

**EC4MACS**

**Uncertainty Treatment**

**Assessment and  
Treatment of  
Uncertainties in the  
EC4MACS Model  
Framework**

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## Executive Summary

This report reviews key uncertainties of the various models of the EC4MACS integrated assessment framework and explores options of uncertainties treatment that would enable robust policy conclusions.

Uncertainties fall into several classes, such as uncertainties in model representation, model parameters (including initial data and technology parameters), and expectations of future developments. The modelling teams reviewed a wide range of uncertainties, starting from implementation of future economic, agricultural and environmental policies, agents' behaviour, energy statistics, technology costs and potentials, and vehicle fleet structure and sizes. The review addresses uncertainties in emission factors, in future livestock numbers and food demand, in food prices, in forest management practices, in bioenergy production projections, in wood demand, in meteorological fields, in empirical critical loads information, and the monetary valuation of impacts.

Some of these uncertainties cannot be avoided even in a perfect world with best scientific efforts. A methodology has been developed that provides ex-post flexibility to the implementation of national emission ceilings to maintain cost-effectiveness of an overall strategy even if important assumptions turned out to be wrong. Such emission offsetting would allow countries to compensate lower reductions of a given pollutants by additional cuts of other pollutants while safeguarding the achievement of the original air quality targets for which the emission ceilings have been established at the first instance. The GAINS model analysis has identified critical questions that policy makers face when they consider such an offsetting as a viable option to hedge against the risk of over- or under-constraining future emission levels. Answering these questions can lead to a pragmatic solution to the question how to make progress with defining legally binding emission targets in an uncertain future based on uncertain data.

## More information on the Internet

More information about the EC4MACS methodology and interactive access to models and their results is available at the Internet at <http://www.ec4macs.eu>.

## *Glossary*

|                   |  |
|-------------------|--|
| AAE               | Average accumulated exceedance                                     |
| AGLINK            | OECD supply demand model of world agriculture                      |
| CAPRI             | Agricultural model developed by the University of Bonn             |
| CH <sub>4</sub>   | Methane  |
| CHP               | Combined Heat and Power  |
| CLRTAP            | Convention on Long-Range Transport of Air Pollution                |
| CO <sub>2</sub>   | Carbon dioxide   |
| COPERT            | Model of air pollutant emissions from road transport               |
| ECE               | Economic Commission for Europe                                     |
| EEA               | European Environmental Agency                                      |
| EFMA              | European Fertilizer Manufacturers Association (Fertilizers Europe) |
| EMEP              | European Monitoring and Evaluation Programme                       |
| EPIC              | Environmental Policy Integrated Climate Model                      |
| ESAP              | Energy System Analysis and Planning Tool                           |
| ETS               | Emission Trading System of the European Union for greenhouse gases |
| EU                | European Union   |
| EUROSTAT          | Statistical office of the European Union                           |
| FAO               | UN Food and Agriculture Organization                               |
| FASOM             | Forest and Agricultural Sector Optimization Model                  |
| GAINS             | Greenhouse gas - Air pollution Interactions and Synergies model    |
| GDP               | Gross domestic product   |
| GEM-E3            | General equilibrium model covering Economy-Energy- Environment     |
| GLOBIOM           | Global Biomass Optimization Model                                  |
| G4M               | Global Forest Model  |
| IEA               | International Energy Agency  |
| IFPRI             | International Food Policy Research Institute                       |
| IIASA             | International Institute for Applied Systems Analysis               |
| kt                | kilotons = 10 <sup>3</sup> tons                                    |
| LULUCF            | Land Use, Land-Use Change and Forestry                             |
| MFR               | Maximum Feasible Reductions in the GAINS model scenarios           |
| MSC-W             | EMEP's Meteorological Synthesizing Centre - West                   |
| N <sub>2</sub> O  | Nitrous Oxide  |
| NEC               | National Emissions Ceiling   |
| NH <sub>3</sub>   | Ammonia  |
| NO <sub>x</sub>   | Nitrogen oxides  |
| O <sub>3</sub>    | Ozone  |
| OECD              | Organisation for Economic Co-operation and Development             |
| PM <sub>2.5</sub> | Fine particles with an aerodynamic diameter of less than 2.5 µm    |

|                 |   |
|-----------------|---|
| PRIMES          | Energy Systems Model of the National Technical University of Athens             |
| RES             | Research Environment Database   |
| SO <sub>2</sub> | Sulphur dioxide   |
| SOMO35          | Sum Of Means Over 35ppb (daily max. 8-hour): measure of O <sub>3</sub> exposure |
| TFIAM           | Task Force on Integrated Assessment Modelling                                   |
| TREMOVE         | EU-wide transport model   |
| UNFCCC          | United Nations Framework Convention on Climate Change                           |
| VOC             | Volatile organic compounds  |
| WTO             | World Trade Organization  |
| YOLL            | Years of Life Lost  |

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## 1 Introduction

EC4MACS establishes a suite of modelling tools for a comprehensive integrated assessment of the effectiveness of emission control strategies for air pollutants and greenhouse gases. The common assessment framework (GAINS) links the RAINS integrated assessment model for air pollution, the PRIMES energy model, the TREMOVE transport model, the CAPRI agriculture model, the EMEP atmospheric dispersion model, the GAINS-Europe model for greenhouse gas mitigation, models for health and ecosystems impacts, the GEM-E3 macro-economic general equilibrium model and the Alpha-2 and EXTERNE benefit assessment approaches.

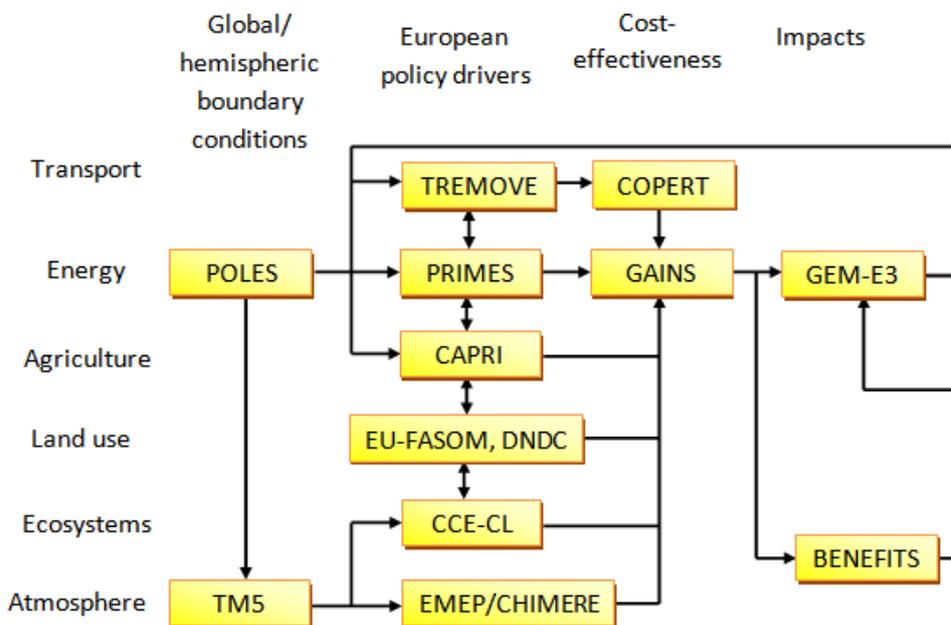


Figure 1 EC4MACS modelling framework and its components

Each of these modelling components is associated with uncertainties. The combination of these components introduces further uncertainties, as the outputs from some models are inputs to others. Uncertainties may undermine the validity of the conclusions drawn with an integrated assessment framework. They may introduce biases, or they may play out in either direction. It is therefore important to better understand the uncertainties present in the model system, their interrelation and their eventual relevance in the decision making process.

There are rather generic frameworks for dealing with uncertainties (Halpern 2005), some of which are not very practical in the context of integrated assessment modelling. Previous work on uncertainties in integrated assessment frameworks of air pollution control has focussed on the role of potential biases and used methods of error propagation (Syri, Suutari, & Posch 2000) (Suutari et al. 2001) (Schöpp et al. 2005).

In the context of EC4MACS, a two-track approach to uncertainties and their relevance for decision making was taken. On the one hand, the main uncertainties were assessed by each modelling team of the consortium individually. Different methods were used, ranging from sensitivity scenario analysis establishing a range of plausible outcomes, to full-blown Monte-Carlo simulations establishing probability density functions. As an alternative to a detailed error-propagation (which would be shaky also from a methodological point of view, given the dissimilarity of modelling approaches and epistemological claims), the synthesizing GAINS analysis focuses on the question of how decision makers can use results of an integrated assessment modelling exercise for designing effective air pollution control policies despite the fact that the assessment results are to some degree uncertain.

The remainder of this document is thus structured as follows. Section 2 briefly summarizes important findings over the last decade on various dimensions of uncertainty analyses and treatment, and identifies those that are most relevant to stakeholders. Section 3 summarizes the uncertainty assessment of the main EC4MACS models, including important results of their respective sensitivity studies. Uncertainties cannot be eliminated. Therefore Section 4 develops a pragmatic approach that addresses the question of how the ultimate outcome of an integrated assessment of least-cost solutions, i.e., a set of emission ceilings, can reflect the uncertainties in future emissions and emission control cost, while at the same time honour the original purpose of the ceilings, namely to reduce the environmental impacts by a certain amount. Section 5 summarizes the results and concludes on the effectiveness of the uncertainty treatment.

## 2 *Conceptual approaches to uncertainty*

A workshop on uncertainty treatment in the integrated assessment of air pollution and climate strategies has been organised by the EC4MACS-project together with the Task Force on Integrated Assessment Modelling (TFIAM) of the Convention on Long-range Transboundary Air Pollution (November 3-4, 2010; International Institute for Applied Systems Analysis (IIASA); see (TFIAM 2010). The purposes of the workshop were: (1) to review the main sources of uncertainty in integrated assessment modelling; (2) to identify approaches for treating uncertainties and for risk management strategies in the context of the revision of the Gothenburg Protocol; and (3) to discuss possibilities for improved communication of uncertainties to decision makers.

### 2.1 *Dimensions of uncertainty*

A variety of classifications of the types of uncertainties has been proposed in the scientific literature, and different approaches to identify and manage risks have been developed. Basically, one can distinguish knowledge-related uncertainty and variability-related uncertainty. The level of uncertainty can be described in terms of statistical uncertainty, scenario uncertainty and recognized ignorance. Uncertainties appear at various points in an integrated assessment. A model representation can be uncertain in terms of structure, model parameters and input data. Data themselves are uncertain as a result of the methods they were obtained by (e.g., measurement, monitoring, survey). In absence of data expert judgement are often elicited, which is uncertain as well. Expert judgement also enters in the form of narratives, storylines and general advice. Finally, outputs of an assessment can be uncertain, as far as the indicators used or statements made are imprecise.

The presence of uncertainties amplifies the need to provide quality control mechanisms at each stage of the assessment. This ranges from problem framing (e.g., establishing the link to other problems and system boundaries of the present problem) and stakeholder involvement, to the appraisal of the knowledge base, the assessment of the robustness of conclusions to the clarity of the main messages of the assessment.

A pragmatic approach may distinguish uncertainties in data, in model structures and in expert judgements, as well as biases due to the chosen system boundaries and the choice of output indicators. Some uncertainties could be reduced by more research, but uncertainties due to input variability, lack of knowledge or recognised ignorance will always remain to some extent, and have to be taken into account in the decision making process.

### 2.2 *Stakeholder perspective*

At the workshop on uncertainty treatment (TFIAM 2010), stakeholders from industry, environmental NGOs and policy makers presented their expectations of what an uncertainty assessment can deliver. All stakeholders are aware of the existence and sometime irreducibility of uncertainties in integrated assessment modelling. Different stakeholder groups share concerns about uncertainties,

although with different perspectives. Industrial stakeholders emphasized their interest in avoiding regret investments, especially of expensive policy measures. Particular concerns relate to a too narrow scope of sensitivity analyses (e.g., if limited to energy scenarios with rather similar assumptions on future economic development), too short time scales that do not fully grasp the dynamics of the turnover of the capital stock, and too limited consideration of alternative hypotheses for health impacts of different components of particulate matter.

In contrast, non-governmental environmental organisations were concerned about insufficient health and environmental protection from modelled emission control strategies. These could result from too pessimistic assumptions on achievable emission reductions, e.g., due to limited consideration of the potential offered by technological progress, the on-going renewal of capital stock, and behavioural changes.

The workshop identified key uncertainties that are crucial for the development of robust policy conclusions. These include basic uncertainties about the future economic development; the effectiveness of energy, transport and agricultural policies assumed in the baseline; possible changes in meteorological conditions due to climate change; the impacts of pollution on human health and the environment; and the effectiveness and costs of abatement options (e.g., for road transport and agriculture).

Good communication between integrated assessment modellers, stakeholders and decision makers on uncertainties and policy risks was considered to be important, both at the national and the international scale. Uncertainty analysis should not be placed at the end of the assessment process, but should form an integral part of the workplan for modelling and policy development. Ideally, a wide range of scenarios should be investigated that cover broad ranges of the indicators and parameters that are uncertain, with established priorities.

### *2.3 Insights from earlier work on uncertainties in integrated assessment*

The assessment and treatment of uncertainties in integrated assessment modelling is not a new challenge. A main lesson that can be learned from an earlier workshop of the Task Force on Integrated Assessment Modelling in 2002 is that policy makers, in contrast to scientists, are less interested in detailed quantitative statistics about uncertainties, but rather in robust strategies that do not significantly change due to changes in uncertain model elements.

A systematic approach to uncertainties was considered important for establishing confidence in model results. Such an approach should differentiate between the reducible and the irreducible uncertainties. For the most significant sources of reducible uncertainties, it should determine by how much further scientific effort could increase the robustness of the models. For irreducible uncertainties, sensitivity analyses should be conducted for different assumptions. These should be made explicit and, where they significantly influence the model outcome, alternative scenarios should be explored.

A 2010 workshop of the Network of National Integrated Assessment Modellers (NIAM) emphasized the importance of sensitivity analyses to explore the effects of possible systematic biases that might emerge from missing data, model simplifications, incomplete scientific understanding and

assumptions about the future. At the same time, it was found that recognizing ignorance is often more important than characterizing variability.

