GREENHOUSE GAS–AIR POLLUTION INTERACTIONS AND SYNERGIES

GAINS

POTENTIALS AND COSTS FOR GREENHOUSE GAS MITIGATION IN ANNEX I COUNTRIES

METHODOLOGY

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This report documents the basic methodology of IIASA's GAINS model that has been used for comparing mitigation efforts across Annex I Parties.

The following additional information sources are available at http://gains.iiasa.ac.at/Annex1.html:

- An interactive **GAINS GHG mitigation efforts calculator** that allows online-comparison of mitigation efforts across Annex I Parties. Free access is provided at http://gains.iiasa.ac.at/MEC.
- Access to all input data employed for the calculations for all countries via the on-line version of the GAINS model at http://gains.iiasa.ac.at/Annex1.html.

The following reports document specific methodology details:

- GHG mitigation potentials and costs from energy use and industrial sources in Annex I countries. J. Cofala, P. Purohit, P.Rafaj. Z. Klimont, 2008
- GHG mitigation potentials and costs in the transport sector of Annex I countries. J. Borken-Kleefeld *et al.*, 2008
- GHG mitigation potentials and costs from land-use, land-use changes and forestry (LULUCF) in Annex I countries. H. Böttcher *et al.*, 2008
- Potentials and costs for mitigation of non-CO_2 greenhouse gases in Annex I countries. L. Höglund-Isaksson et al., 2008

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Executive summary

Mitigation efforts and investments over the next two to three decades are critical for the further development of greenhouse gas emissions. Opportunities exist to achieve lower stabilisation levels of greenhouse gases. However, it will be a formidable challenge to negotiating Parties to arrive at a generally accepted scheme for sharing efforts among Annex I countries that achieves the necessary emission reductions.

This report provides a documentation of the GAINS methodology that has been developed to compare greenhouse gas mitigation potentials and costs for Annex I countries.

In this report the International Institute for Applied Systems Analysis (IIASA) presents an approach that aims at a coherent international comparison of greenhouse gas mitigation efforts among Annex I Parties in 2020. In brief, the methodology (i) adopts exogenous projections of future economic activities as a starting point, (ii) develops a corresponding baseline projection of greenhouse gas emissions for 2020 with information derived from the national GHG inventories that have been reported by Parties to the UNFCCC for 2005, (iii) estimates, with a bottom-up approach, for each economic sector in each country the potential emission reductions that could be achieved through application of the available mitigation measures, and (iv) quantifies the associated costs required for these measures under the specific national conditions. The approach includes all six gases that are included in the Kyoto protocol (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and covers all anthropogenic sources that are included in the emission reporting of Annex I countries to UNFCCC (i.e., Energy, Industrial Processes, Agriculture, Waste, and from LULUCF). In addition, the analysis quantifies the implications of GHG mitigation strategies on air pollution.

More detail on the methodology and access to all input data is available over the Internet.

A series of reports describes the methodology for (i) energy related and industrial greenhouse gas emissions, (ii) emissions from transportation, (iii) emissions of non-CO_2 gases, and (iv) emissions from land use, land use change and forestry (LULUCF) in detail. These reports, as well as access to all input data that have been employed for the calculation, are available at http://gains.iiasa.ac.at/Annex1.html.

A GAINS GHG mitigation target calculator (http://gains.iiasa.ac.at/MEC) allows an interactive comparison of mitigation potentials and costs via the Internet.

An Internet tool has been developed that allows interactive comparison of mitigation efforts among the Annex I Parties in 2020. The tool is freely accessible at http://gains.iiasa.ac.at/MEC.

About the authors

The work was carried out by IIASA scientists working at the Atmospheric Pollution and Economic Development programme (led by Markus Amann) and IIASA's Forestry programme (coordinated by Michael Obersteiner). Team members include Imrich Bertok, Jens Borken, Janusz Cofala, Chris Heyes, Lena Hoglund, Zbigniew Klimont, Pallav Purohit, Peter Rafaj, Wolfgang Schöpp, Geza Toth, Fabian Wagner and Wilfried Winiwarter, all working at IIASA's Atmospheric Pollution and Economic Development programme, and Hannes Boettcher, Florian Kraxner from IIASA's Forestry programme.

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Glossary

Annex I	List of industrialised countries which are Parties to the UNFCCC
CCS	Carbon capture and storage
CDM	Clean Development Mechanism under the Kyoto Protocol
CH_4	Methane
CHP	Combined heat and power
CLE	Current legislation
CO_2	Carbon dioxide
F-gas	Fluorinated gas
GAINS	Greenhouse gas - Air pollution Interactions and Synergies model
GHG	Greenhouse gas
GWP	Global warming potential
HCFC-22	Chlorodifluoromethane, CHF_2Cl
HFC	Hydrofluorocarbon
HFC-23	Trifluoromethane, CHF_3
HVAC	Heating/ventilation/air conditioning
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
JI	Joint implementation mechanism under the Kyoto Protocol
Kyoto Protocol	UNFCCC Protocol setting binding GHG emission reduction targets
LULUCF	Land use, land-use change and forestry
N_2O	Nitrous oxide
NF_3	Nitrogen trifluoride
NH_3	Ammonia
NO_x	Nitrogen oxides
PFC	Perfluorocarbon
PFPB	Point Feed Pre Bake (electrolysis cell)
PM2.5	Fine particles with an aerodynamic diameter of less than 2.5 µm
RAINS	Regional Air Pollution Information and Simulation model
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
SWPB	Side-Worked Pre Bake (electrolysis cell)
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
VSS	Vertical Stud Soderberg (aluminium production)

1 Introduction

Climate change impacts can be reduced, delayed or avoided by mitigation of greenhouse gases (GHGs). Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels. Delayed emission reductions significantly constrain the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts (IPCC, 2007). While stabilization of GHG concentrations can only be achieved through the participation of developing countries in coordinated mitigation action in the medium to longer time frame, there is an immediate urgency to reduce emissions from industrialized countries. In particular, the Bali Action Plan refers to cuts in the emissions of Annex I Parties between 25 and 40 percent in 2020 compared to 1990 if greenhouse gas concentrations are to stabilize at 450 ppb (UNFCCC, 2007).

Given this overall target, it will be a formidable challenge to negotiating Parties to arrive at a generally accepted scheme for sharing efforts among Annex I Parties that achieves the indicated emission reductions within the coming decade. Not only must negotiators understand the numerous mitigation measures, their costs, and their impacts on GHG emissions; but the negotiators must forge a politically acceptable agreement to each of the 40 Annex I countries.

Building on IIASA's expertise in helping negotiators agree on international environmental treaties, IIASA has developed a scientific tool to support the current negotiations. Known as GAINS (Greenhouse gas – Air pollution Interactions and Synergies), the tool not only helps negotiators identify the most cost effective way to reduce GHG emissions, but also allows negotiators to compare mitigation efforts among Parties. This is crucial for demonstrating the perceived fairness of a negotiated agreement and therefore its political acceptability.

In developing such a tool, IIASA's researchers have had to meet a range of challenges including:

- the large number of available mitigation measures for multiple gases, in different economic sectors and many countries and their numerous interactions that requires an integrated systems perspective,
- the fact that the assessment needs to be carried out for a future target year (e.g., 2020), and that the baseline transition from today's situation until then will involve numerous dynamic changes that are influenced by a wide range of exogenous factors,
- the limited practical experience in the technical, institutional and economic performances of many mitigation measures, and
- the fact that many mitigation measures involve significant changes in the current infrastructures of energy systems, industry and the housing sector, as well as changes in the personal behaviour of people, with important positive or negative side-effects on a wide range of other, non-climate related aspects (such as energy security, competitiveness, employment, air pollution, agricultural policies, time budgets, etc.).

