



**METHODOLOGIES FOR INTEGRATING IMPACT
ASSESSMENT IN THE FIELD OF SUSTAINABLE
DEVELOPMENT**

Research Project, 5th Framework Programme

Contract N° EVG1 –CT-2002-00082

Partners: ICCS.NTUA, IIASA, ERASME, UOXF, ZEW, VITO

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–FINAL TECHNICAL REPORT–

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PART 1

–PUBLISHABLE FINAL REPORT–

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Athens, March 2006

-EXECUTIVE PUBLISHABLE SUMMARY-

Executive Publishable Summary

Objectives

Sustainable Development (SD) broadly defined as the capacity to meet the welfare needs of present generations without compromising those of future ones, is a concept that for a long time has been accepted implicitly or explicitly as an important ingredient in formulating long-term strategies. In recent years, alongside the priority issue of climate change, a great number of sustainability concerns has emerged (e.g. health, natural resources, bio-diversity, transport congestion, social exclusion, regional imbalances with their attendant political risks etc.) posing particular challenges to analysts, especially those aiming at providing useful and quantitative input to the formulation of strategies aimed at sustainability. Key among these challenges are: the great diversity of these issues, problems of measurability, the impossibility of developing a single detailed tool that could cover a useful range of sustainability objectives and the instruments for influencing them and the substantial uncertainties surrounding the impacts and costs of policy instrument applications. MINIMA-SUD addresses these difficulties by establishing and demonstrating a methodology which leads to meaningful quantitative policy integration in this difficult field.

Description of Work

The methodology consists of: 1) defining measurable sustainability indices covering widely disparate sustainable development concerns 2) identifying common instruments that can be used to promote sustainability in different domains, 3) modelling the complete path from instrument application to impact on the sustainability indicator using large deterministic models, 4) devising direct and indirect ways of measuring costs of implementation of policies, 5) quantifying the risks attached to the efficacy of the application of instruments using stochastic models, 6) building a decision support tool capable of exploring policy priorities in a quest of minimising risks and maximising the economic, environmental, energy, health and physical environment benefits derived from their implementation, and 7) finally carrying out policy exploration and devising systematic methods of exploring options in a multi-objective stochastic environment.

Considerable effort has been made for to the development, radical re-specification and extension of large-scale models to simulate the analytical chain from the application of policy instruments (combined or in isolation) to impact on sustainability indicators. In this context, the 'bottom-up' energy system model ERIS was modified for modelling SD instruments and linked to a stylised climate model. The GEM-E3 World multi-regional and multi-sectoral large scale general equilibrium model has been applied to devise direct and indirect ways of measuring costs of implementing sustainable development policies. The GEM-E3 model was also extended to incorporate a poverty and inequalities module. To assess the environmental impacts and damages to human health, buildings, agriculture and eco-systems arising from different airborne pollutants the EcoSense Point Source model has been applied for the EU-15 region. To fully respond to the requirements of the MINIMA-SUD project, a transport simulation and policy assessment tool has been developed, covering the whole transport sector (road and rail transport, inland shipping and aviation) in the EU-15 region. It addresses the major sustainability issues associated with the transport sector (emissions of air pollutants and greenhouse gases, energy intensity, congestion, road accidents and noise).

Policy integration is carried out in an uncertain environment and therefore a considerable amount of effort has been devoted to assess the risks associated with the whole chain from policy instruments to impact on specific objectives. This involved the development of a stochastic model which contains reduced form stochastic versions of the path from instrument to objective as modelled in the large scale, deterministic analytical tools. To fulfil the requirements of providing the stochastic dimension to the economic analysis,

a more aggregate econometrically estimated stochastic version of the GEM-E3 model has also been developed. This model is unique of its kind in the Computable General Equilibrium family.

A series of policy shocks were subsequently introduced on the instruments using the large models and the stochastic model to obtain the impacts as required for the policy integration tool (TIPA). TIPA takes the form of an optimisation tool where the probability that an objective exceeds a given threshold is maximised subject to the condition that the probability that the other objectives exceed given thresholds is greater than a certain level (it is also subject to a notional 'budget' constraining the policy space). The tool has been used for integrated policy exploration using multi-criteria methods to establish pay-offs between different objectives and obtain a number of compromise solutions (in the form of alternative policy mixes). Such solutions correspond to alternative priorities on given objectives while ensuring that a satisfactory impact is obtained on the other and often conflicting target indicators. The policy exploration focused on the following instruments: R&D for renewables, nuclear and vehicles, internalization of external costs, public transport subsidies, carbon taxes, oil tax increases for transport and road infrastructure expenditures and combinations of these. The objectives addressed were: global temperature, energy security (oil), mortality and morbidity due to air pollution (congestive heart failure, respiratory hospital admissions, asthma, and days of restricted activity) road accidents, traffic congestion and ecosystem damage. The analysis indicates that diverse, robust policy mixes include increases in R&D expenditures, road transport taxation and public transport subsidies. Public budget deficits and energy cost increases may limit the levels of ambition.

Exploitation Plans

The methodology developed within the MINIMA-SUD project has wide potential applications in Sustainable Development strategy elaboration. The quantified information on sustainability indicators, policy instruments and their costs of their application can form the basis and the framework for further studies. The TIPA Policy Integration tool has numerous applications in a great variety of energy/transport/environment/health multi-criteria decision analysis in a stochastic context. The MINIMA-SUD project has delivered advanced versions of all participating models incorporating detailed analytical chains from a variety of policy instruments to diverse sustainable development targets making them much more useful for the analysis of strategies. The stochastic models are unique of their kind and will be used for quantitative risk analysis.

– PUBLISHABLE SYNTHESIS REPORT –

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Objectives and Strategic Aspects

Sustainable development, broadly recognised as the capacity to meet the needs for welfare of present generations without compromising those of future ones, is a concept that for a long time has been accepted implicitly or explicitly as an important ingredient in formulating long-term strategies. Climate change concerns have proved a catalyst in bringing sustainability to the fore. In recent years however, a great number of sustainability concerns has emerged (e.g. health, natural resources, bio-diversity, generalised transport congestion, social exclusion, regional imbalances with their attendant political risks etc.) posing some particular challenges to analysts, especially those aiming at providing useful and quantitative input to the formulation of strategies aimed at sustainability. Key among these challenges are: the great diversity of sustainability issues, problems of measurability, the impossibility of developing a single detailed tool that could cover a useful range of sustainability objectives and the instruments for influencing them but also the substantial uncertainties surrounding the impacts and costs of policy instrument applications.

Scientific / Technological Objectives

The overarching objective of MINIMA-SUD is to demonstrate a methodology opening the way to policy integration in the area of sustainable development. In order to address this, MINIMA-SUD has engaged in a series of ambitious scientific objectives which constitute a clear advancement in the field of sustainable development policy analysis and modelling. These can be summarised as follows:

- Define and concretise measurable sustainability indices covering widely disparate sustainable development concerns and introduce them in a series of different models.
- Identify common instruments that can be used to promote sustainability in different domains and introduce them in different models in a homogeneous fashion so as to ensure comparability of results.
- Model the complete path from instrument application to impact on the sustainability indicator using large models in order to maintain consistency with other sustainability impacts via the consistency provided by the detailed treatment of a large number of key factors incorporated in these models.
- Devise direct and indirect ways of measuring costs of implementation of sustainable development policies using large scale general and partial equilibrium models.
- Quantify the risks attached to the efficacy of the application of instruments using purpose built stochastic models.
- Build a decision support tool capable of exploring policy priorities in a quest of minimising risks, hedging against uncertainty and maximising the economic, environmental, energy, health and physical environment benefits derived from their implementation.
- Integrate into the decision support tool the results of large-scale models through reduced-form relationships that approximately represent the reaction of the models regarding the returns and other impacts resulting from sustainability promoting policies.
- Carry out proxy policy exploration and devise systematic methods of exploring options in a multi-objective stochastic environment as well as obtaining compromise solutions. Such exploration constitutes novel integrated policy assessment and concerns options under real-world conditions and uncertainties, in order to arrive at realistic policy mixes of regulatory and economic instruments to be applied in the pursuit of sustainability objectives.
- Co-ordinate the work from, and promote the synergies between, different economic, sectoral and physical environment models that differ in their methodology and their regional coverage.