Considering that the objective is to provide *robust* advice, one of the important questions that needs to be addressed in any useful uncertainty analysis is, are there any systematic biases in the assessment framework, and how sensitive are the results to such systematic biases? It was found that several factors will always lead to uncertainties and potential biases, such as:

- Imperfect data, such as missing emission sources, actual emission factor and actual vehicle stock numbers;
- Model simplifications, such as representation of technological change, behavioural change and of economic feedbacks, as well as limited spatial and temporal model resolution;
- Incomplete scientific understanding of the underlying mechanisms, e.g., of the gap between modelled and measured concentrations of particulate matter, and the health effects of different species of particulate matter;
- Our fundamental ignorance of the future, in particular energy prices, economic growth and structure, as well as about the effectiveness of economic and environmental policies.

Therefore, even with the best quantitative assessment of the uncertainties, robust advice will have to include how to deal with a future that turns out to be different from the one that was expected to materialize. This will be the subject of Section 4 of this report.

### 3 *Uncertainty assessment in the EC4MACS models*

In this chapter, we review the work that individual modelling teams have carried out to assess the main sources of uncertainty in their respective modelling approaches and frameworks.

#### 3.1 *The PRIMES energy model*

An overview of the uncertainty treatment in the PRIMES model is given in (Capros & Mantzos 2011). The very detailed representation of the energy system in the PRIMES model and its nature as a simulation tool for scenario quantification implies that the uncertainties surrounding the numerical values of parameters can be categorised as follows:

1. Uncertainties related to historical statistical data,
2. uncertainties related to engineering data,
3. uncertainties related to parameters entering the modelling of agents' behaviours,
4. uncertainties related to assumed policy drivers in scenario construction,
5. uncertainties related to assumed future evolution of technologies in scenario construction, and
6. uncertainties related to the context outside the boundaries of the system simulated by PRIMES (e.g., world energy system, macroeconomics, etc.) in scenario construction.

The first three categories concern the model database inputs, whereas the last three categories concern the exogenous assumptions when quantifying a scenario using the PRIMES model.

##### 3.1.1 *Historical statistical data*

The main statistical source used in PRIMES is the EUROSTAT database, complemented by other sources such as the IEA database for energy prices, the PLAITS and ESAP databases for power plants capacities, the EEA and UNFCCC for environmental statistics, various private data bases for renewable potentials, data from professional associations about industry and infrastructure, and others.

The update of the model database is carried out periodically, usually every two or three years in the context of "baseline" scenario construction supervised by DG Energy. Several updates were carried out since the mid 1990's and the most recent is dated back to end 2009, when the latest statistical data available referred to 2007.

Uncertainties related to historical data arise from the quality of available statistics, especially for the most recent statistical years, and the degree of matching of the statistical data with the level of disaggregation used in PRIMES. It is considered that the Eurostat databases are rather robust and so no uncertainty analysis was carried out for these data, which comprise the energy balance sheets, prices, emissions and import-export flows.

However, often Eurostat revises the statistics retrospectively. In that case, it is possible that at a certain point in time, between two database revisions the PRIMES, data for the past are different from the latest Eurostat statistics. This discrepancy is remedied when the PRIMES database is updated. Another source of uncertainty occurs when Eurostat undertakes revisions in the methodology of data definitions and their attribution to the different energy consuming agents. Examples are the CHP statistics and the biomass data.

Data from other sources, especially from industry, professional associations, private sources for RES, etc. are more uncertain regarding their accuracy and their coverage. Usually, before using them in the PRIMES database, a consistency analysis is performed by checking aggregates of these data against Eurostat data. Adjustments are then made to render these data consistent with the energy balances.

As the model is fully calibrated to past statistics (parameter values are derived so as to allow the model simulate the past accurately), the derived numerical values of exogenous parameters influence the simulation of future evolution of the energy system. Thus, statistical revisions and updates have an impact on projections. This type of uncertainties is difficult to be quantified and to be dealt with beforehand. Dealing with them occurs only after the publication of new statistics and involves the revision of the model database and the re-calibration of the model in order to reflect the revised characteristics of the energy system as recorded for the past.

Because of the large size of the model and the very high level of detail of the database, we do not perform sensitivity analyses for the historical database. Only small econometric models could afford doing this. So when database revisions and updates are performed we report on the impacts on projections of the revision of the historical database. One can get an idea of such impacts when comparing the different versions of the Energy Trends publication of DG Energy which is based on PRIMES; the Energy Trends to 2030 publication has published three consecutive versions with different updates, namely updates in 2005, 2007 and 2009.

### 3.1.2 *Engineering data*

The engineering data in the PRIMES database concern the technical and economic parameters that characterise energy efficiencies and costs of energy technologies, both in demand and in supply sectors, which are represented in the model.

The sources for these data are diverse, including the VGB database (a German company providing data derived from power plant construction projects), the International Energy Agency (IEA), European Technology platforms, and databases produced by EU research projects, such as the TECHPOL database. Because engineering data are uncertain and often different depending on the source, the PRIMES team often presents comparisons of engineering data used with data published by other sources; these presentations have been frequently discussed in workshops organised by the European Commission. The engineering data have a form of time series so that part of the data

correspond to the past and part constitute projections to the future. Engineering data for the past are not subject to uncertainty analysis, because they have rather small influence on the model calibration. In contrast, engineering data as projected for the future play an important role in the quantification of scenarios. Uncertainty analysis regarding these projections is discussed below.

### *3.1.3 Parameters entering the modelling of agents' behaviours*

The numerical values of parameters entering the mathematical formulation of agents' behaviours are assumed by the PRIMES modellers based on various sources, literature review and experience. As the model performs microeconomic simulations, these parameters cannot be estimated with econometric techniques in a direct way. However, the values assumed are decided after extensively reviewing econometric estimations published.

Because of the size of the model, we perform uncertainty analysis through sensitivity analysis model runs only for a few behavioural parameters in the model, such as some activities, price elasticities, for parameters reflecting perception of technology costs by consumers, and discount rates. Such sensitivity analyses are carried out by quantifying scenario variants in which the values of these parameters vary.

### *3.1.4 Indicative results of uncertainty exploration through scenarios*

Model outcomes are sensitive to changes of

- (1) macro and global assumptions (macro-economic developments, demographic projections and international fuel prices assumptions),
- (2) policy assumptions (possible policy failures, underestimation or overestimation of the effectiveness of policies in place, introduction of new policy incentives, etc.), and
- (3) technological assumptions (possible technology failures, faster penetration of new technologies than that foreseen in a scenario, availability of new technological options etc.).

These are exogenous to the model and constitute scenario assumptions for the future projections. Analysis for this type of uncertainties is carried out by defining alternative scenarios reflecting different evolutions of the exogenous assumptions projected to the future. Because of model size and complexity, the only way to explore these uncertainties is by quantifying alternative scenarios. This is a common practice for all models with similar size and nature as PRIMES. It is more practical to combine changes of many of the above mentioned exogenous assumptions rather than changing a single exogenous parameter. So an important issue is to define which combinations of assumptions should be changed for a particular sensitivity run.

We have carried out a number of sensitivity analyses in the context of EC4MACS (for details see (Capros & Mantzos 2011)), in particular the sensitivity to (a) future import prices of fossil fuels (b) climate policy for the period between 2020 and 2030 and delays in structural changes in transport

(i.e. electrification), (c) technology deployment supporting policies, and (d) the future level of the carbon prices. Some interesting conclusions can be drawn from the results:

- In (a) part of the total decarbonisation costs (shown as energy system costs) is compensated by the decrease in fossil fuel prices; this effect is seen in the decomposition of costs by sector of final consumption. It is also confirmed when seeing the average electricity prices, which are lower in the cases of low world fossil fuel prices, as expected.
- In (b) both factors may have large impacts on energy system costs and on consumer costs. Cost impacts are less significant in the electricity sector contrasting the effects in the demand sectors, which may face significantly higher costs in case of policy delays. Total costs of the uncertainty are calculated as the cumulative sum of costs per sector over the entire time period, and are estimated in the order of trillions Euro. The policy message is then clear enough: planning for infrastructure and deploying the measure in a timeliness manner during the intermediate time period well before 2050 is of utmost importance for reaching affordable costs in case climate policy requirements require a certain carbon budget in terms of cumulative emissions over the same time period.
- At present considerable uncertainties surround the future development of CCS (carbon capture and storage) and nuclear technologies. It is well known that these technologies are essential components in a cost-effective decarbonisation strategy, for various reasons including the impacts on costs of power generation and because they ensure stable base-load supply of power at competitive costs, which constitute an essential requirement for the competitiveness of energy intensive industry. However, their future deployment is uncertain mainly because of public acceptance issues, as fears exist regarding possible leakages from underground storage of carbon dioxide and regarding nuclear accidents. The development of CCS does not only depend on public acceptance but also on the development of infrastructure for CO<sub>2</sub> transportation and for storage, which are likely to develop according to a regulated monopoly regime at a large scale. The financial risk of such infrastructure development is very high, since CCS applications have not yet been implemented and public opposition may rise. Thus it is unlikely that such infrastructure develops solely on the basis of private initiative. CCS development will depend on the timeliness of public actions and investment by regulated monopolies. Our results show that the impacts from the uncertainty surrounding future development of CCS and nuclear have significant impacts on costs, the energy mix in primary energy terms, and on electricity prices. Possible failure of CCS and nuclear technology developments induce higher costs for the energy system, when accounting for total cumulative costs over the entire time period (annual cost estimates are less relevant for comparing these scenarios). The underlying reason is that it was imposed that all scenarios deliver the same level of carbon budget. Thus, the scenario with success in developing all decarbonisation options has the lowest cumulative cost since it avoids

developing certain decarbonisation options at extreme levels, which may entail incurrence of high non-linear costs.

- Carbon prices constitute important drivers in the various PRIMES energy scenarios and induce emission reductions both through the ETS mechanism in the sectors subject to ETS and through price signals to the non ETS sectors. Carbon prices induce changes in the fuel mix in various sectors, including power generation, push investments towards more efficient and less carbon emitting technologies, and facilitate action and behaviour towards higher energy efficiency. Carbon prices affect prices of energy commodities, which further induce adaptation in the energy demand sectors.

### 3.2 GEM-E3

The uncertainty analysis carried out with the GEM-E3 model (and in conjunction with the PRIMES model) is described in (Capros & Mantzos 2011). GEM-E3 is a general equilibrium model, which includes multiple countries and economic sectors. The model provides projections until 2050 of national accounts, prices, employment, trade, production, investments and use of production factors. A model projection depends on assumptions about the future evolution of technical progress (productivity indices) associated to all production factors in all sectors, changes in demography, public policy in terms of public consumption and investment, taxation schemes, and specific policies such as climate change mitigation objectives and related policy instruments, including ETS mechanisms.

The GEM-E3 equation parameters are of two kinds: coefficients with values derived from econometric estimations and guess-estimates based on literature reviews; secondly, coefficients that are calibrated through a mathematical procedure, which allows the model to reproduce past statistics when running for past years. Uncertainty regarding the values of the estimated coefficients has been explored in the past by sensitivity analyses, for example by running the model for the same policy scenario with varying values of elasticities (e.g., for the Armington foreign trade substitution elasticity parameters).

To explore uncertainties a scenario method is followed: GEM-E3 is used to quantify alternative scenarios and sensitivity analysis cases, as a means for exploring uncertainties about the future; thus results allow assessing policies. For example, within the EC4MACS project, scenarios are developed using GEM-E3 for exploring uncertainties about future participation of world regions in climate change mitigation effort, regarding the scope of participation and the timeliness of actions. Another relevant example is the quantification of alternative European and world economic growth scenarios for the future, based on different assumptions on GDP projections. The GEM-E3 model results for a variety of future economic growth scenarios are used as inputs to PRIMES energy model, which then

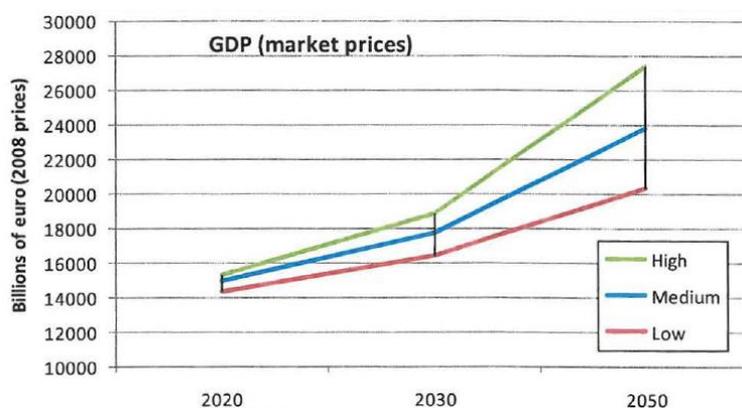
feeds the suite of models represented in EC4MACS. Three examples are discussed here to illustrate the type and scope of the sensitivity analyses.

### 3.2.1 *Uncertainty in economic growth projections simulated with GEM-E3*

Exploring the uncertainties surrounding the economic activity projection is a difficult and complex task. For such exploration, three scenarios were designed and quantified using GEM-E3, which describe three contrasted cases corresponding to low, medium and high growth. The medium case has been retained as the central case for model-based scenario development, whereas the other two cases serve to assess the sensitivity of projections around the central case. For all three scenarios the economic activity projections, energy and emission scenarios have been quantified using the PRIMES model, which uses the economic scenario results as inputs.

The scenarios include projections of activities by sector for a low growth and a high growth case, with a medium scenario as the central case. The projection of activities by scenario is consistent with GDP, investment and employment projections.

The range of uncertainties explored can be shown graphically below:



**Figure 2 Range of uncertainty in GDP projections expressed as alternative growth scenarios generated with GEM-E3**

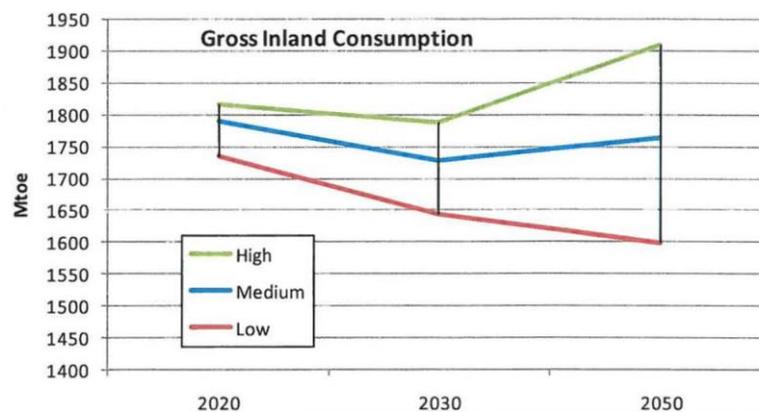
### 3.2.2 *Uncertainty in energy consumption projections simulated with PRIMES*

The GEM-E3 scenarios mentioned in the previous section were used as inputs to the PRIMES model to explore uncertainties related to future economic growth of the European economy.

