which can reveal important synergies and trade-offs between these policy areas.

A comprehensive description of the European version of the GAINS model is given in (Amann et al., 2011), which also illustrates the application of the model using a recent policy analysis. Brief descriptions of those aspects of the model framework of most relevance to the EUCLIMIT project are described in the subsequent sections.

2 Methodology

2.1 Emission estimates

For each of the pollutants shown in Figure 1 GAINS estimates current and future emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied. In the general GAINS methodology, emissions from source s in region i and year t are calculated as the activity data A_{its} times an emission factor ef_{ism}. If emissions are controlled through implementation of technology m, the fraction of the activity controlled is specified by $Appl_{itsm}$, i.e.,

$$E_{its} = \sum_{m} \left[A_{its} * ef_{ism} * Appl_{itsm} \right], \tag{1}$$

where $ef_{ism} = ef_{is}^{NOC} * (1 - remeff_{sm})$ and $\sum_{m} Appl_{its} = 1$, (2)

and where	A_{its}	is the activity (e.g., number of animals, amounts of fuel or waste),
	ef_{ism}	is the emission factor for the fraction of the activity subject to control by technology m,
	$Appl_{itsm}$	is the application rate of technology m to activity s,
	ef_{is}^{NOC}	is the no control emission factor for activity s, and
	$remeff_{sm}$	is the removal efficiency of technology m when applied to activity s.

This approach takes account of critical differences across economic sectors and countries that could justify differentiated emission reduction requirements in a cost-effective strategy. Structural differences in emission sources are reflected through country-specific activity levels. Major differences in emission characteristics of specific sources and fuels are represented through source-specific emission factors, which account for the extent to which emission control measures are applied. Future emissions are estimated by varying the activity levels along external projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures.

The GAINS model holds relevant data for all European countries, employing international energy and agricultural statistics and appropriate emission factors.

2.2 Mitigation potentials and costs

A wide range of technical measures has been developed to capture emissions at their sources before they enter the atmosphere. GAINS considers about 3500 end-of-pipe measures for reducing emissions of SO_2, NOx, VOC, NH_3, PM, CH_4, N_2O and F-gases, as well as 350 options to reduce CO_2 through structural changes.

In order to assess emission control costs accurately, it is important to identify the factors leading to variations in costs between countries, economic sectors and pollutants. Diversity is caused 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 no trade barriers in the market for emission control technologies, the same technology is assumed available to all countries at the same investment costs. However, country- and sector-specific circumstances (e.g., size distributions of plants, plant utilisation, fuel quality, energy and labour costs, etc.) lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources.

For each of the 3500 emission control options, GAINS estimates the costs of local application considering annualised investments, fixed and variable operating costs, and how they depend on technology, country and activity type. Mitigation costs per unit of activity are calculated in GAINS as the sum of investment costs, labour costs, fuel costs (or cost-savings), and operation and maintenance costs (or cost-savings) unrelated to labour and fuel costs. The unit cost of technology *m* in country *i* and year *t* is defined as:

$$C_{itm} = I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right] + M_{im} + \left(L_{im} \times W_{it} \times w_{is}\right) + \left(F_{im} \times p_{it}^{fuel}\right) \qquad (3)$$

where $I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right]$ is the annualized investment cost for technology *m* in country *i* and with interest rate *r* and technology lifetime of *T* years,

M_{im} is the sum of annual operation and maintenance costs (or cost-savings) unrelated to labour or fuel costs,

L_{im} is the fraction of annual work hours for operating technology *m*,

W_{it} is the annual average wage in country *i* in year *t*,

w_{is} is a country-specific wage adjustment factor for type of sector *s* (agriculture or manufacturing industry),

F_{im} is the additional amount of energy used or recovered when applying technology *m*, and

p_{it}^{fuel} is the fuel price in country *i* in year *t* for the energy used or recovered under technology *m*.

3 Modelling non-CO_2 greenhouse gas emissions and mitigation

Non-CO_2 greenhouse gases (GHGs) in the GAINS model include methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), which are all addressed in the Kyoto protocol. The GAINS model has been used on several occasions to estimate current and future emissions of non-CO_2 GHGs in the European Union in support of the EU climate strategy (Amann et al., 2008; Höglund-Isaksson et al. 2010; Höglund-Isaksson et al., 2012). A detailed description by sector of the methodology applied to the estimation of non-CO_2 greenhouse gases in the EU was compiled in a report by Höglund-Isaksson, Winiwarter and Tohka (2010). An updated version of the report is scheduled for April 2012.

