EC4MACS
Uncertainty Treatment

The ALPHA Benefit Assessment Model

European Consortium for Modelling of Air
Pollution and Climate Strategies - EC4MACS

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1.1. Introduction

There is a clear focus for uncertainty assessment in the benefits component of EC4MACS: how confident can we be about quantified relationships between the costs and benefits of action to reduce air pollution?[1] In most cases it is therefore inappropriate to separate uncertainty analysis in the quantification of benefits from the cost-benefit analysis, the comparison providing a policy context.

This provides a useful constraint on the uncertainty analysis. Best estimates of costs generated by GAINS can be compared with the best estimates of benefits generated by ALPHA2 to provide a preliminary impression of the balance of costs and benefits. In cases where benefits are either much larger or much smaller than costs a detailed assessment of uncertainty is typically unnecessary as it would be unlikely to change conclusions on the desirability of a particular scenario. In such cases a general overview of uncertainties should be sufficient, including some limited quantification. In cases where costs and benefits are closer, however, a detailed assessment covering uncertainty in what has been quantified *and* uncertainty arising from a failure to quantify all effects becomes necessary.

Complexity arises because the comparison of costs and benefits comes at the end of the modelling chain. This means that it is necessary to consider uncertainties from all components of the EC4MACS system. In practice, however, this does not require a full appraisal of all model outputs at the stage of the CBA, as sensitivity to certain elements (e.g. energy and transport demand, agricultural activity) can be addressed through sensitivity runs of the GAINS model if they are considered necessary. The outputs from earlier modelling stages, of most direct concern for the uncertainty analysis of the cost-benefit comparison, therefore concern the cost estimates generated by GAINS and the results of dispersion modelling.

The fact that the benefits analysis comes at the end of the modelling chain provides not just added complexity, but also freedom to explore uncertainty in ways that would be difficult to integrate with the other models. For example, we recommend the use of Monte Carlo simulations to quantify the probability of benefits exceeding costs. It is hard to see how this could be integrated into GAINS were the ordering of the models to be reversed.

The comparison of costs and benefits should be done (to the extent possible) by considering marginal costs and marginal benefits. Within the modelling framework of EC4MACS a true marginal comparison is generally not possible because measures are not considered individually in GAINS. However, a proxy can be used – the difference between scenarios (a quasi-marginal approach). The smaller the difference between the scenarios, the closer the analysis is to a true marginal assessment. The use of quasi-marginal CBA is often not apparent from final papers written to inform European air pollution policy as they tend to focus on whatever scenario has been recommended, and then describe the costs and benefits of that scenario relative to business as usual without reference to the way that costs and benefits relate to one another for intermediate positions. However, a larger number of scenarios will typically have been evaluated previously to facilitate a near-marginal comparison.

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[1] These relationships are formulated in terms of whether or not benefits are forecast to exceed costs, and the size of the benefit: cost ratio.

1.2. Types of uncertainty

1.2.1 Statistical uncertainties

Discussion of uncertainty often focuses purely on those aspects of analysis that can be quantified using statistical techniques. These techniques address uncertainty associated with the extraction of information from observations on a limited sample drawn from a population of people, crops, industrial plant, etc. They describe the behaviour of the sample (e.g., how it responds to change in a variable such as increased air pollution) and show how reliable the conclusions drawn from use of the sample are as a representation of the behaviour of the total population. Key characteristics of a sample are average (also referred to as ‘mean’) or median values and the spread of values around them. Spread is typically characterised as the standard deviation and the range within which 90, 95 or 99% of observations are likely to occur.

Whilst statistical analysis provides a benchmark for uncertainty assessment it is important to recognise that a variety of uncertainties cannot be described using standard statistical techniques:

- Omission of impacts from the benefits analysis.
- Existence of alternative views on methodology amongst experts (e.g. in relation to mortality valuation).
- Transfer of data on exposure-response, valuation, etc. from one situation to another.

Although a statistical treatment of these uncertainties is not possible, it is still necessary to account for them in the analysis in some way if they seem likely to have a significant effect on the balance of costs and benefits. This can be done using the other techniques described in this report, bias analysis and sensitivity analysis.

The further the analysis proceeds through the chain from release to exposure to impact assessment to valuation, the greater the uncertainty in the final estimate (simply because more parameters, each bringing their own level of uncertainty to the analysis, are introduced). On this basis, we can have the highest confidence in concentration data, followed by (in order) total population exposure, exposure of specific groups within the population, impact results, and finally monetised estimates of damage.

1.2.2 Biases

Biases reflect limitations in the design of the tools available for quantification of (in this case) the costs and benefits of pollution control. They are issues for which quantification and associated assessment of uncertainty in a sufficiently detailed manner for inclusion in the analysis is not possible. They need to be brought into the assessment in some way because many of them have the potential to influence results significantly (e.g. the omission of secondary organic aerosols from the dispersion modelling, of abatement options from GAINS, and of ecosystem damage from the benefits assessment). Further to this, biases are considered likely to affect results in a systematic manner – either in. In many cases the direction of the bias on the balance of costs and benefits is obvious. In a few cases, however, it is not.

The treatment of biases proceeds through the following stages:

- Identification of biases
- Assessment of the direction of bias
- Assessment of the potential effect of biases on the cost-benefit balance
- Interpretation of the overall effect of the biases identified.

1.2.3 Sensitivities

There are several methods available that come under the general title of sensitivity analysis:

- Observation of the effect on outputs of a systematic stepwise change in one or more variable(s). This could, for example, involve assessment of the effect of a series of incremental changes of 5% or 10% around the core estimate for a specific variable.
- Use of different scenarios for definition of the baseline position on emissions.
- Use of alternate estimates for a specific parameter based on different methodologies. Examples include:
    - Monetisation of mortality impacts using VOLY (value of a life year) and VSL (value of statistical life) based methods.
    - Use of European average or country specific valuations.
    - Use of different approaches to discounting.
- Division of impacts into confidence bands, to differentiate between those effects that can be assessed with greatest confidence and those that can be quantified with less confidence.