Socio-economic objectives and strategic aspects

The MINIMA-SUD project addresses major policy concerns of the European Union, including some of the key priorities identified in recent EU Summit Meetings, namely the issue of strategies for sustainable development, the debate on which has grown to encompass most of the hitherto key issues

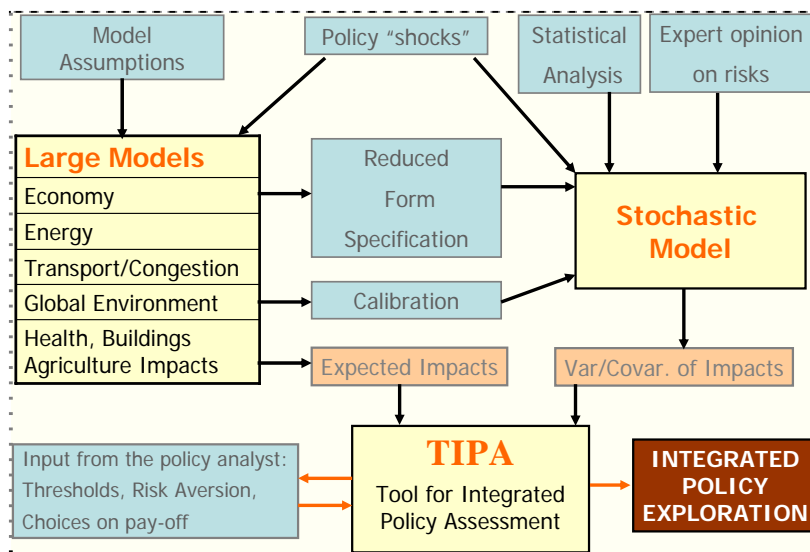
such as global warming, the search for an environmentally compatible and competitive strategy for industry and the priority setting for technology-oriented policy in order to encompass a wide range of concerns which thus far have tended to be treated in isolation. The project provides European policy-makers with a rich set of quantitative and analytical information that can help shape strategic choices. The new insights in this set of information come from the consideration of specific instruments as policy means that can help reduce costs and maximise benefits in the process of adapting the European economic system to the actual needs of sustainable development in Europe, its immediate vicinity and the World as a whole.

The main social objective of the project is to provide input to the policy debate in a way as to contribute to the limitation of damages arising from lack of sustainability, with benefits at the level of the Union but also for other world regions. The methodology used also aims at identifying the ways of limiting the economic costs of the corresponding mitigation strategies and thus their social impacts.

Scientific and Technical Description of the Results

MINIMA-SUD is a very tightly designed project leading to very specific outcomes in the form of integrated policy exploration using the extended Tool for Integrated Policy Assessment (TIPA). The analysis draws from a very diversified set of areas of expertise, where work has been performed in relative isolation due to the specialised knowledge and tools required to analyse the different sustainable development objectives. Output from these sections contributes individually to the overall integration which is performed in the final stage of the project. The following scheme presents an overview of the methodology applied in the MINIMA-SUD project:

MINIMA-SUD Project Overview



Early in the project the need to define and concretise some measurable sustainability indices covering widely disparate sustainable development concerns was identified. A wide, but naturally non-exhaustive set of measurable indicators has been selected, covering the domains of climate change (going beyond emissions to include physical impacts), health concerns (notably those arising from environmental degradation associated with energy production and use), pressure on natural resources, transport congestion, accidents, noise, security of energy supply, measures of social exclusion and regional imbalances as well as more traditional economic performance indicators. Policy instruments affecting differentially these indicators were identified next, covering taxation, subsidies, specific investments, regulatory standards and R&D actions in the broad area of energy and the environment.

Deterministic large-scale models were developed or radically re-specified and extended to enable them to simulate the analytical chain from the application of policy instruments (combined or in isolation) to impact on the sustainability indicator. A considerable amount of effort has been devoted to assessing the risks associated with the whole chain from policy instrument to impact on the objective. This effort involved the development of a stochastic model which contains reduced form stochastic versions of the path from instrument to objective as modelled in the large scale deterministic analytical tools. After

some homogenisation of assumptions a consistent baseline has been constructed for all objectives and key influences on them and policy scenarios promoting Sustainable Development in different thematic areas have been developed. A series of shocks were subsequently introduced on the instruments using the large models and the stochastic module in order to obtain the impacts as required for the policy integration tool. The stochastic model provides the probability distributions of these impacts (essentially the variance, co-variance elements for these impacts). Results from these exercises are used in building TIPA, the decision support tool used to perform integrated policy exploration.

The challenges faced to ensure the credibility of the whole process have been considerable throughout the project. The research agenda constituted from the very beginning a clear advancement in the domain of energy, transport, economy, environment and sustainable development analysis and modelling. The following sections summararily report on all the above mentioned tasks undertaken within the MINIMA-SUD project.

1. Review on Sustainable Development Objectives and Policies

Sustainable Development (SD) as a long-term goal of policy making has its obvious and undisputed attractiveness. At the same time, analysis has still a long way to make this concept operational. This section examines the state of the art in the field of measurable sustainable development indicators and provides, after a careful review of existing literature and taking into account the needs of policy makers and analytical models, a set of some important policy instruments that affect sustainable development. The integrated policy analysis that is one of the main results of this project focuses on the evaluation of the impacts in terms of the selected sustainability objectives and causal relationships defined within the present section of work.

For the identification of the appropriate indicators, important policy documents related to sustainable development and SD indicators have been reviewed. Particular attention was given to the United Nations Commission on Sustainable Development (CSD) work program on *Indicators of Sustainable Development* which resulted in a list of 58 indicators (down from 134 initially) covering social, environmental, economic and institutional aspects of SD (United Nations, 2001). Moreover, the study of the Division for Sustainable Development of the United Nations (co-financed by the European Statistics Office – EUROSTAT) on the linkages and aggregation of SD indicators was taken into account, along with the OECD core set of environmental indicators and the “green national accounting” activities.

The literature survey also covered an area of highly aggregated indicators for sustainable development, with emphasis on nine initiatives covered in the “Report on the Aggregation of Indicators of Sustainable Development”, submitted by UNDSO to the 9th session of the CSD (United Nations, 2001).