In this report the International Institute for Applied Systems Analysis (IIASA) presents an approach that aims at a coherent international comparison of greenhouse gas mitigation efforts among Annex I Parties in 2020. The scientific assessment has been facilitated by:

- IIASA's ample experience in systems analysis that brings together researchers from different disciplines to work in an interdisciplinary setting on policy-relevant topics. The systems perspective enables a comprehensive international comparison of mitigation efforts and an impartial assessment and quantification of the factors that lead to objective differences between countries.
- IIASA's neutrality, stemming from its international constituency and funding by non-governmental scientific organizations from 18 countries in Europe, North America, Asia, and Africa.
- IIASA's past experience in identifying cost-effective strategies to control air pollution and GHG emissions in Europe and Asia.

GAINS estimates emission reduction potentials and costs for a range of greenhouse gases and air pollutants and quantifies the resulting impacts on air quality and total greenhouse gas emissions considering the physical and economic interactions between different control measures. As a principle, the analysis employs only such input data that are available in the public domain and that appear credible and consistent in an international perspective. While the IIASA team collaborated with national experts to validate important input data and assumptions for individual countries, constraints on time and financial resources did not allow for an extensive validation of all input data. As IIASA has ample experience in consulting with national experts on input data to the GAINS model, inter alia in its function as the Centre for Integrated Assessment Modelling of the Convention on Long-range Transboundary Air Pollution, such a consultation process could be organized in the future if required.

In brief, the methodology (i) adopts exogenous projections of future economic activities as a starting point, (ii) develops a corresponding baseline projection of greenhouse gas emissions for 2020 with information derived from the national GHG inventories that have been reported by Parties to the UNFCCC for 2005, (iii) estimates, with a bottom-up approach, for each economic sector in each country the potential emission reductions that could be achieved in 2020 through application of the available mitigation measures, and (iv) quantifies the associated costs that would emerge for these measures under the specific national conditions. The approach includes all six gases that are included in the Kyoto protocol (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and covers all anthropogenic sources that are included in the emission reporting of Annex I countries to UNFCCC (i.e., Energy, Industrial Processes, Agriculture, Waste, and from LULUCF).

This report introduces the basic methodology of the approach (Section 2) and describes key results from a first implementation for 36 Annex I Parties (Section 3).

Detailed documentation of the methodologies and assumptions that have been employed for the analysis of the various source sectors is available in companion documents (Amann *et al.*, 2008a, Borken-Kleefeld *et al.*, 2008, Höglund-Isaksson *et al.*, 2008, Böttcher *et al.*, 2008). Open access to all input data that are used for the assessment is provided through the on-line implementation of the GAINS model. In addition, a GAINS GHG mitigation efforts calculator which allows interactive exploration of mitigation efforts and costs using a range of indicators is freely accessible at http://gains.iiasa.ac.at/MEC.

2 Methodology

To assess mitigation potentials and costs in Annex I countries, IIASA has employed an extension of its Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model. The GAINS (and its predecessor, the RAINS) models have been applied before in international negotiations to identify cost-effective air pollution control strategies, and to study the co-benefits between greenhouse gas mitigation and air pollution control in Europe and Asia (Hordijk and Amann, 2007, Tuinstra, 2007).

The GAINS approach provides a framework for a coherent international comparison of the potentials and costs for emission control measures, both for greenhouse gases and air pollutants. It estimates with which measures in which economic sector the emissions of the six greenhouse gases could be reduced to what extent, as well as the costs for such action. It identifies for each country the portfolio of measures that achieves a given reduction target in the most cost-effective way, and provides national cost curves that allow a direct comparison of mitigation potentials and associated costs across countries. Using a bottom-up approach that distinguishes a large set of specific mitigation measures, relevant information can be provided on a sectoral basis, and implied costs can be reported in terms of upfront investments, operating costs and costs (or savings) for fuel input.

The following sections provide a general outline of the basic rationale, the approach and data sources that have been employed for estimating mitigation potentials and costs for the various countries. Adjustments of the general approach to address specific requirements for individual gases are described in the companion reports (Amann *et al.*, 2008a, Borken-Kleefeld *et al.*, 2008, Höglund-Isaksson *et al.*, 2008, Böttcher *et al.*, 2008).

2.1 Emission calculation

For each of the greenhouse gases and air pollutants, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of mitigation 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.

For calculating total greenhouse gas emissions, the GAINS model uses the global warming potentials defined in the Kyoto protocol (Table 2.1).

Table 2.1: Global warming potentials (GWPs) over 100 years used in GAINS emission calculations (UNFCCC, 1997)

GAS/SECTOR	Gas	Average GWP
CARBON DIOXIDE	CO_2	1
METHANE	CH_4	21
NITROUS OXIDE	N_2O	310
HCFC-22 PRODUCTION	HFC	11700
INDUSTRIAL REFRIGERATION	HFC	2600
COMMERCIAL REFRIGERATION	HFC	2726
TRANSPORT REFRIGERATION	HFC	2000
DOMESTIC REFRIGERATION	HFC	1300
STATIONARY AIR CONDITIONING	HFC	1670
MOBILE AIR CONDITIONING	HFC	1300
AEROSOLS	HFC	1300
OTHER HFC	HFC	815-1300
PRIMARY ALUMINIUM PRODUCTION	HFC	6500-9200
SEMICONDUCTOR INDUSTRY	HFC	6500
HIGH AND MID VOLTAGE SWITCHES	SF_6	23900
MAGNESIUM PRODUCTION AND CASTING	SF_6	23900
OTHER USE OF SF_6	SF_6	23900

With this approach critical differences across economic sectors and countries that are important for estimating emission control potentials in different countries can be captured. 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 extent to which emission control measures are applied. More detail is available in Amann *et al.*, 2008a, Borken-Kleefeld *et al.*, 2008, Höglund-Isaksson *et al.*, 2008, Böttcher *et al.*, 2008. GAINS estimates 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 Mitigation potentials

2.2.1 APPROACH

Mitigation potentials for future years are estimated through the following steps:

- As a starting point GAINS considers a comprehensive inventory of mitigation measures that could be applied at the different source sectors to reduce emissions of the various greenhouse gases. For each measure the inventory holds information on technical and economic specifications and on key factors that lead to objective differences in mitigation efficiencies, applicability and costs across countries. It also considers (positive or negative) effects on other pollutants. For the mitigation of greenhouse gas emissions, four generic groups of measures are distinguished:

  - End-of-pipe measures that can be applied to reduce the release of emissions without changing the activity level (e.g., CCS, methane recovery, catalytic reduction of N_2O, incineration of F-gases, etc.),
  - energy efficiency improvements that reduce the combustion of fossil fuels but deliver the same level of energy services (e.g., improved insulation, higher combustion efficiencies, etc)
  - substitution of high-carbon fuels by fuels with lower carbon content,
  - application of new technologies that produce less greenhouse gas emissions (hybrid vehicles, etc.)
  - behavioural changes that reduce the demand for energy services.
- For each source sector in each country, emissions reported to UNFCCC for 2005 are reconstructed based on statistical information on activity data and emission factors that explicitly consider (i) country-specific circumstances (e.g., climatic conditions, fleet composition, vintage structure of the capital stock, etc.) and (ii) the rate at which mitigation measures that have been identified in the preceding step have been implemented in 2005.
- For each source sector in each country, a baseline emission projection is constructed for 2020 that considers (i) changes in activity levels as specified in the exogenous activity scenario (e.g., the World Energy Outlook), and (ii) changes in emission factors that result either from technological changes that are assumed in the activity projection (e.g., autonomous improvement of energy efficiency) or, where applicable, from the deployment of dedicated mitigation measures that are already laid down in existing national legislation.
- For each of the mitigation measures identified in step 1, the maximum applicability in 2020 is estimated for each sector in each country. The maximum application rate considers structural features in a country (e.g., potentials for fuel substitution, the rate of turnover of the capital stock, the exclusion of premature scrapping of existing capital, etc.),
- Using sector- and country-specific costs for the mitigation measures (see below), an optimization is carried out for each country that identifies, for a given greenhouse gas reduction target, the portfolio of mitigation measures that achieves the target at least cost. The optimization considers, in addition to the different costs of individual measures,
    - the end-use demand for (energy) services as specified in the activity projection,
    - the penetration of mitigation measures that is implied in the activity projection for 2020,
    - application limits of the additional mitigation measures as identified above,
    - the scope for replacement of existing infrastructure,
    - upstream implications of reduced energy demand on the energy supply structure (e.g., that lower demand for electricity from energy savings in the

    end use sector allows phase-out of the most inefficient (i.e., GHG intensive) forms of electricity production), with the resulting economic consequences,
    - (positive or negative) side-effects on emissions of other greenhouse gases or air pollutants.
    - However, this optimization does not consider changes in the export and import of electricity or materials, nor the use of flexible instruments to acquire carbon permits abroad.
- As an outcome, such an optimization run provides a detailed portfolio of mitigation measures that would achieve the given emission reduction target at least cost. Conducted for a sequence of gradually tightened emission reduction targets, national cost curves can be derived that describe how costs for greenhouse gas mitigation in a country change over the full range of the mitigation potential.