As expected, economic activity constitutes a major driver of energy demand, which further drives energy supply changes. The range of uncertainties in future energy demand increases over time as the uncertainty about future economic activity also increases. Such a growing range is specified in detail by sector. A similar range is quantified for GHG emissions, which also expands over time following uncertainty about future economic growth.

The range of uncertainty in future costs and prices also depends on the future economic growth, with two factors that contradict each other: higher economic activity implies higher demand for energy, which in turn requires larger energy resources on the supply side. As a consequence, costs

are higher because additional resources are scarce and more costly to develop. On the other side, however, higher activity, hence higher demand, implies larger production, which tends to decrease average production costs to the extent at which economies of scale are possible. This explains the model results about costs and prices: the table shows that the resulting average electricity prices exhibit a small range of variation, compared to the range of variation of energy demand. Figure 3 illustrates the range of uncertainty regarding total primary energy requirements in relation to uncertainty in future economic growth of the EU economy.



**Figure 3 Range of uncertainty in projections of primary energy requirements as a function of GDP growth assumptions**

### 3.2.3 Uncertainty in carbon prices simulated with GEM-E3

Carbon prices act in a macroeconomic context as drivers for emission reduction restructuring that takes place through readjustment of the production structure of firms and of the consumption mix of households. In addition, carbon prices induce restructuring in the energy industry, and imply higher energy prices, which further propagate in the economy and influence decisions by firms and by households. Carbon prices generally induce less use of fossil fuels, which are mostly imported in the European Union. Consequently, carbon prices lead to higher use of low or free carbon sources of energy that are produced with domestically produced equipment, and also imply higher investments to increase energy use efficiency. The substitution of fossil fuels is thus affected by increasing investments and spending on capital goods, and this further induces higher domestic activity. The higher costs and prices, however, owing to the carbon prices and the higher costs of fossil fuel substitution also influence domestic activity. However, unlike the investment, this occurs in a negative way, as foreign competitiveness of domestically produced goods is weakened. On the other hand, additional investments and the carbon prices trigger more efforts in innovation. The resulting technology progress increases productivities and may favour exports if foreign trade partners do not engage in similar innovations.

The above reasoning illustrates that estimating the net macroeconomic effects of carbon prices is a complex task. It is of course expected that carbon prices do induce lower emissions, despite the

possible increase of domestic production in some sectors; however, the degree of responsiveness of the overall economic system to various levels of carbon prices is uncertain.

Similarly, the impact of various levels of carbon prices on GDP and domestic production, as well as on investment and employment, is also uncertain. The model-based exercise presented in this section explores the uncertainty about the impacts of carbon prices at the level of the entire economic system. The analysis is based on a series of scenario runs using the full scale (with learning and productivity effects) global version of the GEM-E3 model.

In most cases the effects of carbon prices on EU's GDP are negative (i.e., there is a reduction in volume trends from a reference scenario). They also show that the degree of loss of GDP is generally lower than the rate of increase of carbon prices. A significant part of potential losses is compensated by gains from increased domestic activity and improved productivity from induced technological change. The latter is limited in the cases shown above, as it is assumed that carbon prices apply globally and thus induce technology progress also in other countries in the world.

The analysis demonstrates that the effects of carbon prices on the activity of various sectors are very unequal. Industries producing metals, building materials and chemicals profit from rising carbon prices as the demand for the corresponding commodities increase due to additional demand for capital goods and construction needed to substitute fossil fuels. Similar effects apply to the equipment goods industry, as spending in equipment goods increases because of their use in building investment, which enables lower emissions and also because of the additional cost needed to increase their energy efficiency. In contrast, other sectors of the economy are negatively affected, as for example the consumer goods industry and to a large extent the service sectors. Activities related to fossil fuels and to distributed forms of energy strongly decrease as a result of carbon prices.

The graphic below shows the relationship between the loss of welfare equivalent variation and the carbon prices. The change in welfare is negative in all carbon price cases and the magnitude of the loss is almost proportional to the level of the carbon prices. This result is consistent with the general equilibrium approach implemented in the GEM-E3 model, since carbon prices constitute a counter-factual case relative to a baseline that also reaches a general equilibrium.

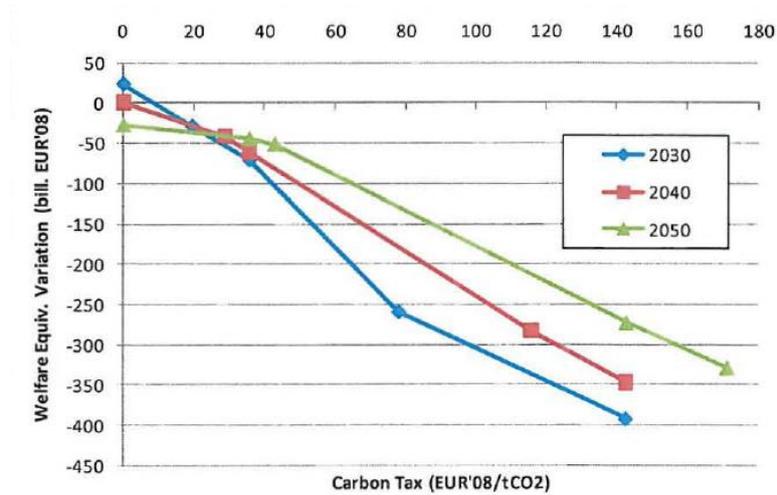


Figure 4: Loss of EU welfare as a function of carbon price at different time horizons.

### 3.3 The COPERT road transport model

Uncertainties pertaining to the COPERT model in the context of EC4MACS are discussed in (Ntziachristos et al. 2010), a more generic discussion can be found in (Kouridis et al. 2011).

The transport sector, as modelled by the COPERT model, provides a prime example of emission control regulations that have not fully achieved the desired outcomes. While earlier versions of the COPERT model employed the designed efficiency of NO<sub>x</sub>-control measures, higher real life emissions have been observed for e.g. Euro-3 vehicles, inter alia, as a consequence of different real-life driving patterns compared with the regulatory test cycle. For heavy duty vehicles, the SCR equipment proved to be malfunctioning at low temperatures, leading at lower speed to 50% higher NO<sub>x</sub>-emissions than estimated on the basis of the test cycle. While the effect on total national emissions is estimated at a few percent, the impact on urban emissions and concentrations could be substantially higher, and represents a major area of uncertainty in projections of emissions and local air quality.

Uncertainties have been estimated for the year 2005 for Italy and Poland. 2005 was selected as this is a rather recent year, in the sense that uncertainty calculations for 2005 should be similar to today. On the other hand, it is already sufficiently dated so all relevant databases with information should have been updated for the particular year. The selection of Italy and Poland was made in an effort to simulate two very different cases, one with detailed statistical information (Italy) and another one with poorer data (Poland). The latter is due to the fact that Eastern European countries joined the EU-standards of motor vehicle emission control at a later stage than their introduction in Western Europe. For example, catalyst vehicles were first introduced in the Polish stock only in the period 1995-1997. In addition, pre-catalyst vehicles did not necessarily follow the ECE standards, but

adhered to national legislation. The conversion of these old vehicles to the COPERT classification increases this uncertainty. Therefore, a comparison of the Italian and Polish calculations provides a measure of the uncertainty due to the stock of vehicles.

### 3.3.1 *Uncertainty of the vehicle stock*

The uncertainty of the number of operating vehicles in the five vehicle categories has been quantified based on information collected from different sources. The standard deviation for light-duty and heavy duty vehicles is around 8% for Italy and 15% for Poland, while it is much smaller for the other vehicle categories. This assessment was carried out also for more disaggregated data. For example, (Ntziachristos et al. 2010) estimates the mean and standard deviation for some 30 subsectors in Poland. In the absence of more detailed data, assumptions were made to estimate the standard deviation. In the case of passenger cars, the standard deviation was calculated by assuming the standard deviation at one third of the difference of the national statistics and FLEETS project data for each subsector. In case of Light Duty Vehicles, the uncertainty was calculated from national statistics and was proportionally allocated to the stock of diesel and gasoline trucks. For all other vehicle categories, the standard deviation was estimated 7% of the average value.

To calculate the technology split for each country and vehicle category, the following procedure was followed. First, the probability of vehicles to remain in the stock, as a function of their age, was described with a Weibull distribution. By taking an initial age distribution at a historical year (in our case: 1995) and by introducing the new registrations per year (vehicles of age 0) and the Weibull scrappage probability, one may calculate the age distribution of the vehicles at any given year. We calculated the age distribution for the year 2005 by introducing to our calculations the stock and new registrations from the FLEETS project. At a second step, the technology split for each country is calculated by applying the technology implementation matrix of the particular country to the age distribution. The technology implementation matrix contains the distribution of new registrations of different years to the various technologies.

In the case of Italy, the technology classification was considered exact. However, in the case of Poland, the uncertainty in classification to different technologies was translated into a problem of age distribution. The central estimate for the age distribution of vehicles of Poland was based on the FLEETS data. Then, an artificial uncertainty range was assigned to the probability function of Poland. It was assumed that the survival probability for vehicles with age of five and fifteen years ranges between +/- 5 and +/- 10 percentage units, respectively, from the central value. The combination of assumptions about the Weibull distribution parameters and the initial conditions results in a probability distribution in the form of a histogram for the number of vehicles, for example, for Euro 1 passenger vehicles < 1.4l in Poland in the year 2005 (cf. Figure 5).

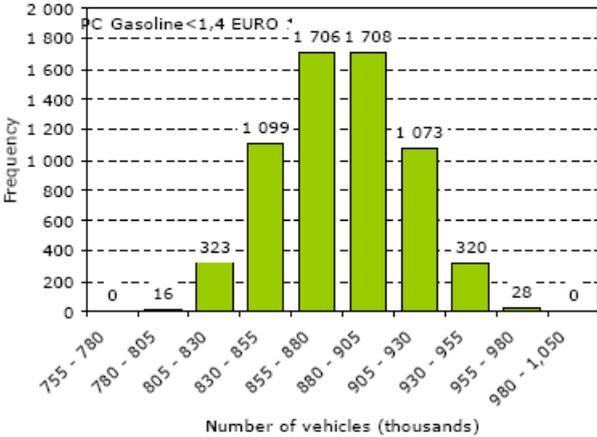


Figure 5 Probability distribution for Euro 1 passenger vehicles < 1.4l in Poland in 2005

3.3.2 Uncertainties in emission factors and parameters

The uncertainty of the emission factors originates from the variability of the underlying experimental data, i.e., the variability in the emission level of each individual vehicle that has been included in the sample of vehicles for which emission factors have been measured. A typical range of the variability of individual measurements for emission factors is shown in Figure 6 for gasoline passenger cars with Euro 3 technology.

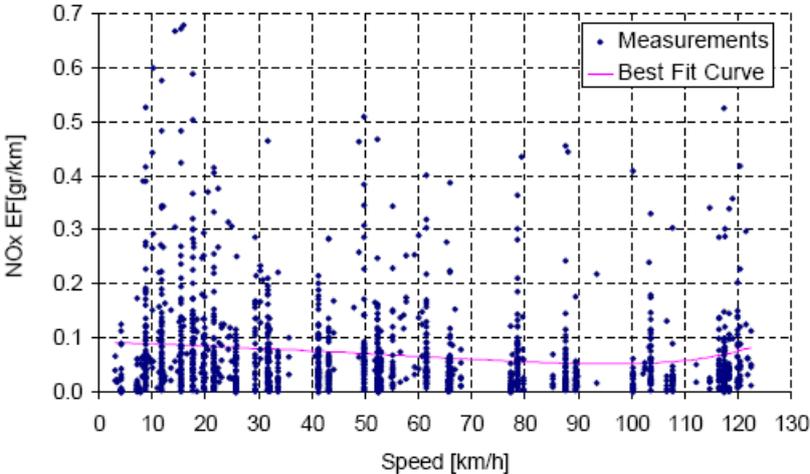


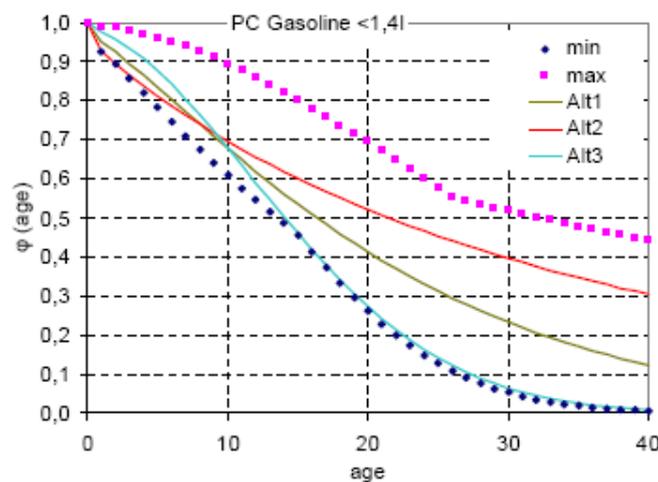
Figure 6 Example of empirical NO<sub>x</sub> emission factors as a function of speed, illustrating the variability in the measurements of emission factors (here gasoline Euro 3 passenger cars)

In COPERT, there are two sets of emission factors, hot emission factors and the cold-start emission factors. The uncertainty of old emission factors has not changed since the previous Monte Carlo exercise conducted in COPERT 3. However, emission factors for Euro 1 and later technologies are solely based on ARTEMIS. Emission factors on non-exhaust PM and the related uncertainty has been taken from the relevant chapter in the Atmospheric Emission Inventory Guidebook. The N<sub>2</sub>O and CH<sub>4</sub> uncertainty has been based on work conducted at the Laboratory of Applied Thermodynamics. The uncertainty of cold-start emission factors was more difficult to assess, as the values used in COPERT

are a hybrid of the Artemis and the older CORINAIR methodologies. In the absence of detailed data and in order not to neglect the contribution of cold start variability, we assumed that the ratio of standard deviation over mean for the cold emission factors is equal to the hot ones.