The final selection of the relevant indicators retained in the present analysis was principally based on the Communication from the Commission: “A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development” which constituted a proposal to the Göteborg European Council and is largely reflected in the Presidency Conclusions (Göteborg, 15 and 16 June 2001). Four relevant EU/CEC policy documents were also reviewed:

1. Reports from the Commission to the Spring Council in Barcelona 2002 (CEC, 2002) and the Spring Council in Brussels (CEC, 2003);
2. Integrating Environment and Sustainable Development in Energy and Transport Policies (CEC, 2001);
3. Analysis of the ‘open list’ of environment related headline indicators (CEC, 2002)
4. The EU funded GREENSENSE project (Markandya *et al.*, 2002)

Initially, there has been a maximalist tendency in the selection of measurable objectives (wide number, difficult to measure and/or model indicators considered). As modelling progressed and especially preliminary exercises of applying policy shocks were performed, the list of the SD objectives to be retained had to be re-examined. Given data availability and model’s capabilities, the list of SD indicators quantitatively examined within MINIMA-SUD has been defined as follows:

1. **Costs of Energy**
 - a. *Energy cost reduction to European final consumer:*
 - b. *Electricity cost reduction to European final consumer:*
2. **Climate Change**
 - a. *Cumulative world CO₂ emissions*
 - b. *Temperature change from 2000 levels in the post 2050 commitment period.*
3. **Security of Supply**
 - a. *Oil Resources to production ratio*
 - b. *Gas Resources to production ratio*
4. **Transport**
 - a. *Road Congestion*
 - b. *Road Safety*
 - c. *Noise Emissions from Transport Activity*
5. **Human Health**
 - a. *Mortality Change due to Air Pollution*
 - b. *Morbidity Change due to Air Pollution (congestive heart failure, restricted activity days, cases of bronchodilator usage, cases of respiratory hospital admissions)*
6. **Environment**
 - a. *Monetary Damage to Crops*
 - b. *Monetary Damage to Buildings/ Materials*
 - c. *Damage to Ecosystems due to Acidification and Eutrophication*

A set of policy instruments that could be used to promote sustainability in these different domains had to be identified next. The selection of the relevant instruments to be retained was guided by actual policy relevance and by the feasibility of modeling the relevant impact of the instrument using the modelling tools participating in the present project. Ultimately, a relatively limited selection was made, since a very wide domain would involve an impossible diversity of tools. All instruments selected are quantifiable and relate to fiscal measures (taxation, subsidies), specific investments, regulatory standards and R&D or demonstration actions in the broad area of energy and the environment. The restricted instruments field was chosen as it was more likely to produce more intensive interaction between instruments and a wider range of diverse sustainability indicators (the same instrument having an impact on many or all the indicators selected, allowing the identification of possible synergies and conflicts). The common set of instruments also had to be introduced in the different models in a homogenous fashion so as to ensure comparability of results.

The final set of policy instruments retained for the integrated policy exploration exercises performed in MINIMA-SUD follows:

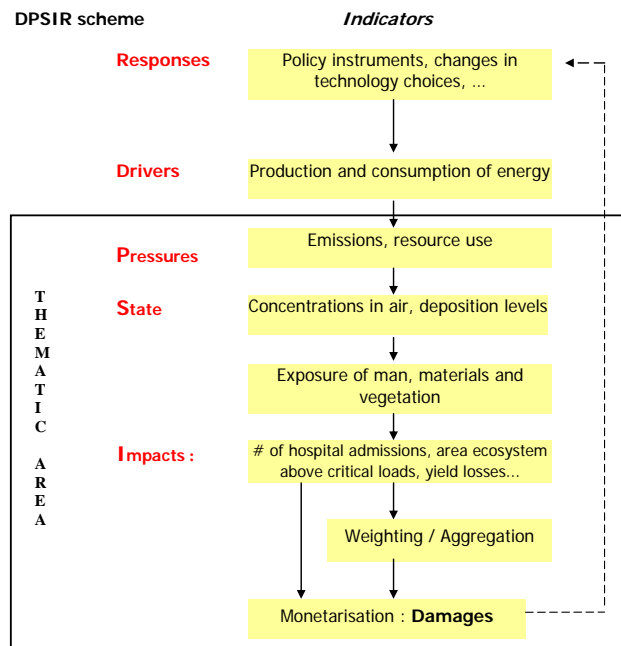
- a. *Increase GERD to 3% of GDP*
- b. *Internalise non-climate externalities*
- c. *Carbon Taxes*
- d. *Taxation of oil for transport*
- e. *Subsidies for public transport*
- f. *Investment on transport infrastructure*

However, additional instruments and sustainable development objectives are also elaborated within each thematic work package and are further analysed in the respective sections of this report. Their inclusion merely depended on the specialization of the large models employed in each thematic area, on the scope of the analysis performed using them and on their relevance with EU sustainability targets.

2. Impacts on Human Health, Buildings, Agriculture and Eco-Systems by Air Pollution

This section provides an assessment of the environmental impacts and damages to human health, buildings, agriculture and ecosystems arising from different airborne pollutants. The assessment of impacts has followed the Impact Pathway Approach as developed within the EU funded ExternE Project series. The Impact Pathway assessment is a bottom-up approach in which environmental benefits and costs are estimated by following the pathway from source emissions (via quality changes of air) to physical impacts on various receptors and, where possible, to the monetary valuation of the resulting welfare losses.

An illustration of the main steps of the Impact Pathway methodology (or DPSIR Demand – Pressure – State – Impact – Response scheme) is shown in the following diagram:



Under the DPSIR scheme (slightly modified for the present project’s research needs) the analysis starts from the “Response” stage (corresponding to the application of “shocks” on the selected policy instruments), followed by changes to “Drivers” (changes in production and consumption of energy) which in turn affect “Pressure” (changes in pollutants emissions). The present thematic area focuses on the chain from “Pressure” down to “Impacts”, i.e. on the causal relationship from the release of the pollutant to its physical or monetary impacts. The output from this (expressed in terms of impact or damage per tonne of pollutant emitted) can then be linked to the impact from the application of the policy instrument shocks on the emissions of pollutants (in the transport or other economic sectors, derived from other thematic areas of MINIMA-SUD) to obtain the overall effect of the shocks on policy instruments to impacts on indicators of interest in this section.

2.1. Sustainable Development Objectives in the Thematic Area

Seven SD indicators have been retained for the present analysis:

- a. *Mortality change due to air pollution* (years / tonne emitted)
- b. *Morbidity changes due to air pollution* (cases / tonne emitted)
- c. *Monetary damage to crops* (€/ tonne emitted)
- d. *Monetary damage to materials* (€/ tonne emitted)
- e. *Damage to ecosystems due to acidification and eutrophication* (km² exceeding critical loads / tonne emitted)

- f. *Change in total external costs due to regional air pollution* (€/ tonne emitted)
- g. *Urban air quality – Population exposure to PM_{2.5}* (Number of persons over threshold / tonne emitted)

The first six indicators are related to impacts and damages on regional level, defining ‘regional’ as the EU15 area. The final indicator is related to impacts and damages on local level¹. Impacts on human health and ecosystems (indicators *a*, *b* and *e*) are expressed in physical terms while impacts on agricultural yields, materials and total external costs (indicator *c*, *d* and *f*) are expressed in monetary terms.

2.2. Methodology

2.2.1. The EcoSense Point Source Model

For the modelling of the exposure-response chain, the EcoSense integrated impact assessment model developed within ExternE has been applied. EcoSense models the causal relationships from release of pollutants through their interactions with the environment to a physical measure of impact and the monetary valuation of the resulting welfare losses. Following the “impact pathway approach”, the analysis with EcoSense has been performed in three steps:

- **Dispersion Modelling**

Emissions of air pollutants are often transported over hundreds of kilometers. Air quality models that simulate both the transport and the chemical transformation of pollutants in the atmosphere have been integrated in the EcoSense model to accommodate regional dispersion modelling. For the present assessment needs, the Windrose Trajectory Model (WTM) has been used to estimate the concentration and deposition of acid species on a regional scale. WTM calculates immission levels of PM₁₀, SO₂, NO_x, sulphates, nitrates, acid depositions and nitrogen depositions resulting from NO_x, SO₂, PM₁₀ and NH₃ emissions.