With this approach, the GAINS framework builds upon information provided in

- the national submissions to UNFCCC of GHG inventories for the year 2005,
- additional statistical information for 2005 that complements data provided in the national submissions to UNFCCC,
- exogenous projections that specify the levels of activities in each economic sector and country in the target year 2020 (e.g., the IEA World Energy Outlook 2008 (IEA, 2008),
- an inventory of several hundred mitigation measures to control emissions of CO_2, CH_4, N_2O and F-gases.

2.2.2 MITIGATION MEASURES

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

- *Behavioural changes* reduce anthropogenic driving forces that generate pollution. Such changes in human activities can be autonomous (e.g., changes in lifestyles), 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 GAINS concept does not internalize such behavioural 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* 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 several

hundred options for greenhouse gases and about 1,500 pollutant-specific end-of-pipe measures for reducing SO_2, NO_x, VOC, NH_3 and PM emissions and assesses their application potentials and costs.

Table 2.2: Major groups of structural measures to reduce emissions of air pollutants and greenhouse gases considered in GAINS. For more details consult Klaassen *et al.*, 2005.

Sector	Measure
Power plants	• Use of renewables, such as o wind, o solar photo-voltaic, o large hydro power plants, o small hydro power, o geothermal power instead of fossil fuels. • Gas-fired power plants instead of coal-fired power plants. • Biomass power plants instead of fossil fuel plants. • Combined heat and power (CHP) systems to substitute electric power plants on the one hand, and either industrial boilers or residential boilers. CHP systems increase the overall energy system efficiency. • (Efficiency measures that reduce electricity consumption in industry and the residential/commercial sector that reduce electricity consumption)
Residential sector	• Energy saving packages (3 stages each) for heating, cooling, air conditioning for o existing houses, o new houses, o existing apartments, o new apartments. • Energy saving packages (3 stages each) for o water heating, o cooking, o lighting, o small appliances, o large appliances.
Commercial sector	• Energy saving packages (3 stages each) for heating, cooling, air conditioning for o existing buildings, o new buildings. • Energy saving packages (3 stages each) for o water heating o cooking, o lighting, o small appliances, o large appliances.
All industries	• Gas-fired boilers instead of coal-fired boilers. • Combined Heat and Power instead of industrial boilers.
Cement production	• Energy saving packages (3 stages)
Iron and steel industry	• Energy saving packages (3 stages)
Paper and pulp industry	• Energy saving packages (3 stages)
Non-ferrous metals	• Energy saving packages (3 stages)
Chemicals	• Energy saving packages (3 stages)
All transport	• Substitute fossil fuel with bio-fuels

Table 2.3: Major groups of technical measures to reduce emissions of CO_2 considered in GAINS. For more details consult Klaassen *et al.*, 2005.

Sector	Measure
Power plants	• IGCC (Integrated Gasification Combined Cycle) instead of conventional coal fired power plants • Carbon capture and storage
Passenger cars	• Advanced internal combustion engines • Hybrid vehicles • Plug-in hybrids • Electric vehicles • Hydrogen fuel-cell vehicle • Non-traction related efficiency improvements
Light-duty trucks	• Advanced internal combustion engines • Hybrid vehicles • Plug-in hybrids • Electric vehicles • Hydrogen fuel-cell vehicles • Non-traction related efficiency improvements
Heavy-duty trucks	• Advanced internal combustion engine • Non-traction related efficiency improvements
Buses	• Electric vehicle • Hydrogen fuel-cell vehicle • Non-traction related efficiency improvements (2 stages)
Motorcycles	• Advanced internal combustion engine

Table 2.4: Major groups of control measures for CH_4 emissions considered in GAINS. More details are available in Höglund-Isaksson and Mechler, 2005

CH_4	Measure
Agriculture	• Anaerobic digestion of animal manure • Dietary changes for dairy cows and cattle • Alternative rice strains and improved aeration of rice fields • Ban on agricultural waste burning
Waste	• Waste diversion options: recycling of paper and wood waste, composting and bio-gasification of food waste, and waste incineration • Landfill options: gas recovery with flaring or gas utilization
Wastewater	• Domestic urban wastewater collection with aerobic or anaerobic treatment with or without gas recovery • Domestic rural wastewater treatment in latrines or septic tanks. • Industrial wastewater treatment –aerobic or anaerobic with or without gas recovery utilization
Coal mining	• Recovery with flaring or utilization of gas
Gas distribution	• Replacement of grey cast iron networks and increased network control frequency
Natural gas and oil production and processing	• Recovery and flaring of gas

Table 2.5: Major groups of control measures for N_2O emissions considered in GAINS. More details are available in Winiwarter, 2005

N_2O	Measure
Agriculture	• Reduced and/or improved timing of fertilizer application • Use of advanced agro-chemicals (e.g., nitrification inhibitors) • Precision farming
Energy combustion	• Combustion modifications in fluidized bed boilers
Industrial processes	• Catalytic reduction in nitric and adipic acid production
Waste water	• Optimization of operating conditions in wastewater plants
Direct N_2O use	• Replacement/reduction in use of N_2O for anaesthetic purposes

Table 2.6: Major groups of control measures for F-gas emissions considered in GAINS. More details are available in Tohka, 2005

F-gases		Measure
HFC	Aerosols	▪ Alternative propellant
HFC	Stationary air conditioning and refrigeration	▪ Good practice: leakage control, improved components, and end-of-life recovery ? ▪ Process modifications for commercial and industrial refrigeration
HFC	Mobile air conditioning and refrigeration	▪ Alternative refrigerant: pressurized CO_2 ▪ Good practice: leakage control, improved components, and end-of-life recovery
HFC	HCFC-22 production	▪ Incineration: post combustion of HFC-23
HFC	Foams	▪ Alternative blowing agents
HFC	Aerosols	▪ Alternative propellant
PFC	Primary aluminium production	▪ Conversion of SWPB or VSS to PFPB ▪ VSS and SWPB retrofitting
PFC	Semiconductor Industry	▪ Alternative solvent use: NF_3
SF6	Magnesium production and casting	▪ Alternative protection gas SO_2
SF6	High and mid voltage switches	▪ Good practice: leakage control, improved components, and end-of-life recovery
SF6	Other SF6 use	▪ Ban of SF6 use

2.2.3 MITIGATION IN THE LULUCF SECTOR

Modelling approach

To estimate mitigation potentials within the Land Use, Land Use Change and Forestry (LULUCF) sector, a framework of models was applied (Figure 2.1). Land use change related options such as afforestation and avoided deforestation are estimated using a global land use model (GLOBIOM) and a spatially explicit forestry model (G4M). The model cluster covers all land-use types and thus allows for fully integrated analysis of competitive interactions between different land uses and land use change types. Combining the different models allows for geographically explicit analysis of afforestation and avoided deforestation policies in a global context. The geographically explicit analysis of policy options is carried out using the G4M (former DIMA) model Kindermann *et al.*, 2008; Kindermann *et al.*, 2006; Rokityanskiy *et al.*, 2007. G4M is driven by exogenous market price assumptions for land and commodities without taking market feedbacks into account. The partial equilibrium model GLOBIOM generates endogenous prices. GLOBIOM has global geographic coverage, it accounts for all land uses and thus allows for land use policy analysis in a wider land use and global change context. The G4M model also provides mitigation potentials and costs of options in management of existing forests. A similar model setup is used to supply costs and potentials of bioenergy measures. Here the optimisation model EUFASOM Schneider *et al.*, 2008 is linked to the biophysical agricultural model EPIC Schmid *et al.*, 2007. The agricultural model supplies EUFASOM with geographically explicit biomass potentials for various energy crops and bioenergy plantations. The more detailed European-scale model AROPA-GHG calculates both mitigation potentials and costs of mitigation options at farm level De Cara *et al.*, 2005. This model is applied to deliver CO_2 mitigation cost curves for agriculture, mainly different tillage options.