Baseline emissions of greenhouse gases in the EU and policy scenarios for mitigation are estimated in a joint effort by the PRIMES, CAPRI, GAINS and GLOBIOM models. All models use economic forecasts from the European Commission (DG-ECFIN) as starting point for model scenarios. While CO_2 emissions are modelled within the PRIMES energy systems model, emissions of non-CO_2 GHGs and air pollutants consistent with the estimated CO_2 emissions, are modelled using the GAINS model. The consistency between the models is maintained in GAINS through the use of energy activity data on e.g., fuel production and consumption from the PRIMES model and agricultural activity data on e.g., livestock numbers and fertilizer application from the CAPRI agricultural sector model. The activity data generated externally for energy and agricultural activities are complemented with data generated internally for other sectors e.g., waste, wastewater, air conditioning and refrigeration. Consistency in these sectors is maintained by using the same macroeconomic forecast from DG-ECFIN as in the PRIMES and CAPRI models. The procedure is illustrated in Figure 2.

The activity data are combined with emission factors to produce estimates of uncontrolled emissions. To the extent possible given the available information, country-specific emission factors are derived following the recommendations in the IPCC guidelines (1997 and 2006). Deriving emission factors from country-specific information on factors important for the emission generation in a sector makes it possible to produce emission estimates that are consistent and comparable across countries. When country-specific information is unavailable or insufficient, default emission factors from the IPCC guidelines or other sources are used.

Baseline emission estimates reflect emissions including the effects of currently implemented control measures or future implementation of control foreseen in already adopted EU-wide or national legislation. EU-wide legislation affecting emissions of non-CO_2 GHGs directly or indirectly that is considered in the GAINS modelling of non-CO2 GHGs as of December 2011 include: the Landfill Directive (1999/31/EC), the Waste Directive (2006/12/EC), the Waste Management Framework Directive (2008/98/EC), the Nitrate Directive (1991/676/EEC), the Common Agricultural Policy Reform (2006/144/EC), the CAP "Health check" and "Set aside" regulation (73/2009), the F-gas regulation (2006/842/EC), the MAC Directive (2006/40/EC), the Biofuels Directive (2009/28/EC), the EU Emission Trading System (2003/87/EC and its subsequent amendments) and the Effort Sharing Decision (2009/406/EC). National legislation affecting emissions of non-CO_2 GHGs includes complete bans on deposition of biodegradable waste on landfills in Denmark, Germany and Sweden, and national legislation controlling emissions of nitrogen compounds (NO_X, NH_3), which indirectly affect N_2O emissions. In addition, baseline emission estimates also regard the effects of a voluntary agreement to reduce PFC emissions in the semiconductor industry (ESIA, 2006).

As shown in Figure 2, once a first set of draft baseline emission estimates has been produced, the result for a historical base year, e.g., 2005 or 2010, is compared on a sector level with emissions reported by countries to UNFCCC under the Kyoto protocol. Reasons for discrepancies are scrutinized and adjustments made when considered justified, i.e. to the extent that the consistent modelling across countries is preserved. To match base year emission estimates with reported emissions on a country level, the remaining sector discrepancies in emissions are summed up on a country-level and enter the modelling of future emissions as a constant factor.

The resulting adjusted baseline emission estimates are provided to experts in the EU member states for review. Improved information received through feedback from member state experts is incorporated into emission estimates to produce a final baseline scenario for non-CO_2 greenhouse gases in the EU.