### 3.3.3 Uncertainty of mileage variables

The calculation of the annual mileage of a particular vehicle technology employs a function of the annual mileage of a new vehicle and a correction function for the effect of vehicle age. The decrease of annual mileage with age has been approached by a Weibull function. This reflects the fact that new cars are driven more than old ones. The shape of the curve is considered to be a good approximation of the actual shape of the mileage reduction with age. The shape of these curves was estimated to be restricted by upper and lower values. Figure 7 shows examples of correction functions for the annual mileage driven per vehicle.



**Figure 7 Illustration of correction functions for annual mileage by age. The dotted curves show minimum and maximum values, the lines show example curves that are considered internally consistent.**

The mean fleet mileage expresses the average odometer reading of a vehicle of a particular technology. This is a value calculated by using the average vehicle age and the average annual vehicle mileage. For this reason, no separate uncertainty had to be estimated, as this was already derived from the annual mileage values used to calculate emissions.

### 3.3.4 Uncertainty of other parameters

Other model parameters that were investigated in the uncertainty analysis included:

- hydrogen-to-carbon ratio (this ratio is required to estimate CO<sub>2</sub> emissions on the basis of fuel consumption and is different for each of the fuel types (diesel, gasoline, natural gas, liquid petroleum gas));
- highway/urban/rural speed (determines emissions per km of, e.g. NO<sub>x</sub>);

- highway/urban/rural share (share of km driven at various speeds/patterns of acceleration, determines emissions per km of, e.g. NO<sub>x</sub>);
- load factor for buses and trucks (determines to large extent the emissions and consumption per km);
- oxygen-to-carbon ratio (this ratio is required to estimate CO<sub>2</sub> emissions on the basis of fuel consumption and is different for each of the fuel types (diesel, gasoline, natural gas, liquid petroleum gas). In principle, natural gas and liquid petroleum gas should only contain traces of oxygen);
- fuel vapour pressure (the vapour pressure is important to calculate NMVOC emissions due to evaporation losses. These are only relevant for gasoline, due to the low volatility of the diesel fuel);
- sulphur content (Sulphur is converted to sulphur dioxide during combustion but it also accelerates the degradation of after-treatment devices);
- average temperature (min/max by month) - (determines cold-start/evaporation emissions).

### 3.3.5 *Uncertainty estimates*

A detailed description of the mathematical background of the analysis that focuses on the key determinants of the uncertainties only can be found in (Kouridis et al. 2010). Here we report only on three illustrative cases of uncertainty analysis in the emissions of air pollutants and greenhouse gases.

First, emissions were calculated for Italy and Poland, using Monte-Carlo methods, with the additional constraint that the overall fuel use was given. The spread in emission calculation (histograms) of the Monte-Carlo simulations is shown in Figure 8 and Figure 9.

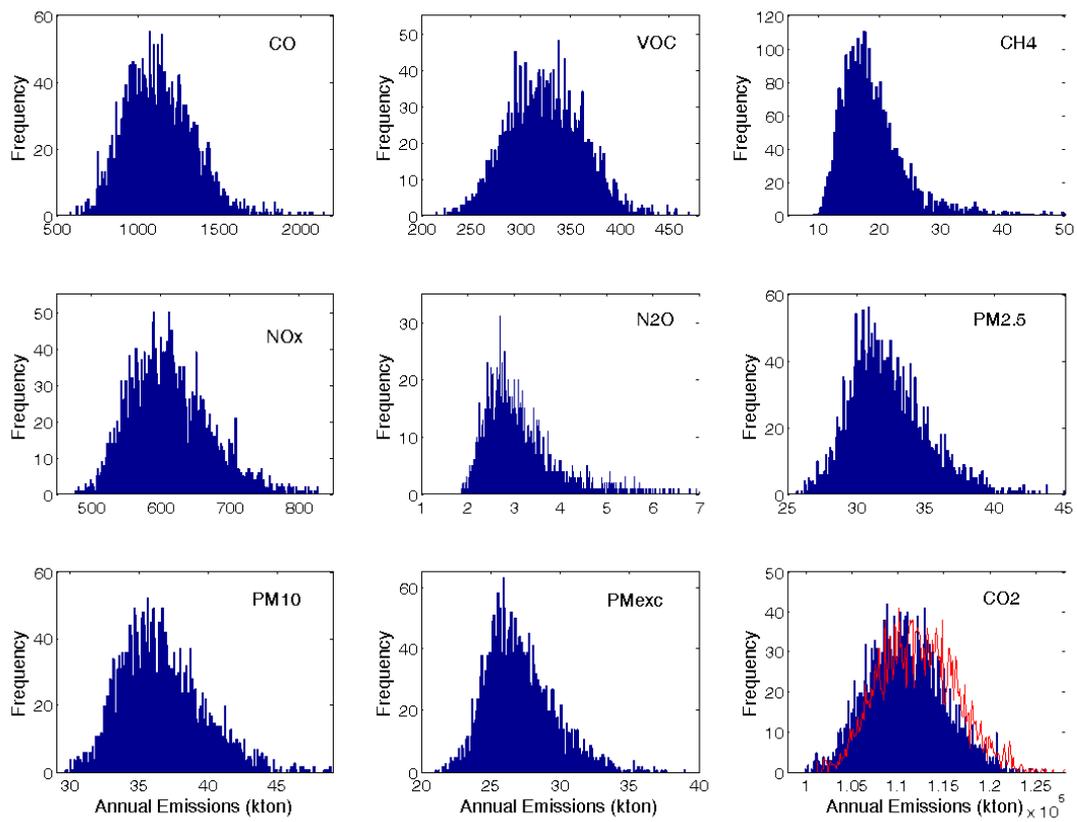


Figure 8 Uncertainty Analysis of the annual emissions from road transport for Italy (year 2005) for the simulations with predicted fuel consumption within a small range of the official value

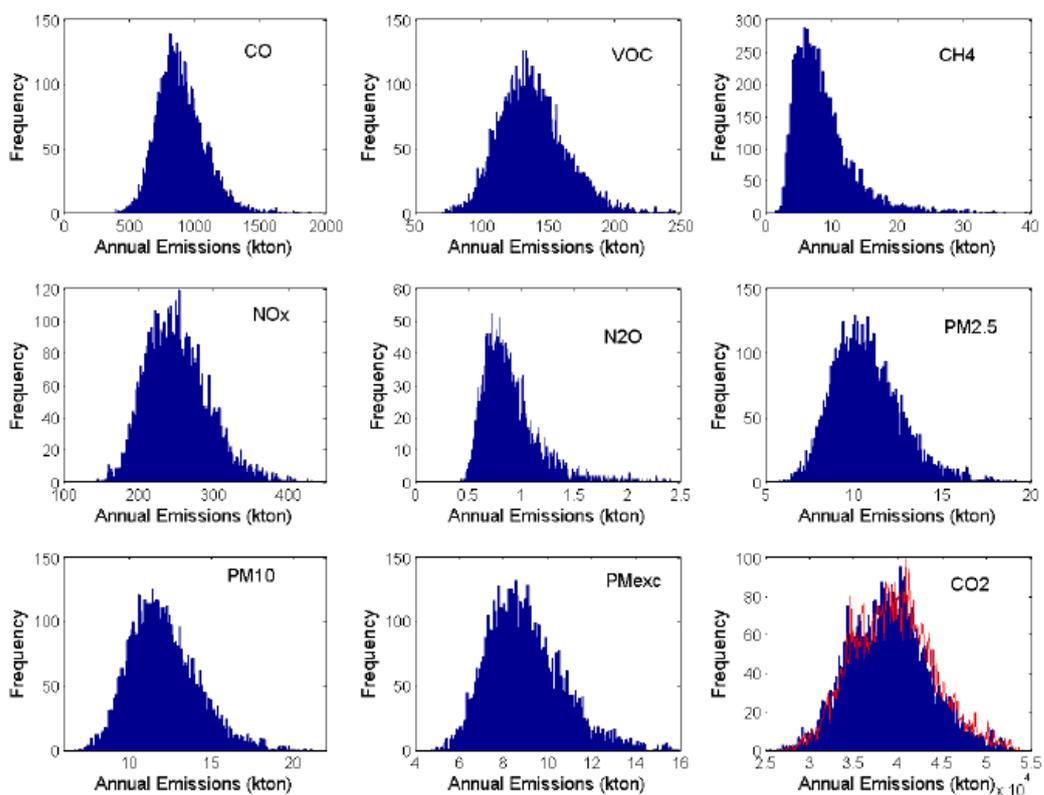


Figure 9 Uncertainty Analysis of the annual emissions from road transport for Poland (year 2005) for the simulations with predicted fuel consumption within a small range of the official value

Table 1 Descriptive statistics of the histograms presented in Figure 8 (Italy). Values are in ktonnes.

|                      | CO    | VOC | CH <sub>4</sub> | NO <sub>x</sub> | N <sub>2</sub> O | PM <sub>2.5</sub> | PM <sub>10</sub> | PM <sub>exh</sub> | FC     | CO <sub>2</sub> | CO <sub>2e</sub> |
|----------------------|-------|-----|-----------------|-----------------|------------------|-------------------|------------------|-------------------|--------|-----------------|------------------|
| <b>Mean</b>          | 1,134 | 325 | 19              | 614             | 3.1              | 32                | 37               | 27                | 36,945 | 110,735         | 112,094          |
| <b>Median</b>        | 1,118 | 324 | 18              | 608             | 2.9              | 32                | 36               | 27                | 36,901 | 110,622         | 111,941          |
| <b>St. Dev.</b>      | 218   | 38  | 7               | 59              | 0.8              | 3                 | 3                | 3                 | 1,241  | 4,079           | 4,203            |
| <b>Variation (%)</b> | 19    | 12  | 34              | 10              | 26               | 9                 | 8                | 9                 | 3      | 4               | 4                |

**Table 2 Descriptive statistics of the histograms presented in Figure 9 (Poland). Values are in ktonnes.**

|                      | CO  | VOC | CH <sub>4</sub> | NO <sub>x</sub> | N <sub>2</sub> O | PM <sub>2.5</sub> | PM <sub>10</sub> | PM <sub>exh</sub> | FC     | CO <sub>2</sub> | CO <sub>2e</sub> |
|----------------------|-----|-----|-----------------|-----------------|------------------|-------------------|------------------|-------------------|--------|-----------------|------------------|
| <b>Mean</b>          | 793 | 124 | 7.2             | 222             | 0.8              | 9.4               | 10.7             | 7.9               | 11,772 | 35,520          | 35,907           |
| <b>Median</b>        | 783 | 123 | 6.3             | 218             | 0.7              | 9.2               | 10.5             | 7.7               | 11,666 | 35,199          | 35,569           |
| <b>St. Dev.</b>      | 134 | 18  | 3.9             | 26              | 0.2              | 1.2               | 1.3              | 1.1               | 934    | 2,891           | 2,933            |
| <b>Variation (%)</b> | 17  | 15  | 54              | 12              | 24               | 13                | 12               | 14                | 8      | 8               | 8                |

Comparing the numerical analysis from these simulations (Table 1 and Table 2) we find that, in general, uncertainties in Poland are higher than in Italy, except for CO and N<sub>2</sub>O, although the differences may not be significant. The differences are most pronounced for CO<sub>2</sub> and CH<sub>4</sub>.

Other aspects that were considered in the uncertainty analysis included:

- **The influence of the emissions of high emitters.** The main conclusions are (a) that their impact is already implemented to a certain extent in the emission factors, and (b) that the policy measures already taken (durability, OBD, roadworthiness testing) will decrease the frequency of high-emitters in real world. Therefore, high emitters are not considered as much as a problem today as they were in the past.
- **The effectiveness of emission standards.** The disparity of emission standards and emission factors is potentially an issue that will continue also in the future, for as long as the type-approval test only covers a small part of vehicle operation. This is expected to have an impact on NO<sub>x</sub> emissions from light duty and heavy duty vehicles, and does not seem much of a problem for other pollutants. This can only be effectively addressed by a new type-approval procedure.
- **Advanced vehicle technologies.** The expected introduction of new vehicle technologies increases the uncertainty in the projections, as there is currently very limited or even no experimental information about emissions of such vehicles. Experimental information needs to be collected as soon as possible as these vehicles are expected to make it to large market volumes.

### 3.4 The CAPRI agricultural model

The uncertainty analysis of the CAPRI model is presented in (Witzke, Becker, & Adenäuer 2011). Agricultural projections prove to be sensitive towards policy initiatives that are assumed in these projections. As in the model the assumed effectiveness of legislation – and thus the basic response of agricultural actors to policy interventions - is based on expert judgment, agricultural baseline projections are strongly influenced by the current perception among European Community experts.

Experience shows that expert perception is often dominated by the current status and by very recent events with a tendency to underestimate the potential for significant and structural changes in the longer term.

### 3.4.1 *Exogenous input uncertainty*

#### **Macroeconomic assumptions**

The CAPRI baseline relies on expert inputs from other modelling systems, for the key agricultural variables mostly on the AGLINK modelling system, which in turn has used a certain set of macro assumptions. In the context of EC4MACS, however, these macro assumptions had to be aligned with those of the PRIMES energy model. To achieve this alignment a so-called “pre-simulation” has been carried out. More precisely, the demand functions have been shifted to account for the differences in population and GDP growth assumptions between AGLINK and PRIMES, and CAPRI has been solved for the revised market equilibrium. Given that EU Member States are linked through the Common Market, it is the aggregate EU27 shift in demand that determines the price changes, and adjustments in national supply quantities and activity levels.

For the year 2020, the GEM-E3/PRIMES assumptions are basically consistent with the initial CAPRI assumptions (inherited from AGLINK) in terms of population. GDP needed to be increased by 2.3%, which translates into a demand shift of about 1.15% with an income elasticity of 0.5 (variable, depending on product and country). In contrast, in 2050 the main agricultural expert source is the combination of FAO and IFPRI. Compared to their assumptions, population is 7.8% higher and GDP 9.5% lower. However, assuming an income elasticity of 0.5, this results in an increase in demand of  $+7.8\% - 0.5 \cdot 9.5\% \sim 3.1\%$ , which is a bit higher than the difference for 2020. Only a part of this demand shift will trigger additional EU production, the rest stimulates demand for imports and thereby further dampens the effects of macro changes on EU herd sizes (which are the key output of CAPRI for GAINS). This results in an aggregate demand shift of about 2% (2020) to 3% (2050). The demand shift effects are rather small in the cattle sector (usually less than 0.5%), but somewhat stronger (up to 4% in single countries, in particular of EU12) for other poultry, pigs and sheep. Note, however, that compared to the strong growth in herd sizes expected in the baseline for some Member States (+40% in Poland and Spain for pigs), a macro correction of 3% does not represent a major uncertainty.