The past cost-benefit analysis of the National Emission Ceilings and Ozone Directives and the Gothenburg Protocol (AEA Technology, 1999a, b, c) used two forms of sensitivity analysis. First, it grouped quantifiable benefits into five confidence bands, demonstrating the confidence of stakeholders and analysts in the quantification of each impact. Those effects for which quantification was considered most robust were put into confidence band 1, whilst those for which quantification was considered least robust were placed in confidence band 5. A stepwise comparison was then made with costs. If the benefits from the impacts in confidence band 1 outweighed abatement costs for any country, that country would have great confidence that overall, benefits would outweigh costs. If all five confidence bands were required, confidence that benefits would outweigh costs would be lower (acknowledging that some important impacts were left out of the quantification altogether, as now). A weakness of the approach is that there is subjectivity in defining which effects can be quantified with greatest confidence. It was noted that few stakeholders felt able to respond to a questionnaire distributed at the time to solicit opinion on how impacts should be ranked. Of those that did, many expressed the view that they could only comment on the impacts (e.g. health effects) with which they were most familiar. Although the approach was clearly not perfect, a number of stakeholders found it useful.

The second method used in the earlier CBAs was the separate investigation of the effect of individual sensitivities, with particular attention given to mortality valuation using the value of statistical life (VSL) and value of life year (VOLY) approaches, and the use of European average and country specific data for valuation.

1.2.4 Model validation and quality control

There is a risk of error in any analysis during model construction, the handling of data and processing and handling of results. The complexity and multi-disciplinary nature of the

CAFE analysis raises the potential for such error. The developers of the EMEP and GAINS models have their own protocols for dealing with the issue of model validation and quality control. For the benefits analysis component of the CBA, the approach for dealing with uncertainty due to model validation and quality control has been as follows:

- The principal modelling tool (ALPHA2) has been developed at AEA Technology. A simpler tool has been developed in parallel by EMRC, permitting results to be compared for each endpoint.
- A series of marginal damage estimates per tonne pollutant emission have been generated by the project team. These can be used to check results of a full scenario analysis. Given some non-linearity in atmospheric chemistry there will not be a perfect match in the results.
- The health functions provided in the methodology report require some computation before integration with the model (e.g. in converting odds ratios to change in incidence per unit pollution). All functions were checked independently of the main authors at IOM by EMRC during the writing of Volume 2 of the CAFE-CBA Methodology report (Hurley et al, 2005).
- Results have been compared against background rates, crop yield, etc., to assess whether or not they are plausible. .
- Whilst direct validation is not possible, consideration has been given during the development of the benefit assessment methodology to information that shows impacts to be real. A good example would be the various ‘intervention studies’ that show significant changes in mortality and morbidity rates following interventions such as the analysis of the Dublin coal ban that lead to a large stepwise reduction in emissions, which showed a clear improvement of health.

1.3. Statistical uncertainties

The approach used here for statistical analysis is based on the use of the @RISK model. @RISK permits investigation of statistical uncertainties through the definition of probability distributions for key parameters in terms of mean values and the spread of values around them, and subsequent sampling across these distributions.

The first stage in the analysis is definition of the scope of the model to be used for quantifying uncertainty. Based on the results from CAFE and the NECD revision, it is appropriate to focus on health impacts, as they provide the largest monetised air pollution damage for the EC4MACS analysis. The next step is to identify the different stages of the analysis, and the areas where quantifiable uncertainties are likely to be most significant. Probability distributions (illustrated in Figure 1) are then defined for each parameter of interest, drawing particularly on data given by Hurley et al (2005).

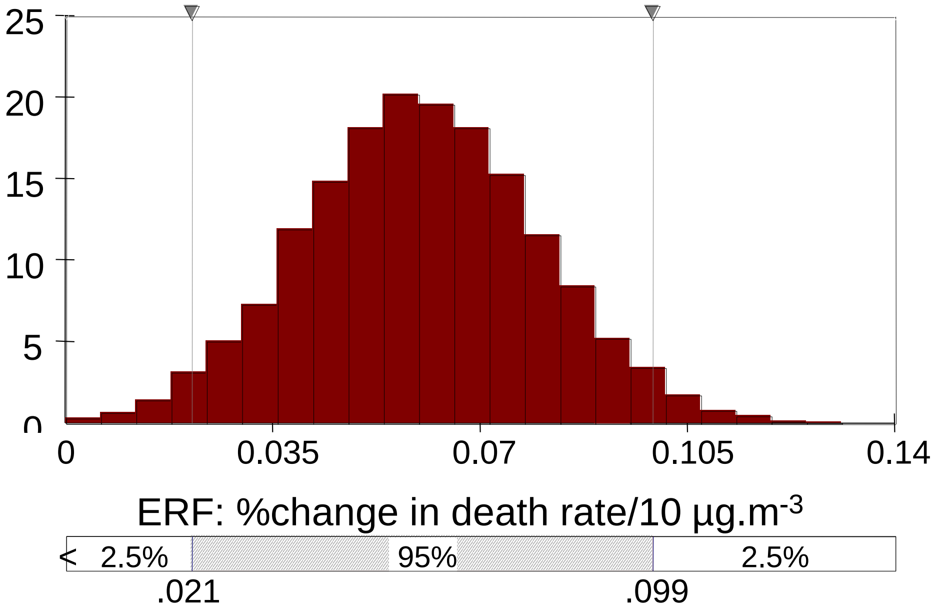

Figure 1. Normal distribution for exposure response function for chronic mortality effects of PM exposure.

Table 1 and Table 2 provide data on the ranges and best estimates entered into the @RISK model as used for analysis in CAFE-CBA (Holland et al, 2005). From comparison of best estimates and standard errors, it may at first sight appear that uncertainty in valuation of mortality is underestimated compared to uncertainty in valuation of morbidity. However, a large part of the uncertainty in mortality valuation is accounted for by the reporting of separate results based on the median and mean estimates of the VOLY and VSL. Against this background, the use of broader spreads than those recommended here around the separate mortality estimates would double count uncertainties.