The EcoSense model has been equipped with the necessary database for an adequate representation of the dispersion of air pollutants (air quality modelling). Its reference technology database has been enriched with information covering technical data describing the emission source (point source), the geographic coordinates of the locations (in terms of longitude, latitude, surface elevation at site) whereas its reference environment database has been enriched with information covering receptor data (population, land use, agricultural production, buildings and materials, etc.), meteorological data (precipitation, wind speed and direction) as well as a European wide emission inventory for SO₂, NO_x, NH₃ and PM concentrations.

Twenty-three point (or emission) sources – at least one located in each EU15 member state – have been entered in the EcoSense model. The selected point sources are located at important European cities in the EU15 Member States, taking into account dispersion over the whole EU15 area. This approach enables to distinguish EU15 wide impacts and damages in function of the location where specific air quality policy measures are taken.

- **Quantification of Physical Impacts**

Dose-response (or exposure-response) functions provide essential input to the EcoSense model for the quantification of impacts and damages of airborne emissions on the selected SD indicators. Exposure-response functions relate the incremental change in pollutant concentration level (exposure) to the damage or benefit (response) on a particular receptor. These receptors can be anything that is affected negatively or positively by a change in the level of air pollution. Dose response functions have been selected from ExternE and updated where needed according to new findings presented at ExternE related projects (for example the NewExt project).

The present analysis is primarily focused on the impacts and damages of SO₂, NO_x and PM emissions. Emissions of NH₃ and NMVOC are included in the analysis as background emissions and not as a variable emission source. Although ozone has some significant impacts on human health and

¹ Due to restricted data availability, impacts on this indicator have only been assessed for Brussels.

agricultural yields, the impacts and damages resulting from ozone formation have not been included in the analysis².

The following table presents the pollutants considered in the analysis and their respective immissions:

Table 2-1: Relation between airborne pollutants and SO₂, NO_x, and PM emissions³

IMMISSIONS	EMISSIONS
<ul style="list-style-type: none"> ▪ Acid deposition (acd, sde) on land and water ▪ Nutric nitrogen deposition (nde) on land and water ▪ SO₂ concentrations in air ▪ Nitrate concentrations in air (Nit) ≈ PM (PM₁₀)* ▪ Sulphate concentrations in air (Sul) ≈ PM (PM_{2.5})* ▪ Total suspended particles (TSP) ≈ PM (PM₁₀)* 	<ul style="list-style-type: none"> ▪ eq (equivalents of H⁺) by SO₂ and NO_x ▪ NO_x ▪ SO₂ ▪ NO_x ▪ SO₂ ▪ PM (PM₁₀) ≈ TSP

▪ Monetary Valuation

The final step in the analysis is the economic evaluation or estimation of the external costs or damages from air pollution. This involves multiplying the number of cases (responses) by the monetary unit cost per incidence (unit cost factors, MUV). A database with monetary values for most of the impacts has been set up following the recommendations of the ExternE economic evaluation task group and is incorporated in the Ecosense Model.

2.3. Impact and Damage Cost Assessment results

2.3.1. Reference Scenario

Impacts are assessed in terms of an incremental change in background concentrations due to a rise (or fall) in emissions from the different economic sectors and nature. The present analysis focuses on three different years (namely 1990, 2010 and 2020), which are characterised by different emission levels, and thus different background concentrations in the atmosphere. These differences in background concentrations over time (for example due to the penetration of new technologies or new regulations) result in different marginal impacts per tonne of emissions. Therefore a reference scenario for present and future concentrations had to be constructed against which the effects of changes in airborne emissions can be evaluated.

The EcoSense model has been run for background changes in concentrations of airborne pollutants in 1994, 2010 and 2020. The European emission inventory for 1994 is taken from the CORINAIR database. For 2010 and 2020, projections of PM₁₀, SO₂, NO_x, NH₃ and NMVOC emissions are provided by the Current Legislation Scenario (CLE, developed by the Centre for Integrated Assessment Modelling) taking into account current legislation and emission control policies and measures. In the year 2010, the Western European average SO₂ emissions decline by 20%, NO_x emissions by 52%, VOC emissions by 54% and PM emissions by 56% relative to 1990 emission levels (emission levels were calculated by the TIMER/RAINS model). Shifts in human receptor data on the overall EU15 age distribution and on the number of asthmatic children and adults⁴ are taken into account. For simplicity reasons it has been assumed that the total population and the dispersion of people over Europe, the build-up area, the agricultural area, and the total area of ecosystems remain relatively constant between 1994 and 2020.

The following sections provide a brief description of the impact indicators and some key results, expressed in terms of ratios of marginal impact (or damage) per tonne of pollutant emitted. The overall

² O₃ formation is a highly non-linear process which heavily depends on meteorological conditions as well as on the background concentrations of NO_x and NMVOC, which in turn differ significantly over time and across different sites in Europe. The non-linear nature of ozone creation coupled with the scarcity of data on emissions of its precursor pollutants for the different locations, rendered it difficult to assess its impacts on human health and agriculture in the context of the present analysis.

³ In EcoSense, all the Exposure Response functions related to impacts of PM (TSP, PM_{2.5} or PM₁₀) are adapted to give impacts per tonne of PM₁₀ as outcome.

assessment has been performed for each of the 23 locations and the years 1994, 2010 and 2020 but the results presented below are aggregates for the EU15 area.

2.3.2. Mortality change due to Air Pollution

The Years of Life Lost (YOLL) indicator has been used to quantify the adverse effects on human mortality resulting from an increase in emissions of air pollutants. Impacts of air pollution on mortality are subdivided into acute effects, implying an increase in fatalities immediately after the initial exposure and chronic effects, indicating long-term effects resulting from an accumulated or prolonged exposure before dying.

The present study explores the acute mortality effects on total population of exposure to an incremental tonne of sulphur dioxide emissions, as well as the chronic mortality effects on adults of exposure to a tonne of sulphur dioxide, total suspended particles or nitrates emissions. In the acute mortality case, a tonne increase in SO₂ emitted adds another 0.003 years of life lost to the exposed population in 2020. The strongest association between chronic mortality and air pollution was observed for total suspended particles emissions (PM), which in 2020 result in two to three times greater loss in years of life among adults in the EU-15 region than nitrate and sulphate emissions respectively.

2.3.3. Morbidity change due to Air Pollution

For impacts of air pollution on morbidity a selection of four endpoints of morbidity for which reasonably strong evidence exists has been made. Some results are summarily presented below:

Respiratory hospital admissions

Variation in ambient air pollution levels has been reported in several studies to be associated with daily variation in indices of respiratory illness frequency. For the purposes of MINIMA-SUD, the impact on the number of hospital admissions for respiratory diseases from a tonne increase in the emissions of SO₂, NO_x and PM pollutants is assessed.

The strongest association between incremental emissions from an individual pollutant and additional respiratory hospital admissions was found for sulphur dioxide; results for 2020 indicate 1.5 and 2.2 times larger impacts per tonne emitted for SO₂, relative to PM and NO_x emissions respectively. The damage factors derived for SO₂ and PM are broadly similar for 1994 and 2020, contrary to the NO_x damage factor which is increased by more than 67%, ranging from four YOLL per kt emitted in 1994 to 6.7 YOLL per kt emitted in 2020.

Restricted activity days

An important measure of morbidity in economic valuation though relatively rarely used in epidemiology is a Restricted Activity Day (RAD). A RAD is defined as a day when a study subject was forced to alter his or her normal activity. RADs include days off work for employed adults and days off school for children, whether or not the subject was confined to bed on those days or medical attention was required.