#### **WTO agreements**

The current CAPRI baseline does not assume a successful conclusion of the Doha round. As the ultimate outcome is quite uncertain, its effect may only be assessed with arbitrary assumptions about details of such a WTO deal. Key proposals are the so-called revised draft modalities ([http://www.wto.org/english/tratop\\_e/agric\\_e/agchairtxt\\_dec08\\_a\\_e.pdf](http://www.wto.org/english/tratop_e/agric_e/agchairtxt_dec08_a_e.pdf)) of chairperson Falconer from December 2008. A stylized interpretation of these proposals in a CAPRI simulation would mainly affect the other cattle and sheep sectors (decline of about 3%), whereas the pig, poultry, and

the dairy sectors will be less affected due to the lower initial protection. It is also noteworthy that the Falconer proposals included the possibility for countries to declare some of their products as “sensitive” to shield them from large tariff cuts if they were prepared to increase market access for imports through enlarged tariff rate quotas. This mechanism has dampened the price cuts for beef, pork, poultry meat, butter and cheese relative to sheep meat (assumed “non-sensitive”). Furthermore, the presence of “sensitive” products in a likely Doha agreement also permits to speculate about a post-Doha WTO round that would further dismantle the remaining protection of the EU livestock sector. If such a follow up agreement was anticipated (entirely plausible for a horizon up to 2050), we might expect a further decline in the EU livestock sector (that has not been simulated yet).

According to the CAPRI greenhouse gas accounting, the decline in the cattle sector would reduce CH<sub>4</sub> emissions in EU27 by 2.4%, N<sub>2</sub>O by 1.1% and aggregate greenhouse gas emissions from agriculture by 1.6%. Note, however, that this neglects the compensating increase in production in other world regions such that the global effects are unknown.

#### 3.4.2 *Parameter uncertainty*

Parameter uncertainty has been investigated for three issues that all are related to a particular methodological innovation in the course of the EC4MACS project.

#### **Weights for EFMA information relative to parameter trends**

EC4MACS has triggered a revision of the methodology to project mineral fertiliser consumption in CAPRI. As uncertainty is usually considered larger in new model components, this has been investigated in more detail and some additional background information will be given. The past versions of CAPRI derive fertiliser projections from trend-based forecasts of two parameters describing changes in the fertiliser management of farmers:

- NAVFAC: Reflects the partial availability of nutrients from manure relative to mineral fertiliser. In many EU15 countries this factor (typical value: 0.6) was trending upwards, reflecting efficiency improvements in fertiliser management, be it autonomous or enforced through more stringent environmental legislation.
- NUTFAC: This reflects the fact that farmers tend to apply more fertiliser than needed, even after accounting for partial availability of nutrients from manure. We may often observe in MS15 that their NUTFACs (typical value: 1.2) are slightly trending downwards whereas those from MS12 are often more irregular and sloping upwards, mirroring some catching up in fertiliser application after the turmoil of the transition phase.

The current trend-based approach has some drawbacks. First of all, trends are sometimes very weak or estimated with a high standard error. The second point is more important. Since a few years, there are contacts to EFMA (European Fertiliser Manufacturers Association) with its network of

national experts. So far it has been used in an ad hoc way only (manual corrections of trend estimated NUTFACs/NAVFACs).

The new solution adopts some principles from the ex-post data consolidation in CAPRI. The EFMA projections are considered to be of high quality, but national EFMA experts may nonetheless be wrong. Therefore, they are treated as a priori information and deviations are penalised, but permitted.

The other source of information for projections comes, as before, from the current trends on NUTFACs/NAVFACs that are now treated as a priori information as well, rather than being imposed strictly. The compromise solution depends on the weights specified for each type of information.

A sensitivity analysis has been carried out to investigate the influence of this specification. The first set of weights has attributed very high confidence to the EFMA information, the second a very high confidence to the statistical parameter trends, and finally the results of a compromise specification is shown. In this case, the relative EFMA weight has been specified higher for EU15 countries than for EU12 countries, assuming that EU15 national experts are on average very experienced.

It may be seen that differences between the EFMA projections and the CAPRI forecasts based on parameter trends only are sometimes remarkable. Note also that the “compromise” solution is not simply a weighted average of columns two and three. If the changes in activity levels, both from the crop and livestock sectors, suggest a crop “need” close to the EFMA projections, these will tend to prevail. If, on the contrary, changes in activity levels imply a crop “need” (net of manure deliveries) that is far away from the EFMA expectations, feasibility of the fertiliser calibration may require stronger deviations from EFMA.

### **Weights for national expert information**

Another major improvement mentioned in the progress report for year 2009 has been the incorporation of information from national experts. This refers to national projections on the key animal categories for individual countries (e.g., the number of dairy cows). The coverage is still very limited as so far none of the large Member States or any of the New Member States has provided national projections. Nonetheless, it is interesting to see what a difference the national expert information could make in the current implementation. As was the case for the EFMA information on fertilisers, the national expert information received implicit weights through the specification of standard errors for this information. Furthermore, the weight may be increased depending on whether related series are also modified by expert supports. For example, national projections on the increase in the pigs herd size will have a larger impact if it is assumed that a related series (say the production of piglets) is increasing with the same rate. By contrast, applying default assumptions for the related series may tie the projections of the pigs herd size indirectly to the default trends for piglet production, thus failing to acknowledge the expert information to a significant degree.

We observe that the current implementation may significantly change the results compared to a zero weight alternative, but that at the aggregate EU15 level these changes are hardly visible, except

for sheep and other cattle. One reason for this is that the national expert information does not systematically change the results upwards or downwards, which is reassuring: It supports the view that overall, national expert information does not systematically “distort” the results in one direction. The other reason is that so far expert information is only included for some of the four smaller EU15 Member States.

### **Extrapolations in long-term projections**

As a part of the CAPRI baseline methodology, long term information from FAO and IFPRI has been gradually introduced for time horizons after 2020. When the projection year moves towards 2050, the weight for extrapolated information decreases, such that by 2050 the final projection is strongly pulled towards the long term information from FAO/IFPRI. This provides projections that gradually approach the long term sources, for example as in the case of pork production in Sweden.

The example has been chosen because historical trends and AGLINK projections on the one hand and long term expectations point into different projections. This is quite typical because medium term forecasts often give a stronger weight to recent production trends, often indicating a stagnating or declining production in the EU, whereas the long term studies tend to focus on the global growth of food demand in the coming decades. It is thus entirely plausible that there will be turning points in the future evolution of agriculture.

We found that even in 2050 the projections come close to the long term information, but do not attain it completely. This is the case because we have retained a weight of 25% for the extrapolation for several reasons: First of all FAO, one of the two sources of long term projections, only provided information for EU15 and EU10 but not at the Member State level, so that an extrapolation adds some national particularities. Furthermore, the extrapolation weight prevents extreme swings in the evolution of some series that may appear implausible. On the other hand, this may be considered an unnecessarily conservative approach. Thus, it is another matter of judgement rather than clear superiority: the differences in the projected animal herds depend on whether the remaining weight for the extrapolation is set to 0% or 25%. For intermediate years between 2020 and 2050, the differences are smaller according to the gradual shifts in the weighting scheme explained above. As the basic uncertainty is qualitatively similar in EU15 and EU12 countries this sensitivity analysis has been carried out for EU15 countries only.

It may be seen that the choice of this parameter has considerable importance for the long run projections at the member state level. For the EU15, the sensitivity is less marked, except in the case of the sheep herd where the strong effect in the UK remains clearly visible also at the aggregate level.

### 3.5 *The EUFASOM/GLOBIOM land use models*

Uncertainty analysis of the FASOM/GLOBIOM Model is discussed in (Böttcher 2010). The economic land use models EUFASOM and GLOBIOM use as macro-economic drivers recent baseline projections by DGTREN for future bioenergy demand (from PRIMES model) and related assumptions on population growth, economic development (GDP), and technical progress rates. Data on potential yields and GHG emissions and removals for diverse agricultural and forest management alternatives are derived from the more detailed forestry model (G4M) and the agricultural model (EPIC). The PRIMES projection on bioenergy production provides only one part of total wood demand in Europe. The GLOBIOM model was used to integrate energy wood demand from PRIMES and demand for other wood products.

Under EC4MACS, first a baseline scenario was constructed. In this baseline, deforestation emissions will slowly decrease until 2030. While emissions and removals from cropland and grassland will stay relatively stable, the forest sink will decline quickly to less than 50% of the 2010 sink. The decline in removals from forest management is partly compensated by an increasing sink of new forests. However, in 2030 forest management will still be the dominating term in Europe's LULUCF carbon budget. In total, the models expect a decrease of the land carbon sink by about 20%.

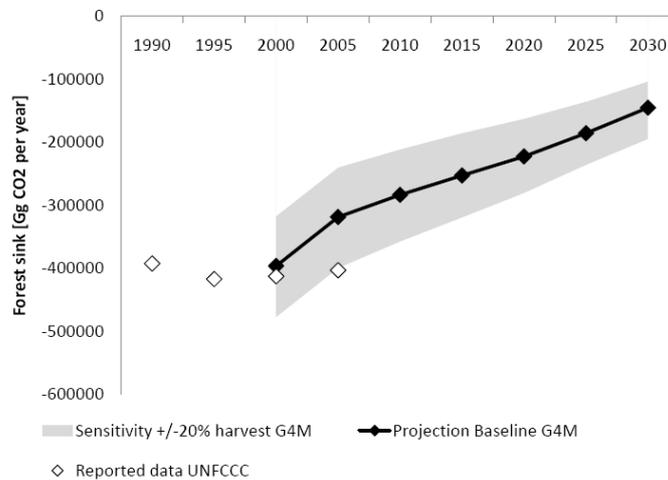
A reference scenario was constructed based on the same macroeconomic, price, technology and policy assumptions as the baseline. In addition to the measures reflected in the baseline, it includes policies adopted between April 2009 and December 2009 and assumes that national targets under the Renewables directive 2009/28/EC and the GHG Effort sharing decision 2009/406/EC are achieved in 2020. The most relevant changes to the baseline for LULUCF are related to bioenergy production.

#### 3.5.1 *Sensitivity analysis*

The sensitivity of the baseline is explicitly addressed by varying some key model and scenario parameters (e.g., GDP or bio-energy demand) that may affect the projections of the GHG emissions and removals from the LULUCF sector. To explore sensitivities of the forestry model further, a systematic sensitivity analysis was carried out by feeding G4M with two additional scenarios of wood demand, being 1) 20% higher and 2) 20% lower compared to the baseline. The effects on the projected forest sink are displayed in Figure 10. A 20% reduction of harvest levels increases the sink by about 20%. The same applies for an increase in harvest levels. The sensitivity of the projected sink in both models is not symmetrical over the entire period. Especially in the years 2020 to 2030, the reduction effect of increased harvest is less than the increase effect of decreased harvest.

The scenario case of constant harvest rates from 2000 to 2030 reveals the different drivers of the decreasing sink. Despite constant harvest rates, the sink further diminishes indicating the role of forest aging. The sensitivity analysis gives also an indication of the effect of underlying uncertainties. The projection of future harvest is highly uncertain and depends on many parameters that cannot be

modelled explicitly. However, the sensitivity analysis shows the likely effects of changes in the driver wood demand. It also shows that both models produce robust results.



**Figure 10 Projection of baseline emissions and removals of forest management activities for EU27 and estimates of 20% higher and lower total wood demand compared to the baseline. Sums do not include values of Cyprus, Malta and Greece in order to make numbers comparable among models**

### 3.5.2 Model limitations

The GLOBIOM model projects future wood production for the entire EU under the assumption that production of wood for material use in all EU countries will increase by the same factor. However, the rate is likely to vary between countries, see e.g. (Mantau et al. 2010). For some countries, “ceilings” on maximum wood removals should be built in to constrain the GLOBIOM model. Current ceilings are based on forest growth, but do not take into account environmental, technical, social and economic constraints that further limit the potential wood supply.

Finally, the impact of growth changes and large-scale disturbances due to environmental and/or climate change on the estimated CO<sub>2</sub> emissions and removals were not included. It is expected that growth may decrease in Southern Europe due to reduced water availability, whereas growth in Northern regions may increase much more (Lindner et al. 2010). Changes in growth will reflect in changes in future CO<sub>2</sub> removals and emissions. In addition, disturbances were also not included in the analysis, but could have an important impact. The impact of growth changes and large-scale disturbances on the development of the LULUCF sector is difficult to model and would require further investigation.

### 3.5.3 *Uncertainty of input data and economic drivers*

The approach applied in (Böttcher 2010) is to a large degree data-driven. Hence, the quality of the results depends heavily on the quality of the datasets that were used. A sensitivity analysis showed that the projections are rather sensitive to the assumed harvest rates. Historical round wood removals (excl. harvest losses) were used to initialize the forest models and to estimate the future round wood removals. Comparison of FAOSTAT data on historical wood removals with national statistics included in the EU submission to UNFCCC shows significant differences. For example, for France annual round wood removals deviated up to 22 million m<sup>3</sup> per year (after converting FAOSTAT data from underbark to overbark volume). Such differences can have substantial impacts on the projected CO<sub>2</sub> emissions or removals.

The future round wood production is based on projections by GLOBIOM and PRIMES. The projection of these two models employs the same macro-economic development. Furthermore, it was ensured that GLOBIOM reproduced the same numbers on bioenergy production. However, the development of the forest sector was not harmonized between the models. This could lead to discrepancies in the availability of e.g. black liquor and/or wood waste between GLOBIOM and PRIMES. Further harmonization between PRIMES and GLOBIOM could improve the projections of CO<sub>2</sub> emission or removals by forests.

## 3.6 *The CHIMERE atmospheric dispersion model*

In its uncertainty analysis, the CHIMERE modelling team addressed specifically the calculation of the urban increment (Debry & Malherbe 2010). The goal was to quantify the uncertainty associated with predicted concentrations and to determine which of the parameters contribute the most to it, with a focus on the most populated areas. The study focuses on a representative domain centred in France.