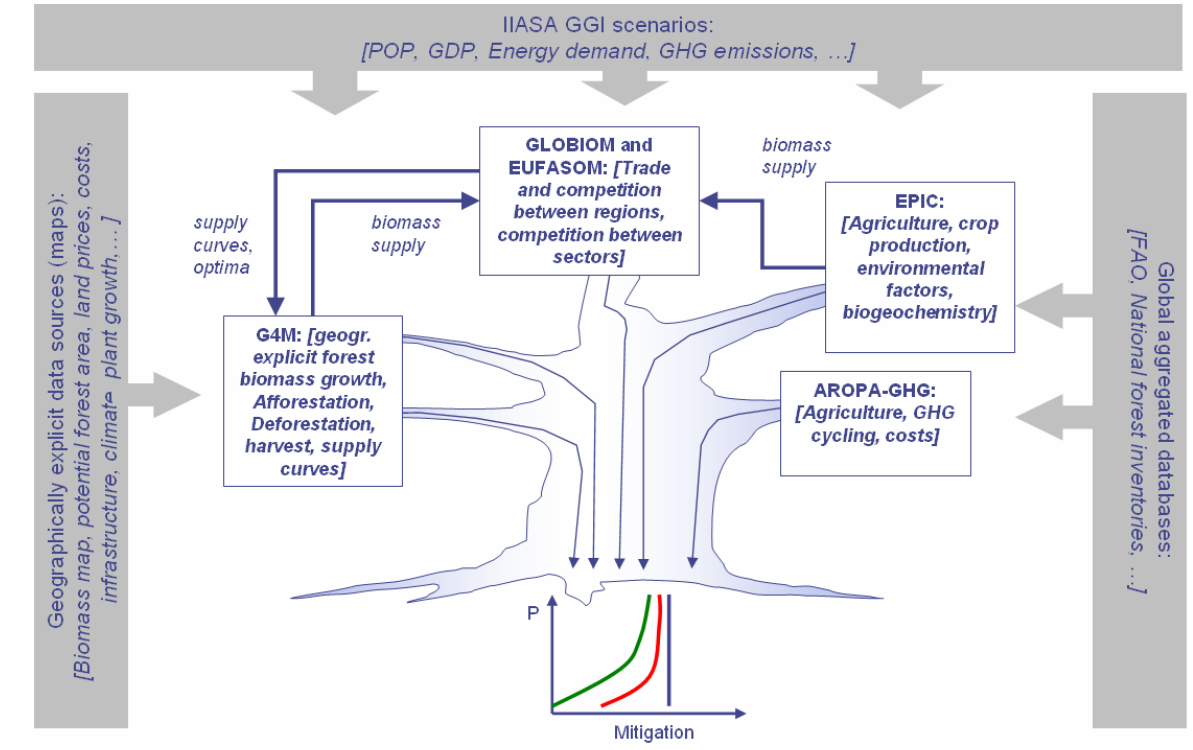

Figure 2.1: IIASA's forestry-land use modeling cluster

Mitigation measures

The special role of LULUCF in the global carbon cycle that differs significantly from other sectors is due to the properties of carbon pools these ecosystems. Management of terrestrial ecosystem carbon stocks can introduce and enhance sinks of CO_2 from the atmosphere through different measures as a service of atmospheric carbon mitigation. Three strategies to curb the increase of CO_2 in the atmosphere are available within LULUCF:

- *Conservation* to prevent emissions from existing carbon pools. This measure has an immediate benefit for the atmosphere. Its theoretical potential equals the current existing carbon stock in terrestrial ecosystems that could potentially be released. Conservation is important in regions with high carbon stocks per area. An example is forest conservation from deforestation.
- *Sequestration* to increase stocks in existing pools. The effect of sequestration can be characterized by a slow build up, e.g., following tree growth and accumulation of carbon in litter and soil. The potential of activities aiming at this effect is the carbon gain of the biosphere assuming a complete restoration up to its natural carrying capacity. Sequestration applies to areas where carbon stocks have been depleted. Examples are reduced tillage in agriculture or longer rotations in forestry.
- *Substitution* to substitute energy-intensive products or products on fossil fuel basis with products based on re-growing resources. The effect as a mitigation measure is somewhat similar to the benefits from conservation, and accumulates over time with each harvest and product use. The technical potential can be as high as the emissions from fossil fuel that can potentially be substituted. However, it has to be seen against a theoretical reference case with use of fossil fuels. The effect of fossil fuel substitution depends on whether the substitution actually reduces fossil fuel use or just limits its increase. Substitution relies on harvest and therefore opposes conservation and sequestration objectives in forests. Examples of substitution are bioenergy options based on sustainable land management.

The options for mitigating GHG emissions from the LULUCF sector covered in this analysis are listed in Table 2.7.

Table 2.7: LULUCF mitigation options considered

CO_2	
Agriculture	• Reduced tillage
Forestry	• Prolongation of rotation periods in existing forests
Land use change	• Afforestation of agricultural land • Avoided deforestation
Bioenergy	• Ethanol • Biodiesel • Fuel for combustion, cofiring

2.2.4 THE POTENTIAL FOR EFFICIENCY IMPROVEMENTS

Energy efficiency improvements constitute one of the key options for reducing greenhouse gas emissions in the medium term. The further potential is critically depending on country- and sector-specific factors, such as the current state of energy intensity, the technical features of the most advanced technologies, local factors (climatic conditions, specific operating conditions, etc.). While the importance of the potential for further efficiency improvements is widely acknowledgements and numerous studies explore potentials for individual countries (e.g., Bressand, 2007), there is a general lack of quantitative assessments that compare potentials across countries.

To assess the potential for energy efficiency improvements, the GAINS methodology identifies the most important demand categories of six industrial sectors (Table 2.8 to Table 2.13) and for residential and commercial energy use (Table 2.14) in the Annex I countries. It quantifies the current implementation rates for a set of specific measures that improve energy efficiency for the various end use categories in such a way, that energy statistics reported for the year 2005 are reproduced with activity data from economic statistics. Thereby, the specific energy intensities of the various countries are determined. Correction for country-specific factors (e.g., climatic conditions distinguishing up to three climatic zones in each country, floor space, shares of single and multi-family houses, etc.) enables the assessment of the further technical potential that is available in each country to further improve energy efficiency.

Considering these technical potentials, baseline implementation rates of the various options for improving energy efficiency are determined for the year 2020 in such a way that the projected level of sectoral energy consumption of the baseline energy projection (i.e., the World Energy Outlook 2008 of the International Energy Agency) is matched. This also provides the scope for further improvements that is not assumed as an autonomous development in the baseline projection.