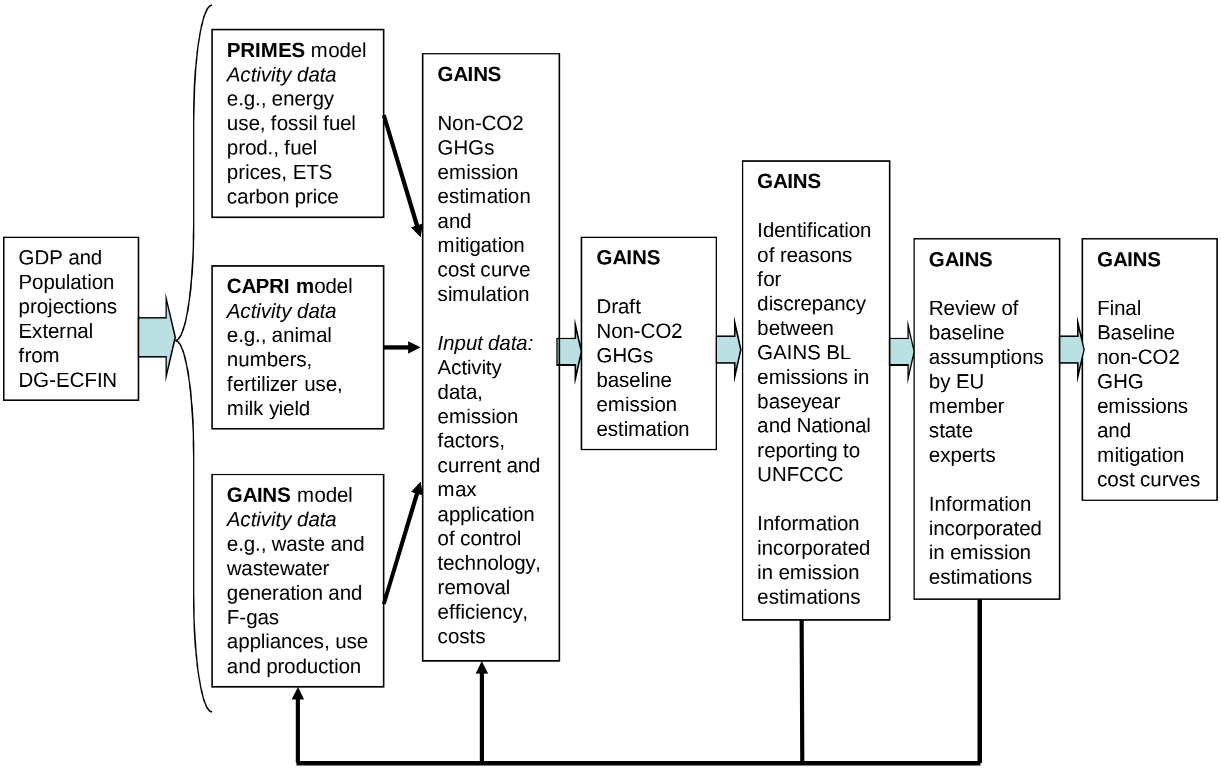


Figure 2: Work procedure for estimation of scenarios for non-CO2 greenhouse gases in the European Union using the GAINS model.

The uncertainty surrounding the adoption rate of technology and the effect of technological development on reduction potentials and costs several decades from now, is of course very high, in particular for technologies that are currently not commercially available. To give an indication of the uncertainty surrounding a particular technology, we specify three levels of technical maturity of technologies: fully commercially available, starting commercial adoption and not yet commercially available. For the fully commercially available technologies, we assume no or very limited effects of technological development. For technologies that are just starting to be adopted commercially a faster rate of technological development is assumed. For technologies that are not yet commercially available, the uncertainty surrounding both removal efficiencies and costs is very high. We therefore refrain from speculating about the future development in removal efficiency and costs and keep these constant over time for this technology group.

4 Modelling air pollution and mitigation

4.1 Atmospheric dispersion

An integrated assessment of air pollution needs to link changes in precursor emissions from the various sources to responses in impact indicators at receptors. Traditionally this task is accomplished by comprehensive atmospheric chemistry and transport models, which simulate a complex range of chemical and physical reactions. The GAINS integrated assessment analysis relies on the Unified EMEP Eulerian model, which describes the fate of emissions in the atmosphere considering more than one hundred chemical reactions involving 70 chemical species with time steps down to 20 seconds, including numerous non-linear mechanisms (Simpson et al., 2003)(Fagerli and Aas, 2008). However, the joint analysis with economic and ecological aspects in the GAINS model requires computationally efficient source-receptor relationships. For this purpose, response surfaces of the impact-relevant air quality indicators are described through mathematically simple formulations. Functional relationships have been developed for changes in annual mean $PM_{2.5}$ concentrations, deposition of sulphur and nitrogen compounds as well as in long-term levels of ground-level ozone. The (grid- or country-specific) parameters of these relationships have been derived from a sample of several hundred runs of the full EMEP Eulerian model with systematically perturbed emissions of the individual sources.