In the context of a dispersion model, uncertainties may arise from

- input data, e.g., fields of emissions, boundary conditions, and meteorological fields,
- physical parameterization, which usually constitute the core of the model,
- numerical schemes for integrating equation (which is not further discussed here).

The CHIMERE model is a deterministic dispersion model that depends on a number of input parameters and functions. For the purpose of this uncertainty analysis, the model was extended to a stochastic version. This is computationally highly demanding and a full computation of the covariance matrix of the concentration field over the whole domain cannot be accomplished. Therefore the uncertainty for one pollutant at a given time and location is assessed with the scalar standard deviation.

In practice, the stochastic approach attaches to each input parameter one probability density function (PDF) that describes the uncertainty of the parameter. The shape of the PDF is most often

log-normal (LN) or normal (N), but can also be uniform (U) if there is too poor knowledge on the parameter uncertainty. Once PDFs have been assigned to input parameters, the joint PDF has to be propagated through the model to obtain the PDF of ambient concentrations. For this purpose, Monte Carlo methods are generally a good choice, as they do not require any a-priori assumptions on the model.

Sensitivity analyses assess the model response to the variation of parameters. A reference simulation is defined and several simulations are performed in which one parameter is varied at a time, all others staying at their reference value. Boundary and initial conditions for particle pollutants are perturbed independently between particle sizes. The model response is defined as the deviation to the reference simulation concentrations. It is then possible to sort parameters according to their sensitivity level by comparing their deviations. This can also be done with Monte Carlo simulations.

The CHIMERE Monte Carlo experiment has been run for two periods. The first one, denoted “summer”, runs during 30 days in 2009 from 30 July to 28 August, and the second one, labelled “winter”, runs during 9 days from 5 to 13 January 2010. For each period, boundary conditions are derived from a simulation at a larger scale over a European domain, and initial conditions are taken from a ten days spin-up simulation.

*Uncertainty patterns over urban areas*

500 simulations have been carried out for the summer period, and 300 for the winter period. In both cases, the Monte Carlo process achieved accuracy below 1%. The purpose of this task was to investigate the uncertainty patterns of O<sub>3</sub> concentrations in summer and PM<sub>10</sub> concentrations in winter. Only hourly concentrations at first height level over urban areas were considered.

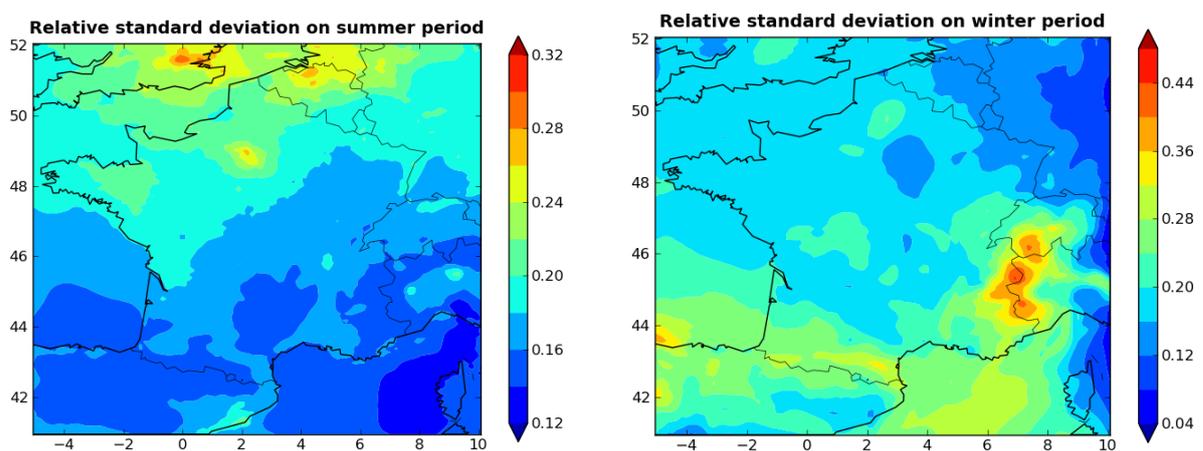


Figure 11 Relative uncertainty (normalized standard deviation) of the O<sub>3</sub> (left) and PM<sub>10</sub> (right) concentration fields.

For O<sub>3</sub>, the time averaged concentration and absolute standard deviations tend to be lower over urban areas, whereas urban areas are clearly highlighted by the relative standard deviation. The relative standard deviation on PM<sub>10</sub> concentrations tends to be lower over urban areas, as concentrations are often higher in these areas. The peaks observed over mountain regions (Alps and the Pyrenees) are mainly due to very low concentrations.

Uncertainty distribution

Figure 12 and Figure 13 depict the absolute and relative standard deviations with respect to concentration levels. For each figure and concentration level, the average uncertainty is represented as a black square. Within one concentration level, the standard deviation of uncertainty is displayed as a green error bar. As uncertainty values are time averaged, the green error bar only accounts for space dispersion.

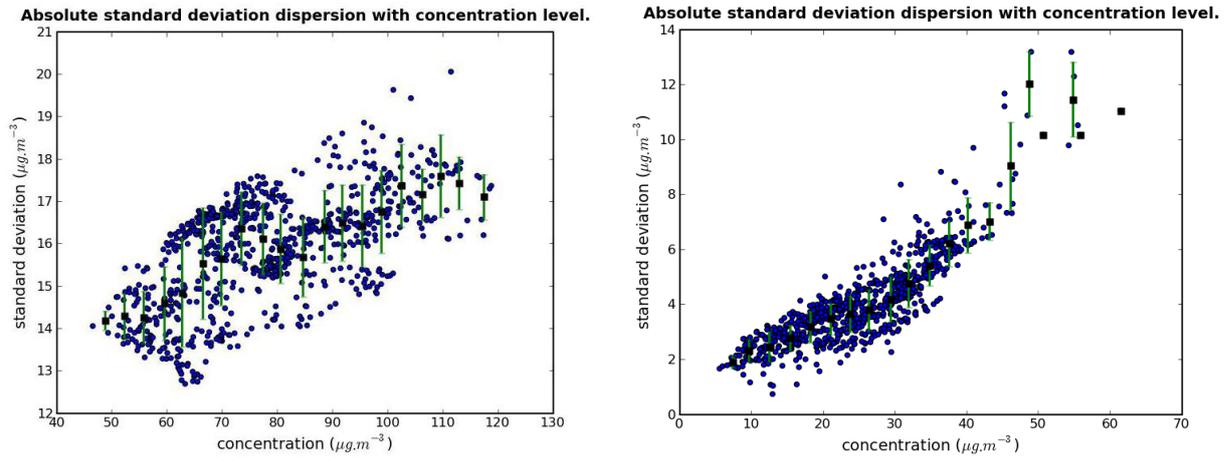


Figure 12 Absolute uncertainty dispersion for O<sub>3</sub> (left) and PM<sub>10</sub> (right)

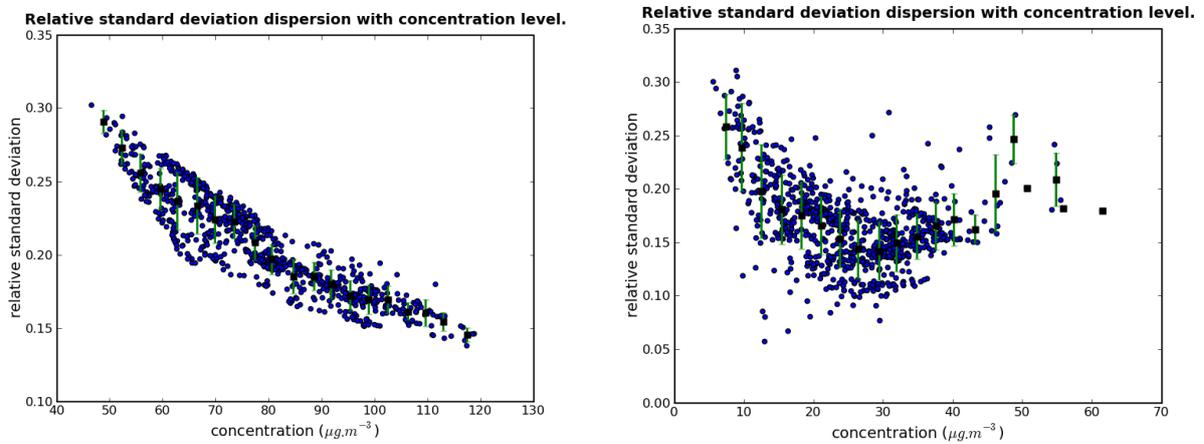


Figure 13 Relative uncertainty dispersion for O<sub>3</sub> (left) and PM<sub>10</sub> (right)

Absolute uncertainty and concentration levels appear to be correlated (60% for O<sub>3</sub>, 85% for PM<sub>10</sub>), whereas relative uncertainty is anti-correlated (90% for O<sub>3</sub>, but more weakly for PM<sub>10</sub> (37%)). Absolute uncertainty tends to increase with the concentration level. Absolute uncertainty for O<sub>3</sub> over urban areas is driven not only by the concentration level, but also by their location, whereas for PM<sub>10</sub> absolute uncertainty over urban areas is mainly driven by the concentration level.

The relative uncertainty of O<sub>3</sub> clearly decreases with the concentration level. Its own standard deviation with the concentration level and space are 4% and 1%, respectively. Thus, the relative uncertainty is mainly driven by the concentration level. For PM<sub>10</sub> there is no clear tendency between

relative uncertainty and concentration level. The relative uncertainty of standard deviation with the concentration level and space are respectively 0.2% and 0.3%. Thus, the relative uncertainty for  $PM_{10}$  over urban areas depends not only on the concentration level but also on the specific region.

The CHIMERE modelling team also noted that the most sensitive parameters in the calculations are temperature fields and deposition rates. Lateral boundaries have also a significant positive impact, which may be enhanced by the fact that some of the highlighted urban areas are close to the domain boundaries. Interestingly, the sensitivity of the modelling results to uncertainties in the emissions is not so strong.

Finally, (Debry & Malherbe 2010) noted that the quality of uncertainty estimates depends not only on the accuracy reached by the Monte Carlo process, but also on the relevance of the PDFs chosen for input parameters

### 3.7 *Critical loads and their exceedances*

Scientific progress was also made in quantifying the sensitivity of ecosystems towards acidification and eutrophication (Hettelingh, Posch, & Slootweg 2010). In addition, national focal centres provided critical loads estimates with finer spatial resolution, so that at the moment the European critical loads database holds approximately 1.3 million data points. With all these refinements, however, the current map of critical loads does not differ significantly from the one used 10 years ago, which provides a sense of robustness of these estimates. The robustness had been further enhanced by analysing the implications of empirically determined critical loads, which provides an independent alternative methodological approach. One remaining area of uncertainty in this area is the environmental consequences of exceedances of critical loads and the establishment of deposition-response relationships leading ultimately to a quantification of effects.

Numerous new studies have focused on the quantification of health impacts from air pollution. While earlier studies demonstrated the health impacts of short-term ozone episodes, new research suggests an association between premature mortality and long-term ozone exposure. Thus, health impacts from ozone would be systematically underestimated by analyses that rely only on short-term time series studies, as was done by the GAINS model before. The workshop recommended exploring this aspect through ex-post analyses.

For particulate matter, despite a large body of new scientific studies, uncertainties prevail about the relative toxicities of the various components. The assumption of equal toxicity should be considered as a cautious approach, although the implications on cost-effective mitigation strategies should be further explored in targeted sensitivity analyses. However, the holistic perspective of the multi-effect approach that combines health and vegetation concerns is seen as a practical and powerful way to minimize overall uncertainties of strategies that include multiple pollutants.

An additional source of uncertainty is related to the limited spatial resolution of European wide atmospheric models. As also local measures could reduce population exposure at the sub-grid scale,

integrated assessment should develop methodologies that could provide robust assignments of effective policy actions at the local, national, international and inter-continental scales.

### *Influence of 2020 baseline scenarios on CL exceedances*

For given emission scenarios, deposition fields have been calculated with the linearized EMEP/MSC-W Eulerian dispersion model, using transfer matrices for a five-year average meteorology. These deposition fields, which comprise grid-average deposition as well as deposition onto forests and (semi-)natural ecosystems for every EMEP50km grid cell, have been used for exceedances calculations. Since there are two baseline scenarios given for the year 2020, it is of interest to evaluate how much their differences influence the exceedances of critical loads for that year.

### *Likelihood of exceedance (ensemble assessment)*

(Slootweg, Posch, & Hettelingh 2007) present an approach to assess the likelihood of exceedances, based on the methodology of the IPCC. Using this approach, the areas exceeded by the modelled (CLnutN) and empirical (CLempN) critical loads for nutrient nitrogen (N) in every EMEP grid cell are combined. For the baseline scenarios, this yields the maps in Figure 14. The maps show the likelihoods of exceedances of critical loads of nitrogen for the year 2000 (top left; NAT09), for maximum of feasible reductions (MFR) in 2020 (top right; MFR). These are the extremes currently available: the historic situation for 2000 and the maximum technically feasible reductions in 2020. The centre maps show results for the two baseline scenarios for 2020: using national data (left; NAT09) and using PRIMES output (right; PRI09). These maps confirm the conclusion that the likelihood of exceedance of nutrient N critical loads for the two different baseline scenarios for 2020 do not give very different results (centre maps), and that this likelihood for excess of critical loads is decreasing (i.e., less red shaded areas) in many regions in comparison to 2000 (top left). The bottom map shows results with PRIMES output for the year 2030 (PRI09); they do not differ much from those for 2020.