Industrial sector

A wide field of options for saving energy exists in industry (IEA, 2008c). Some of them are highly sector and even plant-specific, and analysis of too many details within a global analysis with the GAINS model would not have been practical. Thus the assessment of energy efficiency potentials (on top of the baseline improvement) has been based on:

- Studies on “Best practices” in manufacturing industry (Worrell and et al., 2007), and
- the analysis of changes in the levels and structures of industrial energy consumption for the 27 EU countries in response to different carbon prices, as modelled with the PRIMES model (Capros and Mantzos, 2006).

Since the “Best Practice” study refers to energy–intensive products only, the potential for reducing remaining energy consumption in each sector (related to value added) has been estimated assuming that the annual intensity improvement of that part of energy demand will be faster than in the baseline by 1.5 percentage points for thermal energy, and by 1.0 percentage point for electricity. Costs of the “Best practice” measures are estimated based on international sectoral studies (Chen *et al.*, 1999; Martin and et al., 2000; Martin *et al.*, 1999; Nilsson and et al., 1996; Worrell and et al., 2000

Table 2.8 : Industrial sub-sectors considered in the GAINS analysis

Sector name
Iron and steel
Non-ferrous metals
Chemicals
Non-metallic minerals
Pulp, paper, paper products and printing
Other industries

Table 2.9: Activities in the iron and steel industry

Activity	Unit	Projection method and data sources
Value added	10^9 €	IEA macro forecast, correlation with industrial GDP, national studies
Raw steel	10^6 tons	Correlation with value added
Finished products	10^6 tons	Percentage raw steel production
Scrap supply	10^6 tons	Depends on dynamics of steel production methods
Coke oven coke	10^6 tons	Demand by blast furnaces and sintering processes, demand by other economic sectors plus net exports
Sinter	10^6 tons	Correlation with pig iron production
Pellets	10^6 tons	Correlation with pig iron production
Pig iron	10^6 tons	Related to steel basic oxygen steel production
Direct reduced iron	10^6 tons	National forecasts. If not available, extrapolation of historic trends
Open hearth furnace steel	10^6 tons	National forecasts. If not available, extrapolation of historic trends
Basic oxygen steel	10^6 tons	Derived from the raw steel balance
Electric arc furnace steel	10^6 tons	National forecasts. If not available, extrapolation of historic trends
Casting, rolling finishing	10^6 tons	Finished products minus thin slab casting
Thin slab casting	10^6 tons	National forecasts. If not available, extrapolation of historic trends

Table 2.10: Activities in the non-ferrous metals industry

Activity	Unit	Projection method and data sources
Value added	10^9 €	IEA macro forecast, correlation with industrial GDP, national studies
Primary aluminium	10^6 tons	Correlation with sectoral value added
Secondary aluminium	10^6 tons	Correlation with sectoral value added
Other metals - primary	10^6 tons	Correlation with sectoral value added
Other metals - secondary	10^6 tons	Correlation with sectoral value added

Table 2.11: Activities in the basic chemicals industry

Activity	Unit	Projection method and data sources
Value added	10^9 €	IEA macro forecast, correlation with industrial GDP, national studies
Ammonia	10^6 tons N	Correlation with sectoral value added
Ethylene	10^6 tons	Correlation with sectoral value added
Chlorine	10^6 tons	Correlation with sectoral value added

Table 2.12: Activities in the non-metallic minerals industry

Activity	Unit	Projection method and data sources
Value added	10^9 €	IEA macro forecast, correlation with industrial GDP, national studies
Cement production	10^6 tons	Correlation with sectoral value added
of which clinker	10^6 tons	National studies and forecasts
Lime production	10^6 tons	Correlation with sectoral value added

Table 2.13: Activities in the pulp and paper industry

Activity	Unit	Projection method and data sources
Value added	10^9 €	IEA macro forecast, correlation with industrial GDP, national studies
Pulp from wood	10^6 tons	National studies
Pulp from recovered paper	10^6 tons	National studies
Paper and paperboard	10^6 tons	Correlation with sectoral value added

Residential and commercial sector

An accurate assessment of the potential of energy efficiency improvements in the 'domestic' sector, which includes energy consumption of the residential, the commercial and the 'other' (e.g., military) sectors requires detailed considerations of different types of energy demand in these sectors. Therefore, GAINS disaggregates energy consumption that is usually provided in energy statistics for the 'domestic sector' as a whole, into these three sub-sectors. In addition, in each of these sub-sectors several energy needs n need to be distinguished.

For the base year (2005), the share of each sub-sector in total sectoral fuel consumption is determined from energy statistics. For future years, the sub-sectoral split of fuel consumption can be obtained from national studies, or if such estimates are not available, the shares of the base year can be maintained as a first approximation.

$$EC_{j,k,f,r} = EC_{j,f,r} * sh_{j,k,f,2005} \qquad \text{Equation 2.1}$$

where:

EC	fuel consumption
sh	fuel share
j	sector
k	sub-sector
f	fuel
r	time period.

In the next step, various technologies/options t for efficiency improvement are specified for each sub-sector and each need. These options also include the "no improvement" case. Each option is characterized by its unit cost cst, energy demand reduction efficiency x, and the maximum possible penetration (applicability) X^{max}. In addition, a cumulative penetration rate for all options available for a given sub-sector or need $\overline{X}^{\max}$ needs to be determined.

Since an assessment of fuel efficiency improvement for each fuel separately would be impractical, the analysis considers two energy types (c: thermal energy (TH) and electricity (EL)). Thermal energy includes all fuel types (coal, oil, gas, biomass) as well as steam and hot water, either produced locally or supplied via the district heating systems.

Once the reduction of the demand for thermal energy and electricity is determined, the demand for each energy carrier belonging to the "thermal" category can be specified, assuming that the structure of fuel consumption remains the same as in the baseline scenario. This is equivalent to an assumption about a proportional reduction of the demand for each energy carrier. On top of it, GAINS considers fuel substitution options, e.g., switch from coal and oil to gas, or switch to district heating or renewable energy (solar, biomass).

The analysis uses data for 2005 as a base year. Projections cover the period 2020 to 2030, with particular emphasis on the year 2020.

The assessment applies a bottom-up approach, starting from a data set on basic energy needs in each sector. These include space heating and cooling, water heating, lighting, and appliances. Heating, ventilation and air conditioning (HVAC) needs are estimated for existing and new building stock. Also, houses and apartments are treated separately, because the energy intensities for HVAC depend heavily on the building vintage and type. In addition, implementing efficiency measures in new buildings costs only a fraction of costs for retrofitting existing houses. The other needs, which are less depending on the types and age of buildings are determined for an average building/dwelling.

Energy consumption by need n after implementation of efficiency options can be calculated from the following formula:

$$EC_{j,k,n,c,r} = A_{j,k,n,r} * M_{j,k,n,r} * enin_{j,k,n,c} * \sum_t (1-\eta_{j,k,n,c,t}) * X_{j,k,n,t,r}$$

Equation 2.2

where:

n	energy need type (e.g., space heating)
t	energy efficiency technology/option
$A_{j,k,n,r}$	value of activity variable used to assess energy consumption for need n in sub-sector k of sector j in time period r
$M_{j,k,n,r}$	intensity multiplier for need n in sub-sector k of sector j in time period r
$enin_{j,k,n,c}$	consumption of energy type c by need n in sub-sector k of sector j in time period r without energy efficiency measures
$X_{j,k,n,t,r}$	implementation rate of technology t for need n in sub-sector k in time period r
$\eta_{j,k,n,c,t}$	reduction in consumption of energy type c used to satisfy need n in sub-sector k caused by application of technology t.

Activity variables A used in the residential and commercial sector are need-specific. They represent either floor space or number of dwellings (housing units). The demand for certain types of energy services is likely to change in the future. For instance, demand for space cooling is expected to increase with rising incomes. Similarly, the use of electronic equipment in households, and in particular of computer equipment, is likely to increase faster than the number of housing units. In turn, the demand for cooking can decrease because of convenience food, more dining out, etc. Changes in the demand for energy services are included through the so-called intensity multipliers M, which reflect the ratio of the demand per activity unit in the projection year relative to the demand in the base year.