The analysis is focused on the increases in the number of days with restricted activity over the total EU-15 population caused per tonne of sulphur dioxide, nitrogen oxides and particulate matter emissions. Among the three pollutants analysed and for all three years considered, nitrogen oxides cause the largest relative increase in the number of restricted activity days per tonne emitted (almost three additional days in 2020 relative to 1994). Nevertheless, the strongest association between an individual pollutant and RADs was observed for PM which in 2020 accounts for 10 additional restricted activity days per tonne emitted. SO₂ emissions on the other hand have the least significant adverse impact on the population's normal activity days (half the PM impact across all three periods considered).

Congestive heart failure

Large epidemiologic studies have suggested that increased levels of air pollutants such as fine particulate matter (particulate matter $\leq 2.5 \mu\text{m}$ in aerodynamic diameter (PM_{2.5})) and nitrogen dioxide are associated with an increased incidence of myocardial infarction, congestive heart failure, and total cardiac mortality in susceptible populations. In line with these findings, the results of this study indicate that on the EU-15 average, increases in PM emissions demonstrate the strongest positive association to hospital admissions for cardiovascular diseases (only people older than 65 are

considered); impacts range from 1.2 additional cases per tonne emitted in 1994 to 1.6 in 2020. SO₂ emissions display approximately half this impact across all years considered. The damage factor for NO_x – acting through the formation of secondary fine particles (nitrate aerosols) – displays the largest increase (more than doubles) between the end years considered (from 0.5 cases per kt emitted in 1994 to 1.1 in 2020).

Bronchodilator usage

Another endpoint analysed is the increase in ‘asthma attacks’ related to PM₁₀ (TSP, nitrates, sulphates) incremental emissions. ‘Asthma attack’ can be defined in different ways. In ExternE and the present project, an ‘asthma attack’ is defined as ‘shortness of breath’ in asthmatics. One of the 3 dose-response functions used for the assessment of impacts on asthmatics is the increased use of medication (bronchodilator usage). The others are expressed in terms of increase in respiratory symptoms and cough. Asthma is the major cause of childhood admissions to hospital and a common cause for school absenteeism. The following analysis is restricted to the effects of air pollution on asthmatic children.

On the assumption that world-wide the number of asthmatics rises by 50% per decade (WHO 2000), increases in the ambient levels of the pollutants considered in the analysis are associated with significant increases in the number of asthmatic children. Exposure of children to increased levels of particulate matter emissions indicates the strongest association to increased incidence of asthma among this group (920 cases of bronchodilator usage among children per kt of PM emitted in 2020). An incremental tonne of SO₂ emissions in 2020 results in triple the 1994 increase in the number of asthmatic children (almost 500 cases per kt emitted in 2020). The marginal impact of an additional tonne of NO_x emissions on the number of children suffering from asthma rises fivefold between 1994 and 2020 (close to 600 cases per kt emitted in 2020).

2.4. Monetary Damage to Crops

The effects of sulphur dioxide emissions on six crops: wheat, sugar beet, potato, barley, rye and oats have been assessed. As sulphur is also a plant nutrient for agricultural crops, an increase in ambient SO₂ concentration leads to a positive effect on yield at low background concentrations, while there is a negative effect at higher background levels. The modified Baker *et. al* exposure response functions have been used for assessing the changes in yield production due to variations in the SO₂ air concentration level. Physical damages on crops were subsequently evaluated in monetary terms using crop market prices. Unit costs are based on the UN Food and Agriculture Organisation (FAO) international price statistics.

The results for the EU-15 region indicate that wheat crops and to a lesser extent sugar beet and potato crops are susceptible to the most severe monetary damage per tonne of SO₂ emitted (damages range between 17.000 € for the former to about 10.000 € per kt SO₂ emitted for the latter two). Estimated costs were considerably lower in the case of barley crops (3.340 € per kt SO₂) whereas rye and oats crops were found to be largely unaffected.

2.5. Monetary damage to Materials

Air pollutants accelerate the corrosion and deterioration of materials. To serve the present research needs, dose response functions have been selected that quantify the corrosion impacts on building materials from acidic deposition resulting from SO₂ emissions. Damages are expressed in terms of affected material area per tonne of SO₂. The monetary damage to materials has been calculated as the product of the stock at risk, times the repair or replacement frequency, times the renovation costs (MUV). For the present assessment the direct effects of SO₂ on four types of building surfaces are considered: limestone, mortar, natural stone and sandstone.

The 2020 results on the EU-15 average suggest that damage costs range from 1.000 to 1.500 €/kt of SO₂ for natural stone, limestone and sandstone. The role of SO₂ on mortar materials is much more detrimental; the repair/maintenance cost per kt emitted (in euro2000) is four to six times higher for mortar than for the remaining materials examined.

2.6. Damage to ecosystems due to Acidification and Eutrophication

The impacts of air pollution on ecosystems due to acidification and eutrophication is quantified in terms of exceedance or not of the critical loads specific for that ecosystem. “Critical load” can be defined as a ‘quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur, according to present knowledge’ (UNECE, 1999; European Commission, 2001).

For eutrophication, the critical load depends only on the deposition of nitrogen (by NO_x and NH₃ emissions). For acidification, the critical load depends on the deposition of both sulphur (by SO₂ emissions) and nitrogen (by NO_x and NH₃) emissions. An ecosystem can be defined as ‘protected’ if the acidifying or eutrophying depositions don’t ‘exceed’ the critical loads for that specific ecosystem. Impacts are expressed in terms of unprotected ecosystem area (in km²) exceeding the critical loads for acidification and eutrophication per tonne of pollutant (SO₂ and NO_x).

Considering the critical loads for acidity, the results for the EU-15 average yield 1.5 times higher damage factor per tonne for sulphur dioxide emissions relative to nitrogen emissions in 2020. Considering the critical loads for nitrifying nitrogen, the results indicate an increase to the total unprotected to eutrophication area by almost 30 km² per kt of NO_x emitted.

3. Climate Change and Security of Energy Supply

The increasing evidence of human-induced interference with the earth’s climate system and mounting concerns about potentially serious future adverse impacts make global climate change one of the most important challenges of sustainable development in the long term. Security of energy supply has also become a more pressing concern for policy makers, especially in view of the re-emergence of supply shortfalls leading to hydrocarbon fuel price hikes in recent years. An excessive reliance on fossil fuels, oil and natural gas in particular, is an issue of concern because of the economic, physical and geopolitical risks associated with it. Specifically, the current overall dependence of OECD countries on oil supply from politically-volatile regions and the definition of appropriate responses to potential supply disruptions remain formidable issues.

This section examines the impact of a set of representative policy instruments on sustainability indicators in the areas of climate change and security of energy supply, two important dimensions of sustainable development addressed in the MINIMA-SUD project.

3.1. Sustainable Development Objectives and Policies addressing them

The climate change indicators considered here are: *Greenhouse Gas atmospheric concentrations* (CO₂ and CH₄), *global temperature change* and *global sea-level rise*. These indicators are reported for the year 2100. The indicators for security of energy supply are long-term *global resources-to-production* (denoted here as Ru/P) ratios for oil and natural gas, both of them reported for the year 2050. The policy instruments examined are Energy-related Demonstration and Deployment (D&D) programmes, a Carbon Equivalent (hereon referred to as C-eq) tax, R&D Investments and the Internalisation of non-climate external costs.

Climate change and security of supply are complex issues, encompassing multiple aspects. In pursuit of sustainability in these areas, a combination of different policy instruments may prove more effective. In this context, an assessment of the impacts of a combination of different C-eq tax levels with D&D programs on the sustainability indicators in these two areas is also examined.