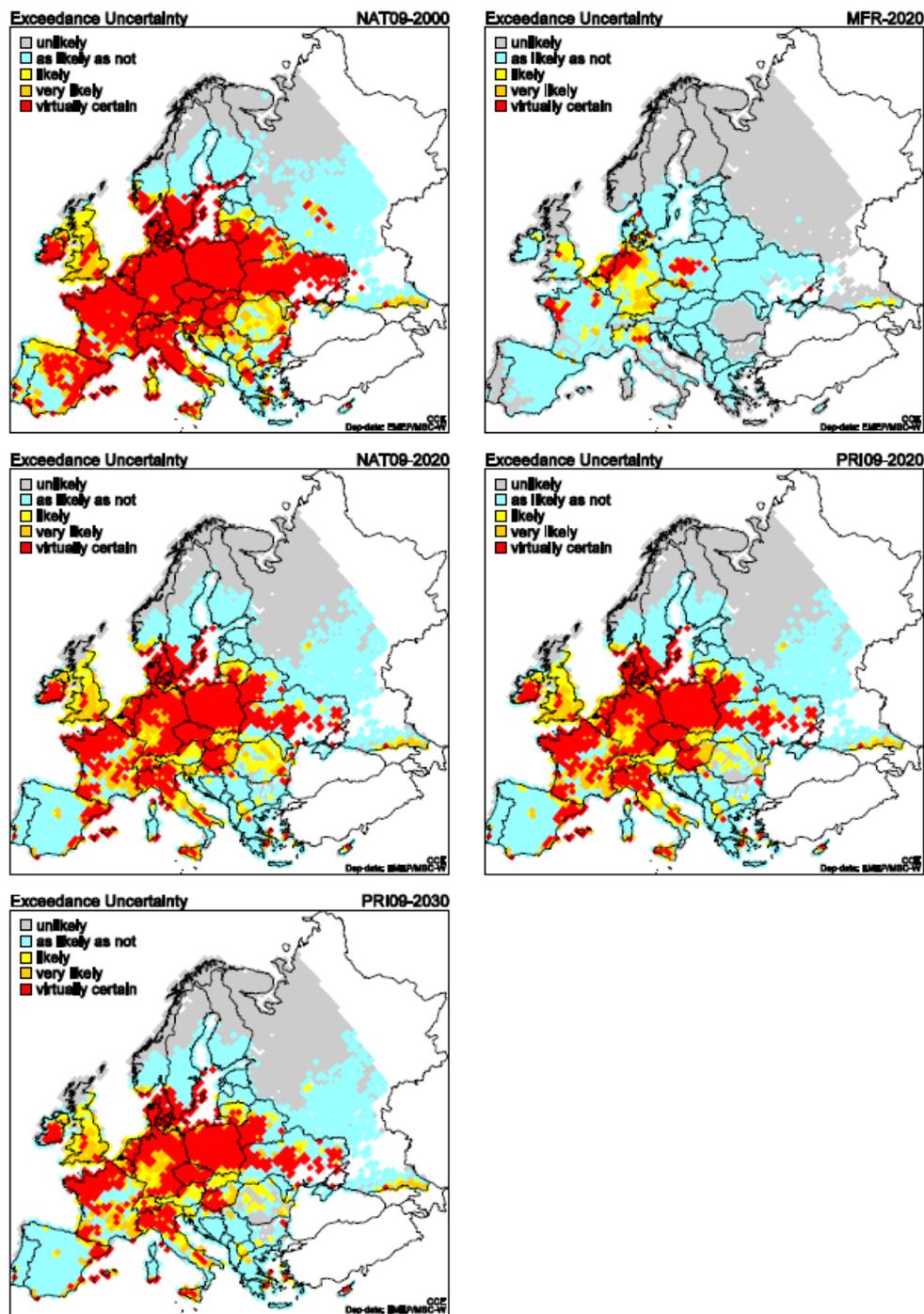


Figure 14 Likelihood of exceedances of critical loads of nitrogen for the year 2000 (top left), for maximum technically feasible reductions (MFR) in 2020 (top right); the two baseline scenarios for 2020 (centre): using national data (left) and using PRIMES output (right); and with PRIMES output for the year 2030 (bottom)

***Influence of deposition correlations on CL exceedances***

Deposition calculations have been carried out with the unified Eulerian dispersion model of EMEP/MSC-W for a few selected scenarios. Routine calculations of critical load exceedances (and other impact indicators within the GAINS model) are performed with depositions generated with a linearized version of the unified model, so-called transfer matrices (see, e.g., (Posch, Slootweg J., &

Hettelingh J.-P. 2005)). In contrast to the transfer matrices that have been used in the 1990s (i.e., derived from the Lagrangian EMEP model), the new unified EMEP model provides now transfer matrices together with correlations between pollutants. This enables consideration of the interactions between, e.g., ammonium and sulphate in the atmosphere. In routine exceedance calculations at the CCE the correlations between pollutants are always included. Since this is not the case everywhere – neglecting the correlative matrices saves matrix storage and multiplications – we investigate here in the influence of neglecting the correlations on critical load exceedances. Mapping the exceedances for the NAT09-2020 scenario indicates that the differences are not large (Figure 15).

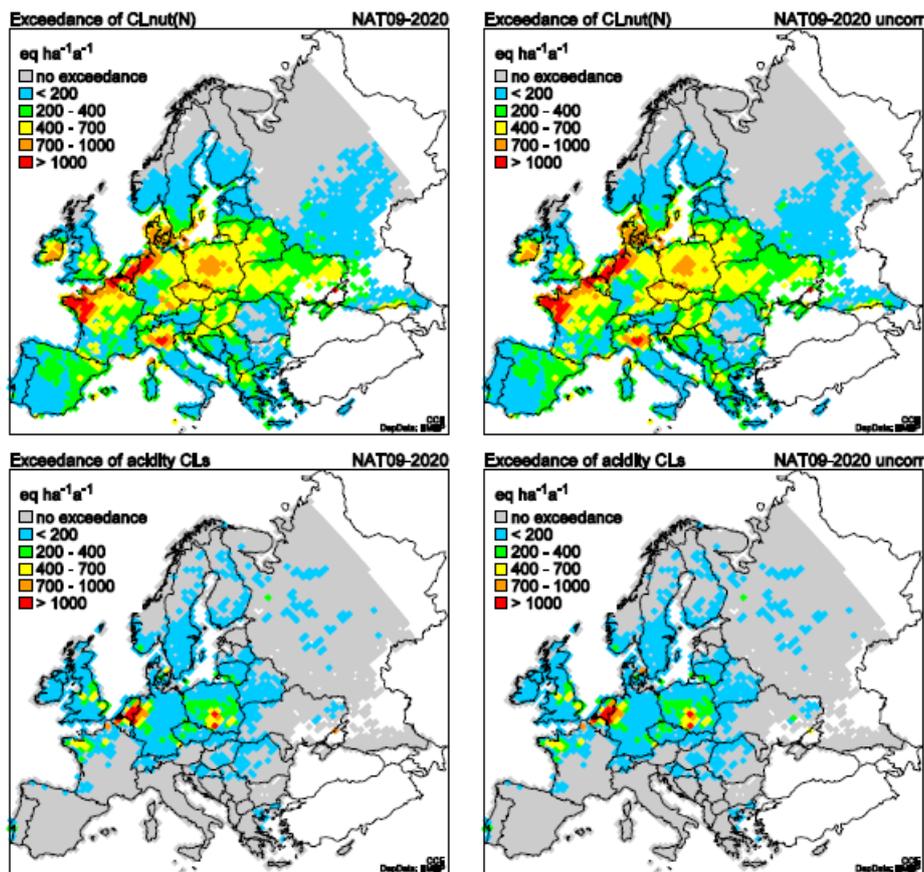


Figure 15 Exceedance of the critical loads of nutrient N (top) and acidity CLs (bottom) for the NAT09-2020 scenario using correlated depositions (standard case; left) and uncorrelated depositions (right)

For policy advice, it is the exceedance of critical loads that is of importance, which is also influenced by the uncertainties in emission estimates and in atmospheric dispersion modelling. While the uncertainties of the whole chain has been investigated earlier (Suutari et al. 2001), for EC4MACS the influence of (a) the existence of two different emission estimates (baseline scenarios) for 2020 and (b) the exclusion of correlation in the dispersion of pollutants was investigated. In both cases the influence is not big, but discernible; and most likely (much) larger when examining it for individual (small) countries. Limiting the assessment to comparing scenarios (as opposed to looking at absolute values) will reduce uncertainties.

### 3.8 *Benefits and cost-benefit Analysis*

In addition to the uncertainties in the previous parts of the causality chain, cost-benefit analysis faces uncertainties in the valuation of impacts. Current estimates relate about 90% of the economic damage to health effects, mainly determined by the valuation of mortality. Five percent of total monetary damage is currently estimated for crops, and five percent from damage to materials. However, these estimates are incomplete as there is no accepted method yet to estimate the damage of air pollution to ecosystems services and cultural heritage. It was recommended to focus sensitivity analysis on alternative assumptions for the valuation of mortality and abatement costs.

Uncertainties in cost-benefit analysis were analysed in (Holland et al. 2010). Estimates of costs and benefits are subject to uncertainties, and some of them (on both sides of the cost-benefit equation) are significant. The quality of knowledge for identification of these uncertainties is variable, as is the availability of quantitative data for a good description. Further, some uncertainties are statistical and continuous in nature, some relate to discrete choices (e.g., selection of approaches for the valuation of air pollution – related mortality), and some relate to a lack of knowledge.

The extent to which uncertainty needs to be considered in an analysis is largely dependent on the balance of costs and benefits. Where estimated costs far exceed estimated benefits it is unlikely that any assessment of uncertainty would change the perception of that relationship unless some possible outcomes were politically untenable (an obvious example, though not one directly relevant to EC4MACS, concerns major nuclear accidents). Similarly, where benefits far exceed costs, uncertainties should be of limited importance.

Some of the uncertainties can be addressed relatively easily in quantitative terms. Others cannot, and require a more subjective assessment. Irrespective of whether they can be addressed quantitatively or semi-quantitatively, all of the uncertainties identified here are potentially important and need to be considered.

It is worth considering the objective of cost-benefit analysis, namely to identify approaches that represent least cost to society. „Cost“ here includes environmental and health costs as well as pollution abatement costs. (Rabl, Spadaro, & van der Zwaan 2005) focused on the effect of uncertainty in determining the least cost position. They concluded that for continuous choices such as the development of emission ceilings for sectors or regions, the cost penalty turns out to be “remarkably insensitive to error”. They observed that an error of a factor 3 up or down in damage estimates for NO<sub>x</sub> and SO<sub>2</sub> would potentially increase the social cost by at most 20% and in many cases much less.

## *4 Emission ceilings in an uncertain world – A methodology for emissions offsets*

The ultimate purpose of the integrated assessment framework one developed under EC4MACS is to provide scientific advice to decision makers about cost-effective control strategies and policies. Typically, the outcome of such an integrated assessment analysis can be translated into quantitative national emission ceilings that limit the transboundary impacts of emissions from a given country on other countries.

Such ceilings for SO<sub>2</sub>, NO<sub>x</sub>, NH<sub>3</sub> and VOC are established in several environmental impact agreements (IEA), for example, in the Gothenburg Protocol of the Convention on Long-range Transboundary Air Pollution (LRTAP) and the National Emission Ceilings Directive of the European Union. They prescribe for each pollutant a fixed cap on emissions for a specific year that must be achieved by each country.

While the final numbers for such ceilings emerge from a political negotiation process, they are guided by cost-effectiveness analyses that explored the international allocation of emission reductions that would achieve prescribed air quality targets at least cost. The cost-effectiveness analysis, e.g., with the GAINS model, is usually based on ex-ante assumptions of future baseline economic development trends and estimates of mitigation potentials for the target year. However, cost-effectiveness might be lost if reality develops differently from what has been originally assumed in the cost-effectiveness analyses.

Emission ceilings are specified as fixed absolute caps on emissions that need to be complied with by countries. In principle, if all factors evolve as assumed in the cost-effectiveness analysis, these ceilings should achieve the envisaged environmental targets at least-cost. However, reality might develop differently than assumed, and models that are used to derive emission ceilings are associated with uncertainties, as discussed in the preceding sections. If original assumptions change, the original allocation of emissions reductions could turn out as inefficient, i.e., the same environmental improvements could be achieved by a different allocation at lower costs. Hence meeting a given set of emission ceilings may ex-post be economically inefficient.

Flexibility in achieving emission ceilings offers the potential to increase their economic efficiency if reality develops differently than originally assumed. Emission trading across countries has been suggested as one mean to maintain efficiency if ex-ante estimates of mitigation costs are uncertain. While this is conceptually appropriate for uniformly dispersed pollutants where the location of emissions does not matter, emission ceilings of the above-mentioned agreements on air pollution have been derived for environmental air quality targets that are spatially specific as they take into account, e.g., differences in the sensitivity of different ecosystems towards pollutant. In these cases, the location where emission reductions take place is important, and emission reductions cannot be freely moved around without changing their environmental impacts.

An alternative approach that could preserve the originally envisaged environmental improvements could provide flexibility by allowing compensating lower reductions of one pollutant by additional cuts in another. This flexibility emerges from a multi-pollutant approach, which quantifies the

contributions of multiple emissions to a specific impact. For instance, the analysis for the Gothenburg Protocol and the EU NEC directive consider the contributions of primary particles,  $\text{SO}_2$ ,  $\text{NO}_x$ , and  $\text{NH}_3$  to ambient concentrations of fine particulate matter (PM<sub>2.5</sub>). Thereby, lower reductions of one pollutant (e.g., primary particles) could be compensated by additional reductions of the emissions of secondary aerosols (e.g.,  $\text{SO}_2$ ,  $\text{NO}_x$ , and  $\text{NH}_3$ ) without changing the impact on ambient PM<sub>2.5</sub> levels.

Within the EC4MACS project, an exploratory analysis was carried out to identify conditions under which emission reductions of one pollutant could be offset by additional cuts of another pollutant in the same country. Our basic tenet is that increasing flexibility to the implementation of emission ceilings could increase the acceptability of an environmental agreement. As the guiding principle for offsetting regimes, the notion of environmental integrity was used. Environmental integrity requires that the environmental impacts of the original set of emission ceilings must not deteriorate.

Using the GAINS model, possible offsetting regimes were classified and then (lower limits for) exchange rates between different pollutants *within a country* were calculated.

The starting point of the analysis is a set of national emission ceilings (NECs) for air pollutants that we assume have been arrived at under an international agreement and which are in place for a number of different countries, such as the parties to the CLRTAP. We further assume that the basis for such an international agreement was an effects-based approach, i.e., that the original motivation for imposing NECs was to reduce a set of impact indicators by certain amounts. This means that imposing the NECs is only considered a means to an end rather than a primary objective. As such, however, a set of numerical ceilings are very practical, as they can be monitored and measured, and compliance guarantees that multiple environmental objectives are met simultaneously.

We have analysed whether offsetting emissions is possible at all without deteriorating environmental impacts compared to the original case. And if so, what conditions have to be imposed to make such an offsetting framework self-consistent, i.e., to avoid that creative accounting of 'circular offsets' could reduce the net impact.