Total consumption of energy type c in sub-sector k of sector j in time period r can be obtained through summing up consumption generated by each need n:

$$EC_{j,k,c,r} = \sum_n EC_{j,k,n,c,r}$$

Equation 2.3

An important part of the calculation routine is matching the sum of energy consumption for individual needs with the sectoral total in the base year (2005) and in the projection years for the baseline scenario. Energy demand calculated with this bottom-up approach is usually different from aggregated fuel demand in the baseline scenario. Thus parameters used in the bottom-up calculation (activity levels, energy intensities, uptake of efficiency technologies in the baseline) need to be adjusted so that GAINS reproduces (with a given accuracy) the baseline values. Calibration needs to be done first for the year 2005. This includes modifying data on energy intensities of individual needs, and/or uptake of efficiency measures in the base year. Next, calibration for the projection years occurs. Modifications need to be done in an iterative way until a satisfactory agreement between calculated fuel consumption and historic/projection values is achieved.

$$\left|\overline{EC}_{j,k,c,r} - EC^{BL}_{j,k,c,r}\right| \leq \varepsilon \qquad \text{Equation 2.4}$$

where

$\overline{EC}_{j,k,c,r}$	consumption of energy type *c* in sub-sector *k* of sector *j* in time period *r* in the baseline scenario,
$EC^{BL}_{j,k,c,r}$	calculated energy consumption for the baseline conditions,
ε	accuracy limit.

The calibration for the baseline case is performed through side calculations, if possible with participation of national experts.

Further options for reducing energy consumption are determined taking into account the remaining potential (on top of the baseline) for each efficiency option. Energy consumption for the "maximum efficiency" case can be calculated by the optimisation routine of GAINS assuming minimization of CO_2 emissions under the following conditions:

$$X_{j,k,n,t,r} \leq X^{\max}_{j,k,n,t,r}$$

and

$$\sum_t X_{j,k,n,t,r} \leq \overline{X}^{\max}_{j,k,n,r} \qquad \text{Equation 2.5}$$

where:

$X^{\max}_{j,k,n,t,r}$	maximum implementation rate (potential) for technology *t* used to satisfy need *n* in sub-sector *k* and time period *r*
$\overline{X}^{\max}_{j,k,n,r}$	maximum value of the sum of implementation rates of all technologies used to satisfy need *n* in sub-sector *k* and time period *r.*

The difference in energy consumption caused by the implementation of option *t* is calculated from the following formula:

$$\Delta EC_{j,k,c,n,t,r} = EC^{BL}_{j,k,c,n,t,r} - EC_{j,k,c,n,t,r} \qquad \text{Equation 2.6}$$

Table 2.14: Specific uses/energy needs in the residential and commercial sectors that are considered in the GAINS analysis

Sector/Need	Activity variable	Intensity indicator
Residential sector		
Heating, ventilation and air conditioning	Living space	GJ/m2
- Space heating	Living space	GJ/m2
- Space cooling	Living space	GJ/m2
Water heating	Housing unit	GJ/h_unit
Cooking	Housing unit	GJ/h_unit
Lighting	Housing unit	GJ/h_unit
Large appliances (refrigerators, freezers, washing machines, dishwashers, dryers)	Housing unit	GJ/h_unit
Small appliances (computers, TV sets, audio and other electronic equipment)	Housing unit	GJ/h_unit
Commercial sector		
Heating, ventilation and air conditioning (HVAC)	Building space	GJ/m^2
- Space heating	Building space	GJ/m^2
- Space cooling	Building space	GJ/m^2
- Space ventilation	Building space	GJ/m^2
Water heating	Building space	GJ/m^2
Cooking	Building space	GJ/m^2
Lighting	Building space	GJ/m^2
Large appliances (refrigerators, freezers, washing machines, dishwashers, dryers)	Building space	GJ/m^2
Small appliances (office equipment, other electronic equipment)	Building space	GJ/m^2
Other needs (not included separately)	Building space	GJ/m^2

2.3 Costs of mitigation

2.3.1 CONCEPTUAL APPROACH

The GAINS methodology to estimate potentials and costs of greenhouse gas mitigation uses an extended bottom-up approach. As all bottom-up models, GAINS represents reality by aggregating characteristics of specific activities and processes, considering technological, engineering and cost details. However, in contrast to many other bottom-up approaches, GAINS considers the effects of energy savings in other sectors and structural changes by using a systems approach for quantifying the overall effects of specific measures.

For calculating mitigation costs for an international comparison, the GAINS methodology attempts to quantify the values to society of the resources diverted to reduce emissions. In practice, these values are approximated by estimating costs at the production level rather than at the level of consumer prices. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Any taxes added to production costs are similarly ignored, as are subsidies, as they are transfers and not resource costs.

This societal perspective of GAINS also implies the use of an interest rate for putting up-front investments, operating costs and savings that occur at different points in time on the same scale. As explained in Section 2.3.4, GAINS reports annual costs of all mitigation measures in the target year (2020), adding up operating costs and savings in that year together with investments that are annualized over the technical life time of the equipment. The chosen interest rate for annualizing investments reflects the productivity of capital (Pearce and Turner, 1990), which is comparable to the long-term bond rate. In line with earlier policy analyses that have been conducted with GAINS (e.g., Amann and Lutz, 2000) and the conclusions drawn in the Fourth Assessment Report of the IPCC for social cost calculations in general and greenhouse gas mitigation costs in particular (Halsnæs *et al.*, 2007), an interest rate of four percent per year has been adopted as the central value. Since the societal perspective does not consider profits, investments are depreciated over the full technical life time of the equipment.

These rates do not reflect private rates of return and the discount rates that are used by many private companies, which typically need to be considerably higher to justify investments, and are potentially between 10 and 25 percent. Therefore, the use of a social interest rate provides a different perspective from that of individual actors, and costs that are calculated for such a societal perspective might be different from those that are perceived by companies and private consumers.

With this concept, the GAINS methodology addresses the ‘economic potential’ for mitigation as defined by the IPCC (Halsnæs et al., 2007), i.e., the amount of greenhouse gas mitigation that is cost-effective for a given carbon price, based on social cost pricing and discount rates (including energy savings but without most externalities).

In contrast, the ‘market potential’ as defined by IPCC (Halsnæs *et al.*, 2007) would indicate the amount of GHG mitigation that might be expected to occur under forecast market conditions, including policies and measures in place at the time. It is based on private unit costs and discount rates, as they appear in the base year and as they are expected to change in the absence of any additional policies and measures. In other words, market potential is the conventional assessment of the mitigation potential at current market price, with all barriers, hidden costs, etc. in place.

As a consequence of the chosen costing concept (i.e., use of a social discount rate, exclusion of transfer payments such as taxes, profits, etc., and the omission of transaction costs), the calculation delivers for certain mitigation measures negative costs. This means that from a societal perspective and considering the costs over the full technical life time, some measures result in cost savings (or net benefits) compared to the baseline case. Such measures would generate net social benefits whether or not there is climate change associated with anthropogenic emissions of greenhouse gases.

The existence of a considerable mitigation potential with negative costs has been confirmed by the Fourth Assessment Report of the IPCC (Barker *et al.*, 2007) as well as by numerous business studies (e.g., The Climate Group, 2005, Kreyts, 2007). As the magnitude of the potential with negative costs depends on the costing concept, measures that have negative costs from a social perspective are often not adopted by private actors, which use higher discount rates to justify investments.

To explore the implications of a costing concept that uses the perspective of economic actors, GAINS also performs the cost assessment for the assumption of a private interest rate. For this purpose, an interest rate of 20 percent is assumed. Comparison of the results with the outcome for a social interest rate allows quantifying the financial barrier that would need to be overcome in order to make investments that are cost-effective from a social perspective also economically attractive to private investors.