At the EC4MACS uncertainty workshop in October 2010 at IIASA, a representative of industry suggested that the Monte Carlo analysis should use the full set of data collected in the original mortality valuation studies, in other words, base the distribution on the individual observations from those studies. This is not adopted here. We know that some individuals may, quite validly have a zero valuation of mortality risk (e.g. because they do not consider that they have any money to allocate to mitigate air pollution risk). We also know that some individuals will have a strong preference for reducing health risks. Neither, however, can be considered to be representative of society at large. For that we need to use some estimate of average response. The Monte Carlo analysis then needs to account for likely variation around this average.

Table 1. Best estimates and ranges used for incidence data, exposure response functions and valuation data in the analysis of statistical uncertainties in the health impact assessment for ozone effects, based on information presented by Hurley et al (2005).

Annual incidence rate: distribution – triangular	**+/-**	**Best estimate**
Mortality rate (deaths per head of population)	5%	0.011
Respiratory hospital admissions, >64 years (cases/100,000 population)	20%	2,496
Minor restricted activity days (per person)	40%	7.8
Adult use of respiratory medication (days per person)	40%	0.045
Respiratory symptoms, adults (dummy variable)	40%	1
Response function: distribution - normal	**Std deviation**	**Best estimate**
Acute mortality (% change in mortality rate per 10µg.m^{-3})	0.075%	0.30%
Respiratory hospital admissions (%change in incidence/10 µg.m^{-3} O_3)	0.35%	0.50%
Minor restricted activity days, population 18-64 (%change in incidence/ 10 µg.m^{-3} O_3)	0.45%	1.48%
Respiratory medication use (days /10 µg.m^{-3} O_3 /1000 adults aged 20+)	456	730
Minor restricted activity days, (%change in incidence for population aged >64 /10 µg.m^{-3} O_3)	0.45%	1.48%
Respiratory symptoms (symptom days/1000 adults/10 µg.m^{-3} O_3)	175	343
Valuation (all units - €/case): distribution – normal	**Standard error**	**Best estimate**
Acute mortality (VOLY, mean) (€/case)	14,600	120,000
Acute mortality (VOLY, median) (€/case)	3,700	52,000
Respiratory hospital admissions (€/event)	670	2,000
Minor restricted activity days, (€/day)	13	38
Respiratory symptoms in adults (€/day)	13	38
Respiratory medication use by adults (€/day)	0.33	1

Table 2. Best estimates and ranges used for incidence data in the analysis of statistical uncertainties in the health impact assessment for PM effects. Data are based on information presented by Hurley et al (2005).

Annual incidence rate: distribution - triangular	**+/-**	**Best estimate**
Mortality rate, >30 years	5%	1.61%
Infant mortality rate, ages 1 to 12 months	10%	0.19%
Chronic bronchitis, % of population aged >27 years affected	40%	0.38%
Respiratory hospital admissions (cases/100,000 population)	20%	617
Cardiac hospital admissions (cases/100,000 population)	20%	723
Restricted activity days (RADs, days / person)	40%	19
Use of respiratory medication by adults (% symptomatic adults)	40%	4.50%
Use of respiratory medication by children (% of children who are symptomatic)	40%	20%
Lower respiratory symptoms, adults (% of adults who are symptomatic)	40%	0.30
Lower respiratory symptoms, children (dummy variable)	40%	1
Consultations asthma (consultations / 1000 children)	40%	47.1
Consultations asthma (consultations / 1000 adults of working age)	40%	16.5
Consultations asthma (consultations / 1000 elderly)	40%	15.1
Consultations URS consultations / 1000 children)	40%	574
Consultations URS (consultations / 1000 adults of working age)	40%	180
Consultations URS (consultations / 1000 elderly)	40%	141
RADs, young + elderly (days/person)	40%	19

Table 2 (continued).

Response function: distribution – normal	Std deviation	Best estimate
Mortality (change in mortality risk / 10 µg.m^{-3} PM$_{10}$)	2%	6.00%
Mortality (years of life lost (YOLL)/µg.m^{-3})	11	65.1
Infant mortality (change in mortality risk / 10 µg.m^{-3} PM$_{10}$)	1.00%	4.00%
Chronic bronchitis, >27 years (%change in incidence/10 µg.m^{-3} PM$_{10}$)	3.70%	7.00%
Respiratory hospital admissions (%change in incidence/10 µg.m^{-3} PM$_{10}$)	0.26%	1.14%
Cardiac hospital admissions (%change in incidence/10 µg.m^{-3} PM$_{10}$)	0.15%	0.60%
Restricted activity days (%change in incidence/10 µg.m^{-3} PM$_{10}$)	0.03%	0.48%
Use of respiratory medication by adults (additional days of bronchodilator usage per 1000 symptomatic adults per 10 µg.m^{-3})	900	908
Use of respiratory medication by children (additional days of bronchodilator usage per 1000 children per 10 µg.m^{-3})	430	180
Lower respiratory symptoms (symptom days / symptomatic adult /10 µg.m^{-3} PM$_{10}$)	0.57	1.30
Lower respiratory symptoms (symptom days/child aged 5-14/10 µg.m^{-3} PM$_{10}$)	0.45	1.85
Consultations asthma (% increase in consultations amongst children/ 10 µg.m^{-3} PM$_{10}$)	1.25%	2.50%
Consultations asthma (% increase in consultations amongst working age adults / 10 µg.m^{-3} PM$_{10}$)	0.95%	3.10%
Consultations asthma (% increase in consultations amongst the elderly / 10 µg.m^{-3} PM$_{10}$)	2.30%	6.30%
Consultations URS (% increase in consultations amongst children / 10 µg.m^{-3} PM$_{10}$)	0.35%	0.70%
Consultations URS (% increase in consultations amongst the working age population / 10 µg.m^{-3} PM$_{10}$)	0.45%	1.80%
Consultations URS (% increase in consultations amongst the elderly/ 10 µg.m^{-3} PM$_{10}$)	0.80%	3.30%
RADs, young+elderly (%change in incidence/10 µg.m^{-3} PM$_{10}$)	0.03%	0.48%