In the cost-effectiveness analysis of GAINS, four impact indicators are considered (Amann et al. 2011):

- **Health impacts due to exposure to fine particles.** We use the 'years of life lost' as the metric for this indicator, and calculate it for each grid cell (GAINS is using the 50\*50 km<sup>2</sup> EMEP grid), for each country and for the whole model domain. GAINS considers primary and secondary inorganic aerosol components of PM<sub>2.5</sub>, for which the models takes into account the precursor emissions of primary particles PM<sub>2.5</sub>,  $\text{SO}_2$ ,  $\text{NO}_x$  and  $\text{NH}_3$ .
- **Eutrophication of ecosystem.** We estimate nitrogen deposition in excess of the critical loads for eutrophication (REF CCE), for a specific ecosystem, in each grid cell, in each country, and over the full model domain. Metric: Average Accumulated Exceedance (AAE) for eutrophication.

- **Acidification.** We estimate acidifying sulphur and nitrogen deposition in excess of the critical loads for acidification, for a specific ecosystem, in each grid cell, in each country, and over the full model domain. Metric: Average Accumulated Exceedance (AAE) for acidification.
- **Health impact due to ozone exposure.** Here we estimate premature mortality based on the SOMO35 indicator. SOMO35 measures the number of hours per year during which the 8-hour average concentration of O<sub>3</sub> lies above 35 ppb.

The aim of the offsetting analysis was to calculate numerical rules for offsetting regimes (exchange rates), to provide a complete set of allowed solutions, and to explore potential limitations of the approach to devise robust approximations. Therefore, analytical methods were used to derive explicit consistency conditions for the emissions of different pollutants. These consistency conditions can be used to classify all feasible offsetting regimes and to derive explicit formulae for the exchange rates between pollutants as well as to calculate the numerical values of some exchange rates. These methods can also be generalized for the case in which downwind effects are taken into account.

#### *A classification of admissible offsetting regimes*

In (Wagner, Schöpp, & Amann 2012), we have demonstrated that not all combinations of exceedances can be compensated by reductions of other pollutants. This is caused by the fact that not all five pollutants contribute to all four impact indicators. For example, simultaneous exceedances in NO<sub>x</sub> and VOC cannot be compensated by reductions of other pollutants because none of the other three pollutants affects the SOMO35 value. We have identified all feasible combinations of exceeding and compensating pollutants and found 54 of them. We found that NO<sub>x</sub> exceedances cannot be compensated by additional reductions of a *single* pollutant without violating environmental integrity. This is because the eutrophication constraint and the SOMO35 constraint are compensated by two different pollutants, and they cannot be satisfied simultaneously by reducing only one of the pollutants. The simplest way to offset a NO<sub>x</sub> exceedance is through reducing both NH<sub>3</sub> and VOC. Similarly, NO<sub>x</sub> and NH<sub>3</sub> cannot simultaneously be exceeded, and NO<sub>x</sub>, NH<sub>3</sub> and SO<sub>2</sub> cannot simultaneously be exceeded.

#### *4.1 Exchange rates for simple offsetting regimes*

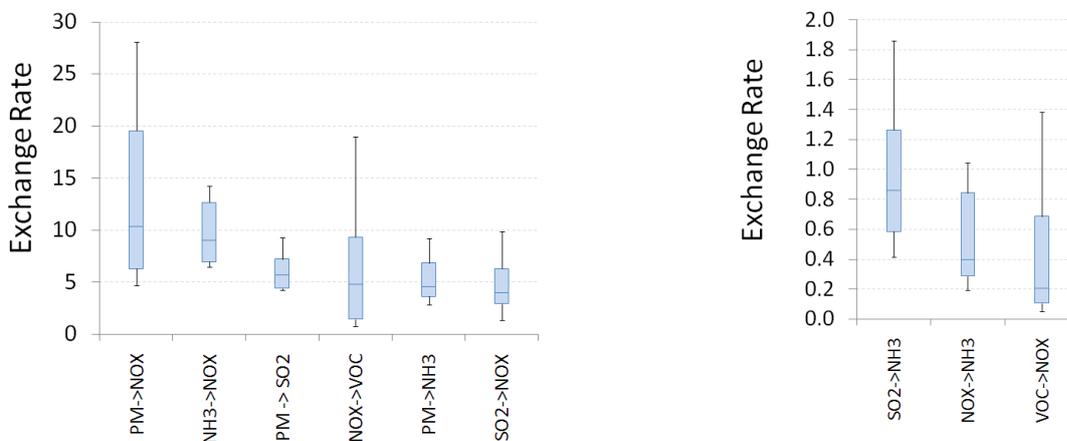
In an offsetting regime, exchange rates specify by how much emissions of one pollutant need to be reduced in order to compensate for the exceedance of another pollutants without deteriorating the environmental improvements of the original solution. In (Wagner et al. 2012) we show how the functional form of an exchange rate is determined.

However, not in all of the 54 cases it is possible to define fixed exchange rates, i.e., rates that do not depend on the amount by which the ceilings are exceeded. We also found that there is room for policy makers to prescribe which of the offsetting regime classes are considered politically acceptable. For example, even though it is theoretically possible to compensate the exceedances of three or even four ceilings, regulators may want to allow violation of at most one of them, in which case only 22 distinct configurations would need to be considered. Also restricting the number of compensating pollutants to exactly one then reduces the number of feasible regimes further.

In general, there are infinitely many values of the exchange rate that are consistent with the environmental constraints. If one pollutant is offset by only one other substance, it is possible to choose the lowest value or the economically most efficient constant exchange rate. We also showed that environmental integrity for *all* environmental indicators will lead to environmental improvements of *some* of impacts, and keep at least one of them at exactly the same level.

In (Wagner et al. 2012) we listed the functional form of fixed exchange rates for a restricted set of offset regimes. They depend on the source-receptor matrices  $T$ , derived from the atmospheric dispersion and effects models. We have calculated the values of these exchange rates for 39 European countries (EU27, Albania, Belarus, Bosnia-Herzegovina, Croatia, Macedonia, Moldova, Norway, Serbia-Montenegro, Switzerland, Turkey, Ukraine, and the European part of Russia).

In Figure 16 we show the box plots (90-75-50-25-10 percentiles) for the nine exchange rates in order of decreasing median. We note a substantial variation across countries for a given pair of pollutants (factor 2 to factor 25), even after removing outliers. Thus, exchange rates depend on the country. The median values across pollutant-pairs also fall naturally in two groups, one with a range from 4 to 10 (above 1), and another from 0.2 to 0.9 (below 1). Not included in the box plots are the outliers. In particular, the VOC-NO<sub>x</sub> exchange rate turns out as infinite for some countries, because the NO<sub>x</sub> transfer coefficients in the SOMO35 calculation is zero in these cases.

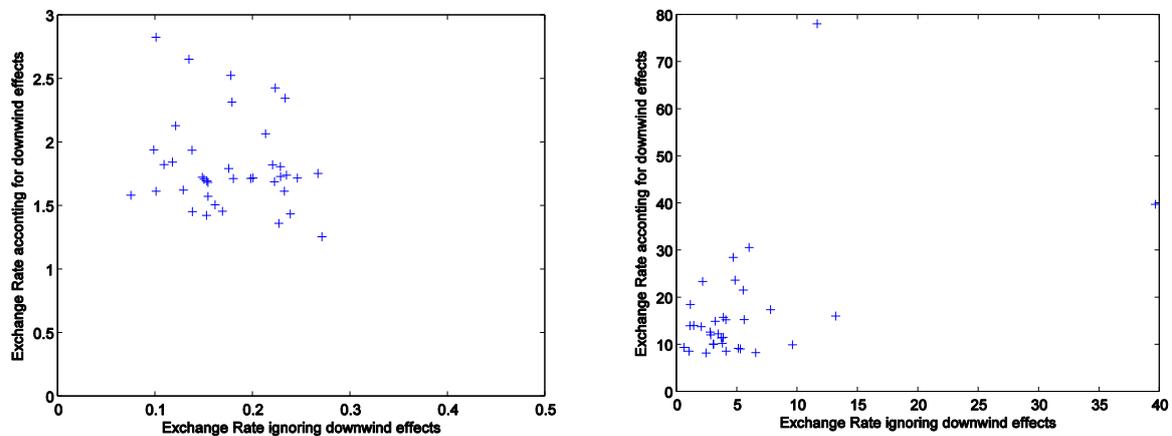


**Figure 16** Box plots of the exchange rates for 39 European countries.

#### 4.2 *The relevance of downwind effects*

We also addressed question of how to ensure that the offsetting of pollutants in one country A does not negatively impact the environment compared to the starting point (e.g., for the initial NEC ceilings) in any country B. This requirement imposes additional conditions that have to hold in downwind countries B. In (Wagner et al. 2012) we have derived these additional conditions and calculated their numerical values.

As an illustration, Figure 17 compares the value of the exchange rates between SO<sub>2</sub> and PM<sub>2.5</sub>, and between SO<sub>2</sub> and NO<sub>x</sub>, without downwind accounting (horizontal axis) against the rate with downwind accounting (vertical axis):



**Figure 17 Comparison of the numerical values with (vertical axis) and without (horizontal axis) taking account of all downwind effects for the exchange rate between PM<sub>2.5</sub> and SO<sub>2</sub> (left), and between NO<sub>x</sub> and SO<sub>2</sub> (right) for European countries.**

In general, the exchange rate that respects the downwind effects is much larger. Does this mean that these much larger values for the exchange rates should be used in practice? Not necessarily: exchange rates are ratios of transfer coefficients  $T$ , which in turn are differentials, i.e., they are obtained by taking the difference of two runs of the atmospheric dispersion-deposition model. Uncertainty in the model inputs and results implies an uncertainty in the  $T$ 's, and the smaller the  $T$ 's the larger the uncertainty. Thus, we expect that, the smaller the  $T$ 's are (i.e., the smaller the influence of the emitter country on the receptor country), the more uncertain are the ratios of the  $T$ 's (i.e. the exchange rates). Thus, the maximum of the ratios may be driven by the (uncertain) value of the ratio in downwind countries that are geographically far away from the offsetting countries and are thus less affected in absolute terms. For these far away countries, the numerical values of the source-receptor matrices  $T$ 's are small and can be considered 'numerical noise'. Thus, in order to avoid that the exchange rate is distorted by 'noise' we may want to first clean the set of source-receptor matrices  $T$  very carefully.

One approach for restricting the influence of small values of the  $T$ 's could be to set them to zero. The key question then is what is considered 'small', i.e., which values can be neglected without ignoring important effects. A practical way of dealing with this is to scale  $T$ 's of the same kind to the highest value and declare all values in a certain percentile to be small. The majority of transfer coefficients into downwind countries is at least two to three orders of magnitude smaller than the local transfer (from one country to itself). Thus, it seems not unreasonable to cut off small values of the ratios and ignore them in downwind calculations. For example, one could declare the lowest x% to be "small" in relation to the other data in the set, where x = 10, 20,... . The choice of x is a policy choice.

Alternatively, much of the “noise” would disappear by removing those values that are smaller than, say,  $10^{-5}$  of the local transfer coefficient, without affecting the impact calculations significantly. In this way the most important downwind effects could be taken into account in the exchange rates, while less important downwind effects are ignored to avoid introducing numerical ‘noise’ and thus unjustifiable large (and therefore economically unattractive) exchange rates for local offsetting.

### 4.3 Policy decisions for offsetting

Before the offsetting rules described above could be operationalized, policy makers and their technical advisors would have to address the following issues:

- Should emission offsets be allowed at all, as a matter of principle?
- If yes, should there be limits to how much can be offset (e.g., a percentage of the original ceiling), since the offset regimes are only defined at the margin in the first place? In practice, the demand for offsets typically may be low anyway, compared to the emission ceilings.
- Should predefined exchange rates be used for checking compliance with NECS? If so, the exceedance of a ceiling would be multiplied with the appropriate exchange rate(s) to calculate the amount of offsets by other pollutants. The alternative would let every country prove *ex post*, with the actual inventoried emission levels, that indeed it is in compliance with the environmental targets implicit in the NECs. The advantage of the latter approach would be that (a) compliance does not depend on the exact exchange rate concept used, and (b) only 11 parameter values would need to be specified for each country in order to check the compliance. However, it would not be clear to what extent downwind effects of local emission offsets would be taken care of too. For this, many more parameters would need to be specified, which would render this approach rather clumsy and impracticable.
- If exchange rates are used, the question remains which values of exchange rates ensure environmental integrity. Naturally, as we have shown, exchange rates will have to be country-specific. However, we have also found that it is not possible to define *ex ante* the set of exchange rates that would be efficient in each of the 54 offset regimes. Finally, some of the efficient exchange rates actually amplify uncertainties in the source-receptor matrices  $T$  and thus would have to be considered more uncertain than these.
- It needs to be decided to what extent downwind effects should be accounted for in the exchange rates as well, and which downwind effects are considered ‘noise’ that can safely be ignored.

## 5 Conclusions

This report reviews key uncertainties of the various models of the EC4MACS integrated assessment framework and explores options of uncertainties treatment that would enable robust policy conclusions.

Uncertainties fall into several classes, such as uncertainties in model representation, model parameters (including initial data and technology parameters), and expectations of future developments. The modelling teams reviewed a wide range of uncertainties, starting from implementation of future economic, agricultural and environmental policies, agents' behaviour, energy statistics, technology costs and potentials, and vehicle fleet structure and sizes. The review addresses uncertainties in emission factors, in future livestock numbers and food demand, in food prices, in forest management practices, in bioenergy production projections, in wood demand, in meteorological fields, in empirical critical loads information, and the monetary valuation of impacts.

Some of these uncertainties cannot be avoided even in a perfect world with best scientific efforts. A methodology has been developed that provides ex-post flexibility to the implementation of national emission ceilings to maintain cost-effectiveness of an overall strategy even if important assumptions turned out to be wrong. Such emission offsetting would allow countries to compensate lower reductions of a given pollutants by additional cuts of other pollutants while safeguarding the achievement of the original air quality targets for which the emission ceilings have been established at the first instance. The GAINS model analysis has identified critical questions that policy makers face when they consider such an offsetting as a viable option to hedge against the risk of over- or under-constraining future emission levels. Answering these questions can lead to a pragmatic solution to the question how to make progress with defining legally binding emission targets in an uncertain future based on uncertain data.

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