2.3.2 SECTORAL AND TEMPORAL ASPECTS

The approach presented in this report quantifies mitigation potentials of measures that are applied domestically within a country. Thereby it does not account for the potential offered by flexible instruments of the Kyoto Protocol, such as Joint Implementation (JI) and the Clean Development Mechanism (CDM). If negotiations allow for such instruments, information on the availability and costs of emission credits that could be acquired abroad need to complement the information on the potentials and costs of domestic measures that is provided in this report.

With its system approach, the GAINS methodology includes changes in full life cycle emissions that are caused by a specific measure in a sector, even if they occur in other sectors or countries. For instance, the approach accounts for the implications of electricity savings measures on the power generation structure or from reduced road fuel consumption on the refinery activities. Also for bio-fuels, the approach assumes that the fuels that are consumed within a country are produced domestically, and accounts for emissions that typically emerge during their production. While this is in contrast to current accounting practices of the UNFCCC emission inventories, it avoids leakage of greenhouse gases to other (non-Annex I) countries.

The cost calculation in GAINS is restricted to incremental costs that occur in comparison to a reference (or baseline) scenario. It is beyond the scope of GAINS to calculate total costs, e.g., of energy systems, or the housing and agricultural sector.

Since the GAINS approach does not model the economics of the driving forces of pollution, it cannot develop projections of future economic development and its implications on activities that cause greenhouse gas emissions (e.g., levels of energy consumption, industrial production, agricultural activities, etc.). Instead, the analysis adopts, for selected years in the future, exogenous projections of such activity levels that have been developed with appropriate tools as an input.

With this approach the GAINS analysis does not internalize the dynamics of economic development, e.g., the turnover and renewal of the capital stock in the general economy. However, although the GAINS assessment is carried out for single points in time in the future (e.g., 2020), it does consider the most important dynamic aspects that influence the potentials and costs for greenhouse gas mitigation. For all important sectors GAINS distinguishes (i) the currently existing capital stock that is expected to be still in operation in 2020, and (ii) new capacities that will be built from 2010 onwards according to the exogenous activity projection. It is assumed that all capacities that, according to the baseline projection, will come into operation after 2010 can be constructed with a less emitting technology than that foreseen in the baseline projection. The incremental costs of the advanced technology compared to the originally foreseen technology are estimated. No premature scrapping before the end of the normal life time is assumed for capital stock that currently exists and that is expected to remain in operation in 2020. However, to the extent they are technically possible retrofit measures are considered.

Thereby, although the cost analysis is formulated for a single year in the future, it incorporates the dynamic nature of the future turnover of the capital stock by assuming that a mitigation strategy that achieves the target emission reduction level in 2020 would start, if necessary, in 2010 by building more efficient equipment instead of the technologies that are foreseen in the baseline projection.

As laid out in Section 2.3.4, the GAINS model calculates annual costs of mitigation that occur in the target year 2020, summing up annual operating costs, savings and annualized investments of all measures that are contained in the mitigation strategy for that particular year. Total mitigation costs in other years are different, reflecting progressive implementation of measures; for years before 2020, annual mitigation costs would gradually increase following the implied phase-in of mitigation measures.

2.3.3 LIMITATIONS

In the current version, the analysis excludes the mitigation potential that results from behavioural changes in the population, essentially since GAINS does not include a methodology to estimate costs of behavioural changes in an international context.

In a similar way, the evaluation does not consider implementation costs (e.g., for education, monitoring and verification of mitigation programs). Such costs can be substantial, inter alia for measures that require widespread implementation by a large number of dispersed actors (e.g., in the agricultural and forestry sectors).

It is assumed that capital to invest in mitigation measures is available in unlimited amounts. Quantification of feedbacks from additional demand for capital for greenhouse gas mitigation on the overall economy would require complex macro-modelling, which is beyond the perspective of the GAINS model.

Similarly, feedbacks of increased costs for mitigation on prices and, subsequently, the demand for energy or other services are excluded from this first-order cost assessment that is presented in this report.

While the limitations posed by these assumptions need to be kept in mind when interpreting results of the analysis, these restrictions are common to all bottom-up approaches[1] which estimate mitigation potentials and costs for individual activities and processes, considering technological, engineering and cost details. These limitations can be overcome by top-down approaches that apply macroeconomic theory, econometric and optimization techniques to aggregate economic variables. Using historical data on consumption, prices, incomes, and factor costs, top-down models assess final demand for goods and services, and supply from main sectors.

The review of results from bottom-up and top-down models presented in the Fourth Assessment Report of the IPCC (Barker *et al.*, 2007) found that the ranges of bottom-up and top-down aggregate estimates of mitigation potentials overlap substantially under all cost ceilings except for the no-regrets bottom-up options, i.e., that different approaches arrive in general at comparable conclusions.

In summary, mitigation costs estimated by GAINS include incremental investments, operating and maintenance costs as well as cost savings that emerge in comparison to a baseline case. The incremental costs computed by GAINS do not include transaction costs, subsidies, taxes, communication and information costs, nor social, welfare and implementation costs. Also, subsequent impacts on the national economies are not considered. While these cost items might be important for a full economic assessment of greenhouse gas mitigation programs, they are likely to have less influence on an international comparison of mitigation efforts across countries.

2.3.4 CALCULATION PROCEDURE

The GAINS methodology estimates costs of greenhouse gas mitigation in a country through the following procedure:

- For each mitigation option in each sector and country, unit costs of emission reduction are calculated with a bottom-up approach that considers investments, operating costs and associated savings.

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[1] Bottom-up models represent reality by aggregating characteristics of specific activities and processes, considering technological, engineering and cost details.

- An optimization analysis is carried out that determines for each country, for a given emission reduction target, the portfolio of measures at all sources that achieve the mitigation target at least cost. This optimization considers, inter alia, the optimal adjustments of the energy supply structure if demand is reduced through energy savings measures.
- A sequence of such optimization analyses is carried out for progressively tightened mitigation targets (starting from the baseline projection to the lowest level of emissions that can be achieved through maximum exploitation of the available mitigation potential). For each case, total mitigation costs in the country, the emission reduction target and the optimized portfolio of measures are recorded.
- With this information, national cost curves are constructed that describe how total mitigation costs in a country increase with progressively tightened emission reductions. For each of the optimized points on the cost curve, the corresponding marginal costs are computed. Marginal costs reflect the highest costs (per unit of emission reductions, i.e., €/ton CO_2eq) of the measures that are contained in the cost-optimal portfolio for the given emission reduction target. While marginal costs represent costs of the most expensive measure of the cost-effective portfolio, average costs that relate total costs to all measures in the portfolio are typically significantly lower.

Unit costs of mitigation

As a first step, the assessment calculates unit costs of mitigation (per unit of reduced greenhouse gas emissions) for each mitigation option in each sector and country, taking into account national circumstances that lead to defensible differences in emission control costs. Expenditures for emission controls are differentiated into:

- investments,
- operating and maintenance costs, and
- cost savings.

For each mitigation option considered in GAINS, costs of local application are estimated 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:

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

Depending on the purpose of the cost calculation, control costs can be expressed in relation to the achieved emission reductions. Such unit costs are useful for cost-effectiveness analysis, as long as a single pollutant is considered. In such a case 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). Such coefficients are also useful for constructing cost curves of emission reductions for a single pollutant, as long as they do not account for interactions with and side-impacts on other pollutants.

In order to avoid arbitrary allocations of costs across several pollutants, the multi-pollutant optimization of the GAINS model compares the cumulative effects on all affected pollutants and compares them with the costs of the measure (per activity) as specified in Equation 3.

For measures that replace existing equipment by less emitting technologies, net costs are derived from the difference in unit costs computed for both technologies.

Details on cost calculation methodologies for the different pollutants that are considered in GAINS are provided in separate reports (Amann *et al.*, 2008a, Borken-Kleefeld *et al.*, 2008, Höglund-Isaksson *et al.*, 2008, Böttcher *et al.*, 2008). Note that actual input data to cost calculations can be extracted from the GAINS-online implementation at the Internet (http://gains.iiasa.ac.at).