Valuation (all units – €/case): distribution – normal	Standard error	Best estimate
Chronic mortality (VOLY, mean, €/life year) [1]	14,600	120,000
Chronic mortality (VOLY, median, €/life year) [1]	3,700	52,000
Chronic mortality (VSL, mean, €/death) [1]	235,000	2,000,000
Chronic mortality (VSL, median, €/death) [1]	74,000	980,000
Infant mortality (€/death) [1]	1,000,000	3,000,000
Chronic bronchitis, >27 years (€/case)	63,000	190,000
Respiratory hospital admissions (€/event)	670	2,000
Cardiac hospital admissions (€/event)	670	2,000
Restricted activity days, working age (€/day)	27	82
Lower respiratory symptoms, adults and children (€/day)	13	38
Consultations asthma, URS (€/event)	18	53
RADs, young, elderly (€/day)	23	69
Use of respiratory medication (€/day)	0.33	1

Notes: 1) To be revised

The distributions given in Table 1 and Table 2 can be brought together within @RISK across all effects to provide an overall estimate of the probability distribution around the best estimate of benefits for any scenario. This is illustrated for two of the earlier CAFE scenarios (the ‘low’ ambition Scenario A [Table 3 and Figure 2], and MTFR, a scenario that assesses the Maximum Theoretically Feasible Reduction in emissions according to the measures included in GAINS [Table 4 and Figure 3]) (all results taken from Holland et al, 2005b). The results shown in the Figures are expressed as net benefits – i.e. after subtraction of costs. The

Figures and Tables include not only assessment of statistical uncertainties, but also assessment of the effect of sensitivity to the way that mortality is valued. Whilst this sensitivity will continue to be explored in EC4MACS, some simplification appears possible by moving to only one case each for VOLY and VSL instead of two. The Tables include quantification of the probability that benefits will exceed costs. For scenario A this is very high (>99% in all cases) whilst for MTFR it is low (a maximum of 33%).

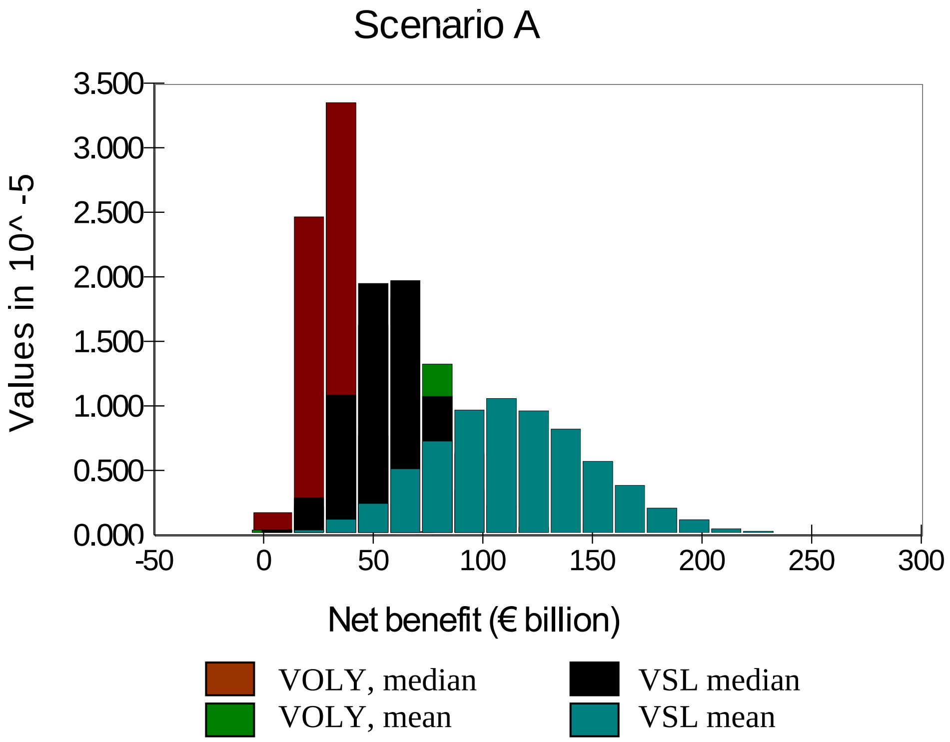

Figure 2. Probability distributions showing net benefit (benefit – cost) for proceeding from the baseline to Scenario A, with sensitivity to different approaches to mortality valuation also shown.

Table 3. Annual costs and benefits for the EU25 of proceeding from the baseline to Scenario A, and the probability that benefit will exceed cost.

	Cost (core estimate, € billion)	Benefit (core estimate, € billion)	Net benefit (core estimate, € billion)	Probability that benefit > cost
VOLY – median	5.9	37	31	>99%
VOLY – mean	5.9	70	64	>99%
VSL – median	5.9	64	58	>99%
VSL – mean	5.9	120	114	>99%