3.2. Modelling the instrument to indicator chain

The modelling framework is based on the “bottom-up” energy-systems ERIS model (**E**nergy **R**esearch and **I**nteraction **S**trategies) and the stylised climate change MAGICC model. In the context of the MINIMA-SUD project, the ERIS model has been extended to adequately represent the causal chain linking the aforementioned policy instruments to the sustainability indicators of interest in the climate change and security of supply areas. In particular, focus is given to the examination of the

effectiveness of alternative policy instruments to stimulate technological pathways that drive to a low-emissions energy system in the long run.

The main extensions to the ERI model include the implementation of a clusters approach to technology learning, the disaggregation and extension of the non-electric sector (in particular the transport sector), the incorporation of emissions and marginal abatement curves for methane (CH₄) and nitrous oxide (N₂O), the inclusion of sulphur dioxide (SO₂) emissions, the addition of an energy carrier production sector (specifically for hydrogen, alcohol and Fischer-Tropsch liquids production) and the inclusion of geological and terrestrial carbon storage.

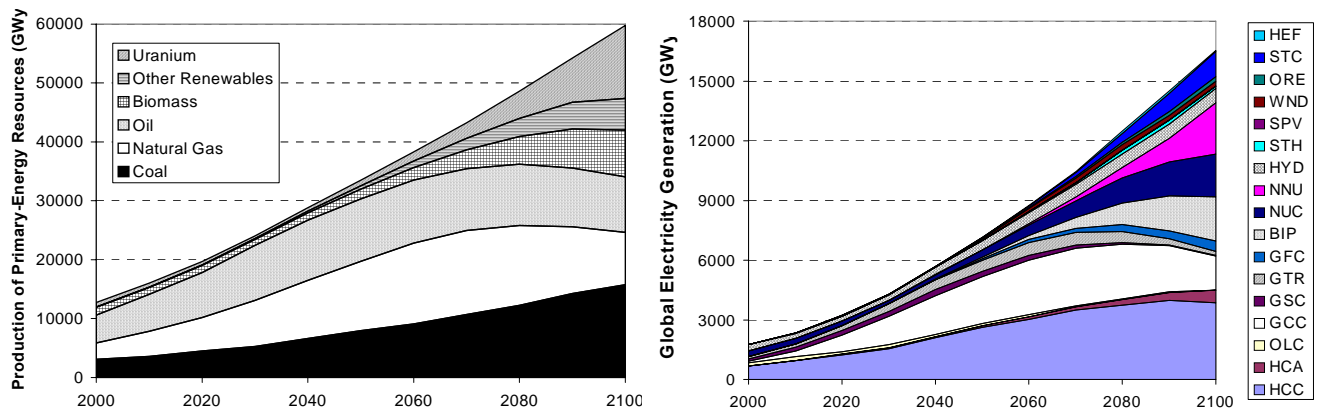
For the quantification of the key global indicators of climate change the ERI model has also been linked to the stylised climate model MAGICC (version 4.1, Wigley, 2003). MAGICC includes all the major greenhouse gases and the effects of rationalised (three world regions) fossil fuel-derived SO₂ emissions through sulphate aerosol effects and allows the estimation of concentrations of greenhouse gases (CO₂, CH₄ and N₂O) in the atmosphere, global temperature change and global sea-level rise.

3.3. Baseline

This section presents the main characteristics of the baseline scenario, as quantified with the ERI-MAGICC modelling framework. For the analysis a “middle-of-the-road” scenario has been constructed. Basic economic, population, energy demand and technology assumptions of this scenario are primarily based on the SRES-B2 scenario, quantified for the IPCC Special Report on Emissions Scenarios.

In the baseline scenario, the world production of primary-energy resources increases fivefold over the 21st century, reaching approximately 60 TWyr in 2100 (Figure 3-1 on the left below). Production from coal increases throughout the century. Oil and natural gas production are subject to supply constraints which become particularly evident towards the end of the century. The contribution of renewables (and in particular biomass) and nuclear energy to world supply registers a significant growth in the second half of the 21st century.

Figure 3-1: World primary energy production (left) and World electricity production by fuel (right) in the ERI baseline scenario between the years 2000-2100⁵.



The figure on the right above presents the global electricity generation mix by fuel in the ERI baseline. Global electricity generation increases ninefold over the century. Electricity from non-fossil resources plays an increasingly significant role over the century. The contribution from standard and advanced nuclear technologies is significant, especially over the second half of the century. Generation from renewables is allocated a significant share of the global electricity production. With regard to fossil-fired generation, installations of conventional coal-fired power plants increase over the century. Advanced coal-based gasification technologies make inroads into the system towards the end of the

⁵ Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

century. Combined-cycle gas turbines experience a significant growth in the medium term but are replaced by other technologies such as gas fuel cells, renewable-based technologies and nuclear power plants in the long run.

In the transportation sector, three main kinds of technologies compete, namely internal-combustion-engine vehicles (today's dominant technology), hybrid-electric vehicles (an advanced technology that may be at least partially compatible with today's technological regime) and fuel-cell vehicles (advanced revolutionary technology that requires the emergence of a new technological regime). A gradual transition away from the conventional petroleum ICE vehicle to more advanced technologies is projected over the century, and in particular to hybrid-electric vehicles, which achieve 50% market share around 2070-80. Penetration of Fuel-Cell vehicles is constrained in this slow-transition scenario (0.5%, mainly hydrogen fuel-cell vehicles).

Climate Change Indicators

Global CO₂, CH₄ and N₂O emissions rise until around 2090, when they peak at almost 29 Gt carbon equivalent per annum. The largest contribution is that of CO₂ emissions, which reach approximately 24 Gt carbon equivalent at their peak in the year 2090. Atmospheric concentrations of carbon dioxide increase from slightly above 350 ppmv in 2000 to 850 ppmv in 2100, whereas CH₄ concentrations are almost double in 2100 relative to 2000 levels (approximately 3200 ppbv in 2100 from slightly above 1750 ppbv in 2000). N₂O concentrations grow much slower and reach approximately 470 ppbv by 2100 (from approximately 300 in 2000).

By the end of the century average global temperature increases by 3.4 °C above 1990 levels, while the average sea-level rise equals to 43 cm.

Security of Energy Supply Indicators

The reference scenario has been based on moderate assumptions on the oil and gas resource base and on rapidly increasing oil and gas consumption patterns. Accordingly, Ru/P ratios for both these fossil primary-energy resources decline throughout the projection period. By the middle of the 21st century, at world level, the oil resources to production ratio equals 59 years, while the gas resources to production ratio is approximately 56 years.

3.4. Results from Policy Shocks

3.4.1. Measurement of the Impacts

The impact measure is defined as the change in the Sustainable Development indicator divided by the cost of applying the given policy instrument. The following general formula was used for the measurement of the impacts:

$$\text{Impact on SD objective} = \frac{\text{(Change in objective measured in specific units)}}{\text{(Estimated cost of applying the policy instrument)}}$$

The change in the indicator is given relative to the baseline case, i.e., the case without the application of the policy instrument. The following sections summarise some key results on the impact analysis performed with the ERIS/MAGICC modeling framework.