Source-receptor relationships have been developed for changes in emissions of SO_2, NOx, NH_3, VOC and $PM_{2.5}$ for 43 countries in Europe and five sea areas, describing their impacts for the European territory on a 50 km × 50 km grid resolution.

4.1.1 Fine particulate matter

The health impact assessment in GAINS relies on epidemiological studies that associate premature mortality with annual mean concentrations of $PM_{2.5}$ monitored at urban background stations. Thus, the source-receptor relationships developed for GAINS describe, for a limited range around a reference emission level, the response in annual mean $PM_{2.5}$ levels to changes in the precursor emissions of SO_2, NOx, NH_3 and primary $PM_{2.5}$.

This formulation describes the formation of particulate matter (PM) from anthropogenic primary PM emissions and secondary inorganic aerosols only. It excludes PM from natural sources and primary and secondary organic aerosols due to insufficient confidence in the current modelling ability. Thus, the approach does not reproduce the full mass of $PM_{2.5}$ that is observed in ambient air. Consequently, results should be compared only against observations of the individual species that are modelled. The health impact assessment in GAINS is consequently only conducted for *changes* in the specified anthropogenic precursor emissions, and excludes the largely unknown role of secondary organic aerosols and natural sources.

The regional-scale assessment is performed for all of Europe with a spatial resolution of 50 km × 50 km. Health impacts are, however, most pertinent to urban areas where a major share of the European population lives. Any assessment with a 50 km resolution will systematically underestimate higher pollution levels in European cities. Based on the results of the City-Delta model intercomparison, which brought together the 17 major European urban and regional scale atmospheric dispersion models (Thunis et al., 2007), a generalized methodology was developed to describe the increments in $PM_{2.5}$ concentrations in urban background air that originate – on top of the long-range transport component – from local emission sources. These relationships associate the difference in the annual mean $PM_{2.5}$ concentrations between an urban area and the average concentrations calculated over the 50 km × 50 km grid cell surrounding the city with spatial variations in emission densities of low-level sources and city-specific meteorological and topographic factors. The GAINS/City-Delta methodology starts from the hypothesis that urban increments in $PM_{2.5}$ concentrations originate predominantly from primary PM emissions from low-level sources within the city. The formation of secondary inorganic aerosols, as well as the dispersion of primary $PM_{2.5}$ emissions from high stacks, is reflected in the background computed by the regional-scale dispersion model.

4.1.2 Deposition of sulphur and nitrogen compounds

The critical loads approach employed by the GAINS model for the quantification of ecosystems risks from acidification and eutrophication uses (ecosystem-specific) annual mean deposition of acidifying compounds (i.e., sulphur, oxidized and reduced nitrogen) as the impact-relevant air quality indicator. Significant non-linearities in the spatial source-receptor relationships due to co-deposition with ammonia have been found for the substantial emission reductions that have occurred over the last two decades (Fowler et al., 2005). However, the EMEP Eulerian model suggests – for the technically feasible range of further emissions reductions beyond the baseline projection – nearly linear responses in annual mean deposition of sulphur and nitrogen compounds towards changes in SO_2, NOx and NH_3 emissions.

4.2 Air quality impacts

4.2.1 Health impacts from PM

Based on the findings of the WHO review on health impacts of air pollution (WHO, 2003)(WHO, 2007), the GAINS model quantifies premature mortality that can be attributed to long-term exposure to $PM_{2.5}$, following the outcomes of the American Cancer Society cohort study (Pope et al., 2002) and its re-analysis (Pope et al., 2009). Cohort- and country-specific mortality data extracted from life table statistics are used to calculate for each cohort the baseline survival function over time (Mechler et al., 2002). The survival function $l_c(t)$ indicates the percentage of a cohort c alive after time t elapsed since starting time w_0. $l_c(t)$ is an exponential function of the sum of the mortality rates $\mu_{a,b}$, which are derived from life tables with a as age and b as calendar time. As the relative risk function taken from (Pope et al., 2002) applies only to cohorts that are at least w_0=30 years old, younger cohorts were excluded from this analysis. Accordingly, for a cohort aged c, $l_c(t)$ is:

$$l_c(t) = \exp\left(-\sum_{z=c}^{t} \mu_{z,z-c+w_0}\right). \tag{1}$$

The survival function is modified by the exposure to PM pollution, which changes the mortality rate and consequently the remaining life expectancy (e_c). For a given exposure to $PM_{2.5}$ (PM), life expectancy $\bar{l}_c$ is calculated as the integral over the remaining life time:

$$e_c = \int_c^{w_1} \bar{l}_c(t)\,dt = \int_c^{w_1} \exp\left(-RR_{PM} \sum_{z=c}^{t} \mu_{z,z-c+w_0}\right) dt \tag{2}$$

where w_1 is the maximum age considered and RR_{PM} the relative risk for a given concentration of $PM_{2.5}$. With some simplifying assumptions and approximations (Vaupel and Yashin, 1985), the change in life expectancy per person (Δe_c) of a cohort c can be expressed as:

$$\Delta e_c = \beta PM \int_c^{w_1} l_c(t) \log\, l_c(t)\,dt \tag{3}$$

where – within the studied exposure range – RR_{PM} has been approximated as $RR_{PM} = \beta \cdot PM + 1$ with $\beta = 0.006$ as given in (Pope et al., 2002). For all cohorts in a country l the change in life years ΔL_l is then calculated as the sum of the change in life years for the cohorts living in the grid cells j of the country l:

$$\Delta L_l = \sum_{c=w_0}^{w_1} \Delta L_{c,i} = \beta \sum_{j \in l} PM_j \frac{Pop_j}{Pop_l} \sum_{c=w_0}^{w_1} Pop_{c,l} \int_c^{w_1} l_c(t) \log\, l_c(t)\,dt \tag{4}$$

where

$\Delta L_{c,l}$	Change in life years lived for cohort c in country l
$Pop_{c,l}$	Population in cohort c in country l
Pop_j	Total population in grid cell j (at least of age w_0=30)
Pop_l	Total population in country l (at least of age w_0=30).

4.2.2 Health impacts from ozone

Based on a comprehensive meta-analysis of time series studies conducted for the World Health Organization (Anderson et al., 2004) and on advice received from the UNECE/WHO Task Force on Health (UNECE/WHO, 2003), the GAINS model quantifies premature mortality through an association with the so-called SOMO35 indicator for long-term ozone concentrations in ambient air. SOMO35 is calculated as the daily eight-hour maximum ozone concentrations in excess of a 35 ppb threshold, summed over the full year. In essence, the GAINS calculation estimates for the full year daily changes in mortality as a function of daily eight-hour maximum ozone concentrations, employing the concentration-response curves derived in the meta-analysis (Anderson et al., 2004). The threshold was introduced (i) to acknowledge uncertainties about the validity of the linear concentration-response function for lower ozone concentrations, and (ii) in order not to overestimate the health effects. The annual cases of premature mortality attributable to ozone are then calculated as

$$Mort_l = \tfrac{2}{365} Deaths_l \cdot RR_{O3} \cdot O3_l \qquad (5)$$

where

$Mort_l$	Cases of premature mortality per year in country l
$Deaths_l$	Baseline mortality (number of deaths per year) in country l
RR_{O3}	Relative risk for one percent increase in daily mortality per µg/m^3 eight-hour maximum ozone concentration per day.
$O3_l$	Population-weighted SOMO35 in country l

In addition to the mortality effects, there is clear evidence of acute morbidity impacts of ozone (e.g., various types of respiratory diseases). However, the GAINS model quantifies only mortality impacts of ozone, as they are seen to be the dominant factor in any economic benefit assessment.

References

M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner, W. Winiwarter: Cost-effective control of air quality and greenhouse gases in Europe: Modelling and policy applications, *Environmental Modelling and Software*, Vol. 26, pp. 1489-1501, 2011.