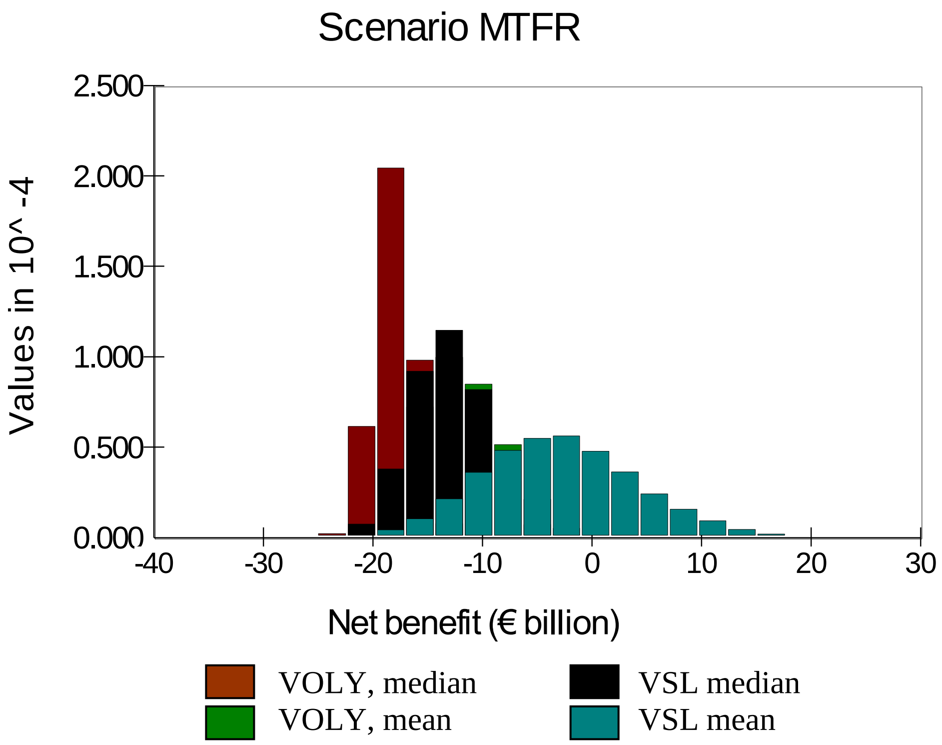

Figure 3. Probability distributions showing net benefit (benefit – cost) for proceeding from Scenario C to the MTFR scenario, with sensitivity to different approaches to mortality valuation also shown.

Table 4. Annual costs and benefits of proceeding from Scenario C to MTFR, and the probability that benefit will exceed cost.

	Cost (core estimate, € billion)	Benefit (core estimate, € billion)	Net benefit (core estimate, € billion)	Probability that benefit > cost
VOLY – median	25	6.9	-18	0%
VOLY – mean	25	13	-12	<1%
VSL – median	25	12	-13	<1%
VSL – mean	25	22	-2.9	33%

1.4. Sensitivities

From consideration of the data used to quantify impacts, the following possible areas for sensitivity analysis are apparent:

- Valuation of mortality in terms of lives impacted or life years lost, using the median or mean value of statistical life (VSL) or value of a life year (VOLY).
- Accounting for variation in the health risk associated with different types of particle.
- Use of a cut-point for the ozone-health analysis.
- Inter-annual variability in meteorology (in cases where this has not been accounted for explicitly in the modelling).
- Inclusion of some health endpoints which are supported by limited research.

The need to consider each sensitivity is scenario dependent: there is clearly no point in considering a sensitivity if there is no chance that it will affect the conclusions reached. To illustrate, the inclusion of additional health endpoints (final bullet point) is unnecessary if there is a high probability that benefits exceed costs already without them.

From a theoretical perspective it may not seem appropriate to treat uncertainty in cost estimates using sensitivity analysis. However, it was treated this way in CAFE because of a lack of information on the probability distribution for costs around the IIASA estimates. From the perspective of understanding the costs, specifically, this approach supplies no additional information. However, it is useful for comparing the robustness of the relationship between costs and benefits. The Monte Carlo analysis was run for the benefits assessment for a series of discrete cost estimates in the range of 50% to 120% of the GAINS forecast (see Figure 4, taking the example of Scenario C, considered 'high' ambition under CAFE). This example shows that if costs are significantly overestimated there is a high probability of achieving a net benefit irrespective of the approach taken to mortality valuation. So far relatively few cost-curve studies have so far attempted to generate a probability distribution (an exception being the work of Handley et al (2001) on the costs of abating non-agricultural ammonia emissions).

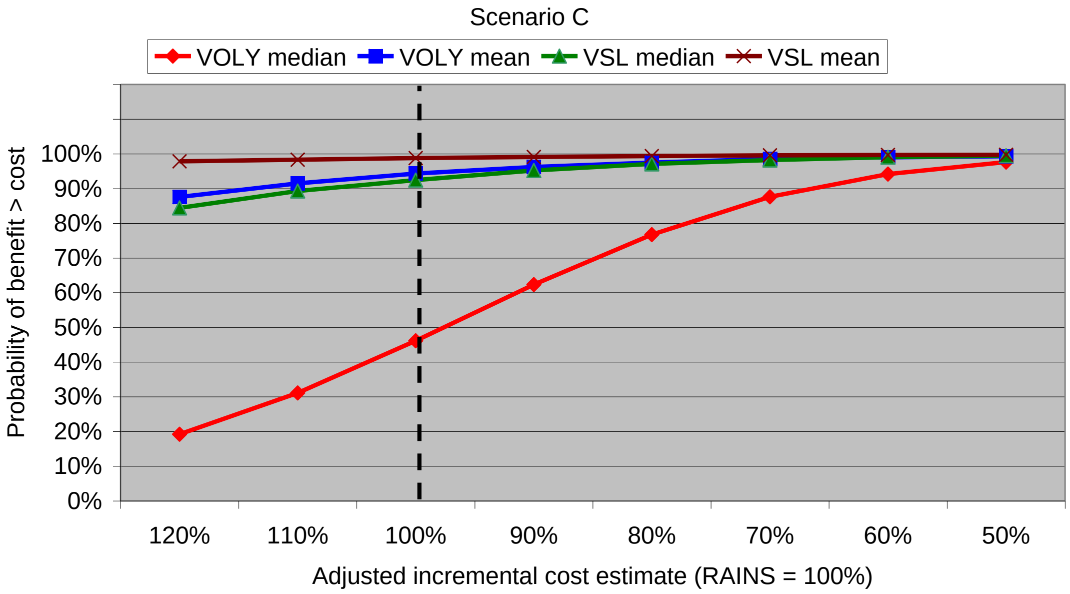

Figure 4. Sensitivity to uncertainty in incremental costs of pollution abatement of the probability of a net benefit in moving from Scenario B to Scenario C.

Two issues have not been considered here that some may have considered worth addressing:

- The use of a threshold for assessment of PM effects. This issue has been addressed in detail by WHO in their input to the CAFE process. In addition to the views expressed there, it is to be remembered that the EMEP and GAINS dispersion modelling excludes non-anthropogenic particles and secondary organic aerosols. On this basis the analysis already operates with an effective threshold of several µg.m^{-3}.
- The use of alternative factors for $PM_{2.5}$ to PM_{10} conversion for some of the morbidity functions[2]. We do not consider that these would have a major effect on the analysis,

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[2] The mortality function was derived from work that directly compared mortality rates with $PM_{2.5}$ exposure. Some of the morbidity functions, in contrast, were based on studies using PM_{10} as the exposure metric. Application in our modelling framework requires conversion to functions in terms of $PM_{2.5}$.

particularly because the dominant PM effect (mortality) is characterised directly against $PM_{2.5}$.