3.4.2. The impact of a Carbon Equivalent tax

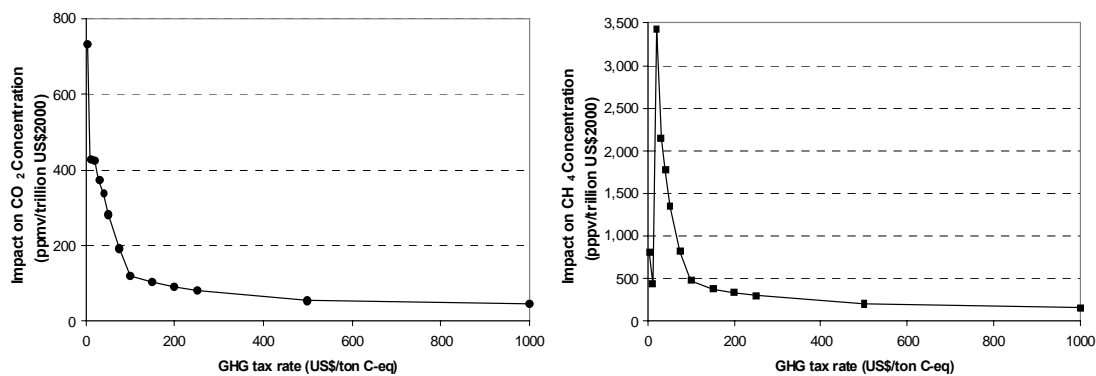
A carbon tax is a generic climate policy instrument that provides an incentive to shift towards low-emissions technologies without imposing a cap on GHG emissions. The imposition of a tax on the carbon-equivalent emissions of the three main GHGs (CO₂, CH₄ and N₂O) at the global level is considered. The C-eq taxes imposed range from 0\$ to 1000\$ per tonne of carbon equivalent emitted. The cost of applying the instrument is estimated using the difference in total discounted system costs between a baseline case with zero C-eq tax and the case where a non-zero C-eq tax is imposed on the global energy system, subtracting the tax revenues.

Impact of a carbon-equivalent tax on climate change

Figure 3-2 below presents the impacts on CO₂ and CH₄ concentrations as a function of the C-eq tax. The imposition of a C-eq tax results to increased total discounted energy-system costs, mainly

attributed to the growing reliance on technological advancements for the transition towards energy sources and technologies with low GHG emissions. At low C-eq tax levels, the use of low-cost abatement measures is sufficient (such as the mitigation opportunities of non-CO₂ GHGs) whereas at higher tax levels, recourse to more expensive mitigation options is necessary (such as CO₂ capture and storage (CCS) facilities or the deployment of fuel-cell hydrogen vehicles in the transportation sector). As illustrated in the figure on the left below, low C-eq tax levels have a significant negative impact on the CO₂ concentration indicator. That is, with a relatively small C-eq tax rate, cheap mitigation options can be applied and a relatively large change in CO₂ concentration is achieved. However, the impact decreases as the C-eq tax rate is raised. This outcome is explained as follows: incremental reductions of CO₂ concentrations achieved under a given level of carbon-equivalent tax become increasingly smaller, as mitigation options are exhausted, while the corresponding costs of application of the policy instrument become higher, as more expensive mitigation options have to be introduced at higher C-eq tax levels.

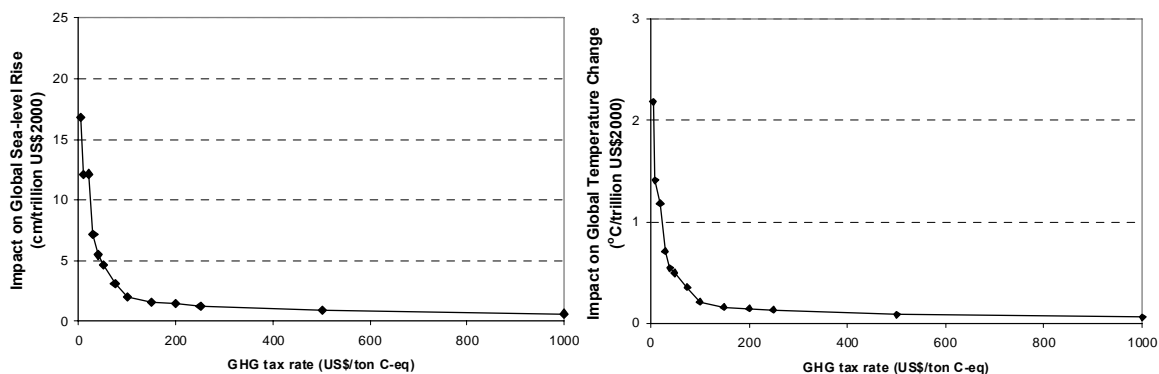
Figure 3-2 Impact of a carbon equivalent tax on the CO₂ and CH₄ concentrations in the atmosphere for the year 2100 as a function of the carbon-equivalent tax (by convention, a positive impact means an improvement in the indicator (in this example a reduction of CO₂/CH₄ concentrations in the atmosphere)



A similar case arises for CH₄ concentrations as shown on Figure 3-2 on the right. CH₄ has considerable potential for cheap abatement options, which is however exhausted at low C-eq tax rates. Accordingly, the impact on CH₄ concentrations is higher at low C-eq tax rates, where the cheaper options for CH₄ mitigation are relatively abundant, but declines at higher C-eq tax rates where CH₄ abatement imposes large costs to the energy system.

Due to the inertia of the climate system, the C-eq tax appears less effective in reducing global temperature change and sea-level rise, which are processes operating over a much longer time scale. The figure below presents the impact of the C-eq tax on global temperature change and sea-level rise indicators in 2100 as a function of the C-eq tax rate. The results indicate higher marginal impacts at lower C-eq tax rates which decline at higher tax levels.

Figure 3-3 Impact of the carbon-equivalent tax on global annual sea-level rise and on global annual temperature change in the year 2100 as a function of the carbon equivalent tax. Positive impacts indicate an improvement in the indicator (a reduction in the global temperature change or sea-level rise).



Impact of a carbon-equivalent tax on security of supply

Increasing the carbon-equivalent tax level leads to improvements in the oil Ru/P ratio, that is, with a higher tax imposed on GHG emissions, the global energy system weans away from oil, a CO₂-intensive fossil energy source, towards less carbon-intensive fossil fuels like natural gas and non-fossil resources (mainly renewables and nuclear energy). The standardised impact on the oil Ru/P ratio is, as with the other indicators discussed above, higher at low C-eq tax rates and declines at larger C-eq tax levels.

Relatively low levels of the C-eq tax lead to a decrease in the Ru/P ratio of natural gas. That is, a larger consumption of natural gas takes place as the system moves away from the more carbon-intensive coal and oil fossil resources. Intermediate C-eq tax levels extend the gas Ru/P ratio as non-fossil-based technologies or fossil-based technologies in combination with CO₂ capture and storage facilities (CCS) become cost-effective. Beyond a certain C-eq tax level (equal to approximately 100 US\$/ton C-eq) no further gains in the long-term gas availability are observed, as more expensive non-fossil resources and technologies are introduced.

3.5. Impact of Demonstration and Deployment (D&D) programmes

This section examines the impact of Demonstration and Deployment (D&D) programmes on energy technologies. D&D programmes can be an effective instrument for gathering experience with a technology or cluster of technologies in the market. Market experience in turn is important in achieving cost reductions and performance/efficiency improvements that could increase the competitiveness of emerging technologies. For the evaluation of the impacts of D&D programmes, a D&D “shock” (small one-off incremental investment) on the cumulative capacity of a given technology has been introduced. The D&D (or capacity) “shock” was applied orthogonally, i.e. affecting a technology at a time. A standard shock size of 10 billion dollars (US\$2000) has been chosen in order to be able to compare the effects of D&D shocks for different technologies on a common basis. Shocks were applied to 21 electricity generation, fuel production and passenger-car technologies.