Least-cost portfolio of mitigation measures

In a second step, the least-cost portfolio of measures that achieves a given reduction target for the total greenhouse gas emissions of a country is determined through an optimization analysis.

The optimization uses two types of decision variables: (i) 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

$$C = \sum_{i,k} \left(\sum_{m} c^{x}_{i,k,m} \cdot x_{i,k,m} + \sum_{k'} c^{y}_{i,k,k'} y_{i,k,k'} \right) \tag{4}$$

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:

$$x^{\min}_{i,k,m} \le x_{i,k,m} \le x^{\max}_{i,k,m}, \quad x^{\min}_{i,k} \le x_{i,k} \le x^{\max}_{i,k}, \quad y^{\min}_{i,k,k'} \le y_{i,k,k'} \le y^{\max}_{i,k,k'} \tag{5}$$

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:

$$x_{i,k,m} \leq appl_{i,k,m}^{\max} x_{i,k}\ , \quad appl_{i,k,m}^{CLE} \leq appl_{i,k,m}^{\max} \tag{6}$$

where the maximum application rate is at least as high as the application rate in the current legislation scenario.

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

$$E_{i,p} = \sum_k \sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \tag{7}$$

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

$$\sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \leq IEF_{i,k,p}^{CLE} \cdot x_{i,k} \tag{8}$$

where $ef_{i,k,m,p}$ is the emission factor for pollutant *p* stemming from activity *k* being controlled by technology *m,* and $IEF_{i,k,p}^{CLE}$ 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

$$x_{i,k} + \sum_{k'} y_{i,k,k'} - \sum_{k'} \eta_{i,k,'k} \cdot y_{i,k,'k} = x_{i,k}^{CLE} \tag{9}$$

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.

This systems perspective of the optimization approach avoids arbitrary allocations of costs to individual pollutants of emission reduction measures that simultaneously affect more than one gas (e.g., lower energy demand reduces all associated emissions at the same time). It also circumvents the necessity to rely on arbitrary a-priori assumptions about upstream adjustments of the supply structure for measures that reduce energy demand (e.g., assuming the mode of electricity production that would be reduced through electricity savings in the end-use sector). As a disadvantage, however, such an approach does not allow direct reporting of emission savings for individual measures, but only for all measures collectively that form part of the optimal solution.

Cost curves

In a third step, a series of optimizations is carried out with gradually tightened mitigation targets (starting from the baseline projection to the lowest level of emissions that can be achieved through maximum exploitation of the available mitigation potential). For each case the emission reduction target, total mitigation costs in the country and the optimized portfolio of measures are recorded.

With this information, national cost curves are constructed that describe how total mitigation costs in a country increase with progressively tightened emission reductions. Each of the optimization results represents a point on the cost curve, providing total mitigation costs in a country for the given mitigation level.

For each of these points, corresponding marginal costs are computed. Marginal costs reflect the costs for changing the emission constraints by one unit and are determined in the GAINS analysis by the highest costs (per unit of emission reductions, i.e., €/ton CO_2eq) of all measures that are contained in the cost-optimal portfolio for the given emission reduction target. Marginal costs represent the carbon price that would be necessary to achieve the emission reduction.

While marginal costs reflect costs of the most expensive measure of the cost-effective portfolio, average costs that relate total costs to all measures in the portfolio are typically significantly lower.

With all the assumptions described above, a cost curve developed with the GAINS model can be considered as a supply curve of greenhouse gas mitigation in a country. It provides incremental costs that would occur in comparison to the reference (baseline) case if greenhouse gas emissions were reduced. GAINS cost curves are constructed from a social perspective using an interest rate that reflects the productivity of capital, and do not include transfer of money within a society (e.g., taxes, profits, etc.). While they consider a wide range of technical mitigation measures, they exclude behavioural changes that affect peoples' lifestyles.

With this understanding, cost curves can be used to provide an integrated perspective of the abatement potentials and costs in different countries. They integrate over the wide range of emission sources in different economic sectors, over different gases and over different measures that are available to mitigate emissions. They take explicit account of objective structural differences across countries that lead to international differences in mitigation potentials and costs. Cost curves address a future situation, which is assumed to be different from today's conditions in the way it is anticipated in the baseline activity projections. Thereby, cost curves are a result of a coherent and transparent framework to quantify international differences in mitigation potentials and costs, which allow tracking down objective reasons for differences among countries.

In order to arrive at a practical tool that could be implemented with the available data within the politically relevant time window, certain methodological choices and assumptions have been made that need to be taken into account when interpreting results. As pointed out above, the methodology aims at a coherent comparison of mitigation efforts based on a set of common assumptions. Following the bottom-up methodology, the current assessment does not quantify absolute costs of greenhouse gas mitigation in a country, and does not consider all conceivable aspects. For instance, the assessment does not consider (i) macro-economic feedbacks (via, e.g., competitiveness, external trade relations, energy supply security, employment, tax revenues, etc.,) (ii) changes in consumer's behaviour that could provide additional mitigation potentials or reduce mitigation costs, (iii) co-benefits and trade-offs with other policy areas (e.g., air pollution control, agricultural policies, etc.). It also refrains from quantifying the benefits from greenhouse gas mitigation to a country, and does not address potential implications on advisable adaptation measures.

These factors are either difficult to quantify in a sufficiently robust way, or some methodologies for such quantifications are controversial, or they would require subjective assumptions, or it was not feasible to conduct the assessment in the available time. However, while all these aspects are important for a full assessment of the costs of climate change, they might be of less importance if the focus of the assessment is put on the international comparison of mitigation costs across different Annex I Parties. To explore the robustness of an international cost comparison, the GAINS methodology allows a range of sensitivity analyses to be conducted to explore the implications of alternative assumptions on, e.g., (i) economic development, (ii) future world energy prices, and (iii) different costing concepts that employ different interest rates.

2.4 Co-benefits on air pollution emissions

The GAINS model also quantifies impacts on air pollution that occur as side-effects of greenhouse gas mitigation.

In a first step, implications of modified energy consumption levels on the emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), ammonia (NH_3) and volatile organic compounds (VOC) are calculated. This is achieved by applying the country-specific 'current legislation' emission factors for the air pollutants that are contained in the GAINS database to the modified activity levels according to Equation 1. This step is readily available for Annex I countries, and results of these calculations are presented in this report.

As a second step, GAINS can quantify the co-benefits from these emission reductions on human health, agricultural crops and ecosystems in physical terms. It has been shown for Europe and Asia that these co-benefits of mitigation strategies can be substantial (Amann *et al.*, 2008b, Amann *et al.*, 2007), although their monetary valuation remains controversial in many cases. As the air quality related modules of GAINS are currently not implemented for Annex I countries outside Europe, this feature is not applied in this report.

Thirdly, the GAINS model can also quantify the cost savings for implementing current national air pollution control legislation that result from a less carbon-intensive energy consumption pattern. With its systems perspective, the GAINS model considers these cost savings already when estimating the net costs of greenhouse gas mitigation as they are presented in this report. While with this approach a double-counting of these cost savings is avoided, estimates of reduced air pollution control costs is useful information to air quality managers, who frequently work in isolation from climate policy analysts. It has been shown that, e.g., in the European Union such cost savings can typically compensate up to 40 percent of the gross costs of greenhouse gas mitigation (Amann *et al.*, 2007).

Fourth, a full implementation of the GAINS model also allows the design of cost-effective emission control strategies that simultaneously achieve policy targets on improved air quality and for lower greenhouse gas emissions. This optimization approach aims at maximizing synergistic effects that some emission control measures have on air pollutants and greenhouse gas emissions (e.g., energy efficiency improvements, replacement of coal and oil, advanced clean coal technologies such as integrated gasification combined cycle (IGCC) plants, etc.). It also avoids measures that exhibit clear trade-offs, such as an increased use of diesel vehicles without particle filters, or end-of-pipe emission control technologies that reduce energy efficiency.

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