It would of course be possible to add in further sensitivity analysis. However, there has to be a clear focus in uncertainty assessment that it is intended to improve understanding of results and their robustness. The addition of further sensitivities may simply serve to confuse.

1.5. Biases

When comparing biases and their effects on the balance of costs and benefits it is necessary to consider not only the benefits assessment based around ALPHA2, but also the EMEP dispersion modelling and the GAINS integrated assessment modelling.

1.5.1 Biases in the EMEP model

With respect to the two main CAFE pollutants, $PM_{2.5}$ and ozone, the 2004 review of EMEP concluded that:

- *The model, in the form presented, underestimated observed PM_{10} and $PM_{2.5}$ due to an incomplete description of relevant processes and emissions. It was, however, able to calculate the regional component of the main anthropogenic PM fractions (sulphate, nitrate, ammonium, some primary components) with enough accuracy to assess the outcome of different control measures.*
- *The model shows an excellent level of performance for daily maximum ozone concentrations.*

These and other issues are considered in Table 5.

Table 5. Biases in the EMEP modelling. Ratings given in brackets are biases that are unlikely to have a significant effect on the outcome of the CAFE modelling.

Source of bias	Likely effect on benefit:cost ratio	Comment
Variability in meteorology from year to year	(+++/---)	The importance of this factor is dependent on how many years' data have been used for the analysis.
Underestimation of suspended particle concentrations, particularly through not accounting for secondary organic aerosols.	---	Overall, secondary organic aerosols contribute around 10% to total aerosol concentrations in the atmosphere over Europe (D. Simpson, personal communication). Part of this will be linked to anthropogenic emissions of VOCs and part to natural emissions.
Lack of specific account of urban concentrations of: • $PM_{2.5}$	0 (assuming CITYDELTA adjustment is correct)	Urban concentrations of PM are factored into the GAINS model using the results of the CITYDELTA Project. Ozone concentrations are generally depressed in urban areas as a result of high local NOx emissions.
• Ozone	++	

1.5.2 Biases in the GAINS modelling

The peer review of the RAINS model carried out as part of the CAFE Process provides detailed consideration of both statistical uncertainties and biases (Swedish Environmental

Research Institute, 2004). This has been used as the basis for the information presented in Table 6. Some of the biases identified in the review are not discussed in the table as they are not considered relevant here. For example, the omission of impacts of particles and ozone on morbidity is addressed through the wider quantification of benefits in ALPHA2[3]. Nonetheless, the modelling is clearly subject to a significant number of possible biases.

Table 6. Biases in the GAINS modelling. Ratings given in brackets are biases that are unlikely to have a significant effect on the outcome of the EC4MACS modelling.

Source of bias	**Likely effect on benefit:cost ratio**	**Comment**
Emission starting point bias for NH_3, NOx, $PM_{2.5}$, SO_2 and VOCs	---/+++	Negative bias arises because of uncertainty in emission inventories and the potential for switching to cleaner fuels or production systems by the baseline year for reasons unrelated to air quality regulation. Positive bias arises through uncertainty in emission inventories and possible legislative change in other areas that could cause emissions to increase.
Omission of some existing and future technical abatement measures from the GAINS model:		Biases to overestimation of costs and underestimation of the maximum feasible reduction.
• Omission of low cost measures	---	
• Omission of mid cost measures	---	
• Omission of high cost measures	--	
Lack of account of future technical developments for existing measures:	---	Leads to an assumption of lower cost-effectiveness of existing technologies than will be achieved through further development
Omission of non-technical measures that would lead to behavioural change	---	Non-technical measures provide additional scope for emission reduction
Lack of differentiation of particles by species for health impact assessment	---/+++	Likely tendency would be to reduce the cost-effectiveness of abatement packages by inadequate focus on the most harmful particles.
Modelling urban exposure:		Application of the results of the CITYDELTA study enables GAINS to account for elevated background concentrations of $PM_{2.5}$ in urban areas. However, the model does not include adjustment of data for urban background ozone, or assessment of hot-spot $PM_{2.5}$ or hot-spot ozone. The lack of account of hot-spot conditions is considered not so important for health effect quantification as models are calibrated against background concentrations. Failure to correct for urban background ozone is of limited importance to this analysis because of the small proportion of benefits attributed to ozone and health.
• Urban background $PM_{2.5}$	Accounted for	
• Hot spot $PM_{2.5}$	(---)	
• Urban background ozone	++	
• Hot spot ozone	(++)	
Underestimation of deposition of S and N to sensitive ecosystems	--	Given that there is no economic quantification of impacts to ecosystems these impacts do not affect the reported cost-benefit relationship directly, but may influence concern over unquantified ecological impacts where stakeholders use the extended CBA to consider how unquantified effects would alter their attitude to reported cost-benefit relationships.
Overestimation of the role of N in critical loads for acidification	++	
Underestimation of ecosystem sensitivity to eutrophication	--	

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[3] It is, in any case, not necessary to include morbidity impacts in GAINS. Environmental impacts are used by GAINS as indicators to permit optimisation against pre-defined targets. So long as the impacts selected for this process reflect changes in related effects, the use of a single impact to act as indicator is sufficient.

Table 6 (continued)

Source of bias	**Likely effect on benefit:cost ratio**	**Comment**
Omission of health impacts on people aged under 30 years	--	When carried through to the CBA of possibly limited importance given the quantification of morbidity effects for all age groups and limited mortality amongst the under 30s in Europe.
Use of year 2000 population data and death rates for quantification of ozone effects on mortality	-	Reduces quantified impacts for future years given demographic changes that lead to an aging population in the EU27. Impact limited because of the relatively low impact of ozone compared to $PM_{2.5}$.
Use of 'cut-point' for quantification of ozone impacts	-	Likely to be of limited importance.

As in any case where a large number of uncertainties are identified, there are likely to be some areas where biases cancel each other out to some degree. An obvious example from Table 6 concerns the effects of N deposition to ecosystems, where the peer review concluded that impacts of N on acidification and eutrophication were likely to be (respectively) overstated and understated.