M. Amann, L. Höglund-Isaksson, W. Winiwarter, A. Tohka, F. Wagner, W. Schöpp, I. Bertok and C. Heyes: Emission scenarios for non-CO_2 greenhouse gases in the EU-27, Final Report to DG Environment, International Institute for Applied Systems Analysis (IIASA), May 2008. http://ec.europa.eu/clima/policies/package/docs/ir_07_nonco2_en.pdf.

Anderson, H.R., R.W. Atkinson, J.L. Peacock, L. Marston, K. Konstantinou: Meta-analysis of time-series studies and panel studies of Particulate Matter (PM) and Ozone (O3). World Health Organization, Bonn, 2004.

L. Höglund-Isaksson, W. Winiwarter, F. Wagner, Z. Klimont and M. Amann: Potentials and costs for mitigation of non-CO_2 greenhouse gases in the European Union until 2030–Results, Report to DG Climate Action, International Institute for Applied Systems Analysis (IIASA), Laxenburg, May 2010. http://ec.europa.eu/clima/policies/package/docs/non_co2emissions_may2010_en.pdf.

L. Höglund-Isaksson, W. Winiwarter, and A. Tohka: Potentials and costs for mitigation of non-CO_2 greenhouse gases in the European Union–Methodology, International Institute for Applied Systems Analysis (IIASA), Laxenburg, May 2010. http://gains.iiasa.ac.at/images/stories/reports/EU27-nonCO2-25May2010_methodology.pdf.

L. Höglund-Isaksson, W. Winiwarter, P. Purohit, P. Rafaj, W. Schöpp and Z. Klimont: EU Low Carbon Roadmap 2050: Potentials and costs for mitigation of non-CO_2 greenhouse gas emissions, Paper submitted to *Energy Strategy Reviews*, January 26, 2012.

ESIA: Intermediate status report of the progress towards the reduction of perfluorocompound (PFC) emissions from European semiconductor manufacturing, European Semiconductor Industry Association (ESIA), Brussels, 2006.

Fagerli, H. and W. Aas: Trends of nitrogen in air and precipitation: Model results and observations at EMEP sites in Europe, 1980–2003. *Environmental Pollution* 154, 448-461, 2008.

Fowler, D., J. Muller, R.I. Smith, J.N. Cape, J.W. Erisman: Nonlinearities in Source Receptor Relationships for Sulfur and Nitrogen Compounds. Ambio 34, 41-46, 2005.

IPCC: IPCC Revised 1996 Guidelines for National Greenhouse Gas Inventories, J.T. Houghton, L.G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, B.A. Callender (Eds.), IPCC/OECD/IEA, UK Meteorological Office, Bracknell, 1997.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, L. B. S. Eggleston, K. Miwa, T. Ngara, K. Tanabe (Eds.), Intergovernmental Panel on Climate Change, Japan, 2006.

Pope, C.A., R. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, G.D. Thurston: Lung Cancer, Cardiopulmonary Mortality and Long-term Exposure to Fine Particulate Air Pollution. Journal of the American Medical Association 287, 1132-1141, 2002.

Pope, C.A., M. Ezzati, D.W. Dockery: Fine-Particulate Air Pollution and Life Expectancy in the United States. The New England Journal of Medicine 360, 376-86, 2009.

Simpson, D., H. Fagerli, J. E. Jonson, S. Tsyro, P. Wind, T.P. Tuovinen: Transboundary Acidification, Eutrophication and Ground-level Ozone in Europe Part I. Unified EMEP Model Description. Norwegian Meteorological Institute, Oslo, 2003.

Thunis, P., L. Rouil, C. Cuvelier, R. Stern, A. Kerschbaumer, B. Bessagnet, M. Schaap, P. Builtjes, L. Tarrason, J. Douros, N. Moussiopoulos, G. Pirovano, M. Bedogni: Analysis of model responses to emission-reduction scenarios within the CityDelta project, *Atmospheric Environment* 41, 208-220, 2007.

UNECE/WHO: Modelling and Assessment of the Health Impact of Particulate Matter and Ozone (No. EB.AIR/WG.1/2003/11). United Nations Economic Commission for Europe, World Health Organization, 2003.

WHO: Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide. World Health Organization, Bonn, 2003.

WHO: Health relevance of particulate matter from various sources. Report on a WHO Workshop Bonn, Germany, 26-27 March 2007. World Health Organization, Regional Office for Europe, Copenhagen, Denmark, 2007.