There is a clear dominance in Table 6 of factors that bias costs up and benefits down. Overall this seems likely to lead to a bias to non-action on air pollution generally. Three questions need to be answered:

1. How large is the bias?
2. Does it apply equally to all pollutants?
3. Does it apply equally to all regions?

Quantification of the bias is clearly very difficult – if it were easy it could be incorporated into the modelling. Unfortunately there have been very few attempts to compare ex-ante estimates of control costs with actual costs. Those analyses that have done this have shown a strong tendency for ex-ante estimates to exaggerate costs. However, such studies are purely retrospective and cannot be used as a reliable guide to the quality of future results without further consideration. Further to this, biases will vary between pollutants, not least because of variability in the quality of emission inventories. SO_2 emissions, for example, are known with a far better level of confidence than PM emissions. Biases will also vary between regions, reflecting differences in the availability of alternative fuels, quality of national data and so on.

Direct analysis of the effect of these biases is not possible given that they are unquantified. However, the sensitivity analysis below assesses the probability that benefits would exceed costs factoring in variation in costs in the range [GAINS estimate +20%] to [GAINS estimate - 50%]. The choice of this interval is skewed downwards (implying that GAINS is more likely to exaggerate costs than underestimate them) because of the dominance in Table 6 of factors leading to cost overestimation and the results of analysis comparing ex-ante and ex-post estimates of abatement costs (Watkiss et al, 2005 and others).

1.5.3 Biases in the benefits analysis

In common with the cost-effectiveness modelling undertaken using the GAINS model, the benefits assessment is prone to a significant number of biases. These are listed in Table 7. Readers who consider that some potential biases have been omitted from this table should consult other sections of the report to see if they are dealt with elsewhere (e.g. alternative positions on mortality valuation and aspects covered in Section 1.3 and Table 5 and Table 6 dealing with the EMEP and GAINS models respectively). Again, views on the direction and likely significance of biases are the authors' own. The omission of impacts from the analysis is dealt with below.

The failure to differentiate particles by species for the health impact assessment seems to be the most important *potential* cause of overestimation of benefits of individual measures, though it could bias results either way depending on which types of particle are targeted under a specific strategy. Other biases that could lead to overestimation seem less important, reflecting more uncertainty in data extrapolation than anything fundamental.

Table 7. Biases in the benefits analysis

Source of bias	**Likely effect on benefit:cost ratio**	**Comment**
Unquantified impacts: • Ecosystem acidification • Ecosystem eutrophication • Impacts of ozone on ecosystems • Damage to cultural heritage • Chronic health effects of exposure to ozone • Effects of coarse particles (size range $PM_{2.5\text{ to }10}$) on health • Chronic effects of PM exposure on cardio-vascular disease • Health effects of secondary organic aerosols (SOAs)	 --- --- --- -- ---? - ---? --	Further information on the likely importance of omissions from the benefits analysis is discussed elsewhere in this report. In some cases importance will vary strongly between abatement options, e.g.; • An option that does not control VOCs will have very little effect on exposure to SOAs. • Abatement options controlling coarse particles could have significant additional benefits for situations where they comprise a major fraction of total particle mass.
Lack of differentiation of particles by species for health impact assessment	+++/---	Effect on quantified benefits will depend on the level of control for each type of particle.
Use of health functions from the US and western Europe	++/--	Further research is needed to test whether there are systematic differences between regions.
Quantification of deaths from chronic exposure to PM using techniques not based on life tables (only relevant where VSL is used for mortality valuation).	++	Some potential for double counting of deaths, depending on the time horizon used for the analysis.
Use of uniform incidence data for the whole of Europe for most morbidity effects	++/--	Again, further research is needed to test whether there are systematic differences between regions. The identification of consistent sets of incidence data is recognised as a problem for transferability of health response functions generally.
Use of AOT40 based relationships to quantify impacts of ozone on crops	+?	Likely to cause overestimation of impacts amongst un-irrigated crops in drier parts of Europe. Overall effect unclear.

Another area where bias is likely, though it is not clear in which direction that bias would go, concerns the morbidity assessment in the benefits analysis. Specifically it relates to two issues, the application of health functions from the US and western Europe across the whole of Europe, and the use of uniform incidence data. Both areas are worthy of further research. Given variability across Europe any biases that are present may tend to cancel each other out.

Despite the best efforts of the teams involved, the results of the various models are subject to a number of unquantified biases. In general terms, the most important appear to be:

- **EMEP modelling**
  - Omission of secondary organic aerosols
- **GAINS modelling**
  - Emission starting point bias
  - Omission of some abatement techniques
  - Lack of account of future technical developments
  - Lack of differentiation of particle species by effect
- **Benefits modelling**
  - Omission of impacts on ecosystems, cultural heritage, etc.
  - Lack of differentiation of particle species by effect

Several of the biases identified will have a more or less equal effect over the whole of Europe. However, the effect of others will vary from country to country. Despite the inter-linkages present between pollutants and effects, the importance of biases will also vary with the objectives defined for any scenario – a scenario focused on PM control may be little affected by sensitivities in the ozone analysis. It is thus difficult to define general rules on the reliability of the analysis for different stakeholders.

However, this does not mean that it is impossible to do anything about the biases that are present. The listing of biases in the preceding tables makes it possible for any scenario to identify which seem likely to have an important impact on the benefit:cost ratio and which are unlikely to be important. Ratings for each bias should be revised in line with the factors that influence results for any scenario. The overall impression of biases can then be considered alongside other information, for example, the probability that benefits will exceed costs for any scenario, assessed using the methods defined in 1.3. Given the qualitative nature of the result it is unlikely to cause a major change in policy, but it may strengthen or weaken the rationale for a specific position.

1.6. Accounting for unquantified effects

In CAFE-CBA the concept of an ‘extended CBA’ was proposed to provide further information for policy makers about the impacts that could not be quantified. It was suggested that datasheets be developed to contain the following types of information:

- Description of the impact, including components of ‘total economic value’
- Discussion of related impacts
- Confidence in attribution of impact to a specific pollutant
- Information on the distribution of impact across Europe (is it a ‘European issue’ or something to be considered at a more local level?)
- Information on importance in economic or other terms, where available (e.g. from results of willingness to pay case studies, past estimates of expenditure to deal with specific problems, etc.)

Some preliminary work was done on these datasheets, but given apparently limited interest in them the idea was put on hold. Consideration was also given to the use of a formal multicriteria assessment (MCA) framework to bring in the unquantified effects. However, it was considered unlikely that agreement would be reached on the various parameters given the diversity of stakeholders active in CAFE, so that idea was also dropped. Holland et al did, however, provide their own assessment (Table 8) of the likely significance of each unquantified effect, using a three point scale:

★★★	Impacts likely to be significant at the European level
★★	Impacts that may be significant at the European level
★	Impacts unlikely to be important at the European level, but of local significance
No stars	Negligible

The intention in providing information in this way is to prompt stakeholders to consider whether the impacts that have not been quantified are likely to be important enough to change the balance of costs and benefits. It is not intended that anyone should add together the star ratings given to the various impacts – they are simply intended as ‘flags’ to distinguish what is probably important from what is probably not. Stakeholders are of course free to come to their own conclusions on the relative importance of the different impacts considered in this process. Decision makers may like to consider these effects in different ways, depending on the result of the quantified cost-benefit comparison:

- In situations where costs exceed benefits:
    - Are unquantified effects likely to be sufficiently important that they would cause benefits to increase to a point where they exceed costs?
- In situations where benefits exceed costs:
    - Are unquantified effects sufficiently important that they would give much greater confidence that benefits are larger than costs?
    - Are unquantified effects large enough to have a significant impact on the ratio of benefits to costs, increasing the importance of dealing with air pollution over other problems?

Another approach that can be used is to ask how large the unquantified benefits must be for total benefits to exceed costs, or for the probability that benefits to exceed costs to be greater than some qualifying percentage. If the surplus of cost over benefit is relatively small, it may be concluded that the unquantified effects are indeed large enough to bridge the gap. If the difference is large, however, it may be concluded that they are not.

Table 8. Position on ratings for the extended CBA proposed in Holland et al (2005a). Effects considered likely to be negligible are omitted from this table.

Effect	Preliminary rating
Health	
Chronic effects of $PM_{2.5}$ on cardio-vascular disease	★★★
Ozone: chronic effects on mortality and morbidity	★★
SO_2: chronic effects on morbidity	★
Effects of secondary organic aerosols	★★
Direct effects of VOCs	★
Social impacts of air pollution on health	★★
Altruistic effects	★★
Materials	
Effects on cultural assets	★★
Crops	
Indirect air pollution effects on livestock	★
Visible injury following ozone exposure	★
Effects of air pollution on the quality of crops, irrespective of issues concerning yield and visible injury	★★
Interactions between pollutants, with pests and pathogens, climate...	★★
Forests	
Effects of O_3, acidification and eutrophication	★★★
Freshwaters	
Acidification and loss of invertebrates, fish, etc.	★★★
Other ecosystems	
Effects of O_3, acidification and eutrophication on biodiversity	★★★
Visibility	
Change in amenity	★
Groundwater quality and supply of drinking water	
Effects of acidification	★

1.7. Discussion

If the costs and benefits of air pollution control were known with absolute confidence there would be no problem in comparing the two. However, 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 with which to describe them. Further to this, 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) whilst some simply relate to a lack of knowledge. It is clear from this that the development of a fully consistent approach to description of uncertainty across the EC4MACS analysis is not straightforward.

The extent to which uncertainty needs to be considered in any situation 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.

Consideration of uncertainty in comparison of costs and benefits cannot, therefore, be an automatic process. Awareness needs to be raised of the component uncertainties of each part of the analysis. This has been addressed in this report. The most important of the component uncertainties should be highlighted and quantified to the extent possible. Again, this is done here. Consideration also needs to be given to how satisfactory the assessment of uncertainty is. We believe that this report lays the ground for a good quality assessment of uncertainty, though this question needs to be asked against analysis of specific scenarios.

This report has identified three main strands for assessment of uncertainty, these being statistical analysis, sensitivity analysis and assessment of biases, the latter being largely associated with gaps in knowledge. Some of these 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.

Guidance is clearly needed on ways in which the analysis defined here can be brought together to form a coherent approach to uncertainty assessment. For most scenarios the following scheme will be appropriate:

Step 1: Quantify costs and emissions.
Step 2: Quantify benefits. As part of the standard assessment, provide results based on VOLY and VSL estimates. Identify meteorological year(s) used. Where only one year has been used, provide material to demonstrate the bias that this has on results. Investigate other key sensitivities as appropriate.
Step 3: Make initial comparison of costs and benefits. Assess under what sets of assumptions results suggest that benefits would exceed costs and vice-versa.
Step 4: Perform statistical analysis around best estimates of benefits, using the methods defined in 1.3. Calculate the probability that quantified benefits will exceed costs.
Step 5: Consider which of the biases listed above are likely to influence the balance of costs and benefits significantly. Then consider the overall effect of these biases – when taken together are they likely to lead to over- or under- estimation of the benefit:cost ratio? Then consider whether the magnitude of bias is likely to be sufficient to alter the benefit:cost relationship significantly.
Step 6: If necessary, carry out a stepwise sensitivity analysis on costs and/or benefits, drawing on the conclusions of the review of biases. Assess the probability that quantified benefits will exceed costs at each point.

It is clear from this report that there are a large number of uncertainties that affect the analysis of scenarios being considered in the EC4MACS Project. It is the view of the authors that this is not a barrier to effective and efficient decision making, primarily because:

- We know a lot about the uncertainties that are present.
- We have a range of tools for assessment of these uncertainties.
- We can use these tools to see how uncertainty could influence the reported relationship between costs and benefits.

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 et al (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 NOx and SO_2 would potentially increase the social cost by at most 20% and in many cases much less. The costs analysis used for the paper was based on RAINS cost curves, and so is particularly relevant to EC4MACS. Much of the reason for this insensitivity rests in the non-linear shape of the marginal abatement cost curve.

1.8. References

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