Impacts of D&D shocks on climate change

The overall results indicate that D&D investment on low-carbon or carbon-free technologies result in positive impacts on climate-change indicators whereas investments on carbon-intensive technologies have adverse effects. Fourth generation nuclear appears to be the most productive technology in terms of CO₂ and CH₄ concentrations reduction, followed by the gas-based hybrid electric car, gas combined-cycle turbines, gas fuel cells, solar photovoltaics and wind turbines. The most noticeable negative impact is produced by the advanced coal power plant, followed by the open cycle gas turbine.

Impacts on global temperature change and sea-level rise appear limited. This is due – on the one hand – to the large inertia of climate and oceanic systems and – on the other – to the effect that the deployment of some technologies has on SO₂ emissions. For instance, when a D&D investments on a specific technology strongly displace coal production, CO₂, CH₄ and SO₂ emissions decrease. The decrease in CO₂ and CH₄ is reflected in lower atmospheric concentrations of these two GHGs, and consequently, in a lower associated radiative forcing. However, since SO₂ has a negative radiative forcing, the decrease in SO₂ emissions offsets some of the impact of lower CO₂ and CH₄ emissions. This has a mitigating effect on the impact of D&D programmes on both global temperature change and sea-level rise (i.e. a smaller decrease).

Impacts of D&D shocks on security of supply

Turning to security of energy supply indicators, and in particular to the oil resources over production ratio in 2050, the results indicate that D&D investment targeted at nearly all the technologies considered in the present analysis contributes to an improvement in oil security of supply (increase to the oil r/p ratio). In terms of gas security of supply, most results are negative, implying a diminution of the gas resources in the long term. On the basis of the assumptions underlying the present analysis (regarding the fossil-resource base and the technology dynamics) and given the set of energy-related

technologies that were examined in this study⁶, it is evident that demonstration and deployment programmes favour a transition of the global energy system away from oil consumption, towards the consumption of natural gas.

Regarding oil security of supply, the most significant impacts are produced by D&D shocks applied to natural gas combined-cycle turbines and fuel cells, followed by shocks to new nuclear, wind turbines and alcohol powered fuel cell vehicles. Concerning the gas Ru/P ratio, the only notable exception enhancing long-term security is the advanced nuclear power plant which demonstrates a relatively significant positive impact.

3.6. Combining Instruments: Carbon taxes and D&D shocks

Policy makers usually resort to a portfolio of policy instruments in addressing sustainability targets. To explore this issue, an analysis of the impacts of a combined application of D&D investments with C-eq taxes for the range of shocks and taxes examined above has also been performed. The results indicate that D&D shocks have the potential to lower the GHG tax threshold at which particular technologies become competitive. Below this threshold, the D&D shock has little impact, whereas above it, it only accelerates the uptake of already attractive technologies. Moreover, a well targeted D&D shock in the context of a climate policy most likely translates into faster cost performance improvements of specific technological options. This is for example the case for deployment and demonstration projects on carbon capture and sequestration technologies, which were found to be more productive in terms of CO₂ reductions at higher tax levels, implying that these technologies require high GHG taxes to become competitive; on the other hand the absence of a stringent climate policy renders D&D investments on them largely ineffective.

The application of combined D&D shock and carbon-equivalent tax may also help the identification and development of technologies that provide synergies between the climate change and security of supply objectives.

3.7. Impact of R&D Investment

Standardised R&D shocks were applied to 33 energy technologies in the electricity generation, fuel production, passenger-car and carbon capture sectors. The size of the shock was equal to two, three, six and twenty times the annual R&D expenditure⁷ on each technology over the time horizon. Results from this exercise indicate that the impact of R&D is limited for most Sustainable Development targets. The most noticeable impacts are produced by advanced nuclear generation technologies on climate change indicators, and in particular on CO₂ atmospheric concentrations reductions. The largest negative impacts on climate indicators were observed for the integrated gasification combined cycle technology. Concerning energy security of supply indicators, impacts rarely exceed one year of additional production per trillion dollars of investment for either oil or gas resources. The most notable exception is the case of the 20-fold R&D shock to the solar thermal electricity generation technology and wind turbines.

This outcome is not necessarily unexpected, given that some technologies were already attractive in the baseline, hence additional R&D support may have little impact. Conversely, in other cases a technology may suffer a significant competitive disadvantage which R&D support alone is unable to overcome.

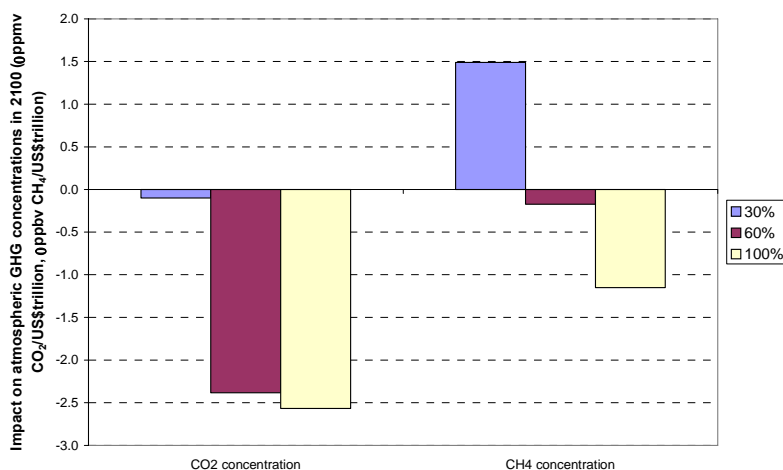
⁶ It should be noted that with the exception of the petroleum-based fuel-cell passenger car, no other oil-based technologies were considered in this set of exercises

⁷ The baseline R&D investment scenario upon which the analysis was based is derived from the EU-funded SAPIENTIA project (already completed within the 5th Framework Programme).

3.8. Impact of internalising external costs associated with fuel production and use

Finally, this section explores the effect of internalising the non-climate related external costs⁸ associated with fuel production and use. Three internalisation scenarios have been examined which differ according to the proportion of external costs assumed to be internalised: 30 percent (mild), 60 percent (medium) or 100 percent (strong). The results indicate that medium and strong internalisation results in a significant reduction in atmospheric greenhouse gas concentrations (Figure 3-4) and temperature relative to the baseline scenario.

Figure 3-4: Impact on atmospheric CO₂ and CH₄ concentrations in 2100 of internalising non-climate external costs, relative to the baseline



On the other hand, adverse impacts are produced for both oil and gas resources to production ratios: all three scenarios indicate similar reduction in the oil Ru/P ratio (by approximately 1.8 years) and reductions in the gas Ru/P ratio ranging from 3.4 to 4.8 years. This can be attributed to the preference for gas and oil over coal in terms of external costs, as indicated by the cost estimates introduced in the analysis following the ACROPOLIS project (double to quintuple costs for the latter - across different regions - in 2050) resulting in faster depletion of gas and oil resources.

4. Congestion/Transport

Transport represents one of the most important sustainability challenges in terms of energy consumption, air pollution, resource depletion and safety. A sustainable transport policy should tackle rising volumes of traffic and levels of congestion, noise and pollution and encourage the use of environment-friendly modes of transport as well as the full internalisation of social and environmental costs⁹. Because of the inherent complexity of this sector, the integration and quantification of these issues has posed particular challenges to the analysts. The MINIMA-SUD project addresses the issue of sustainability in the transport sector, by analysing the impacts of transport policy measures on well-defined sustainable development targets through the construction of an expanded and detailed deterministic transport modelling tool. This section presents the methodological approach and the basic results of the reference scenario and of a series of alternative scenario runs designed to assess the importance of individual policies in influencing the transport system towards sustainability.

⁸ External costs are based on the results of the Case Study IV of the EU funded ACROPOLIS project (Assessing Climate Response Options: Policy Simulations) project (http://www.ier.uni-stuttgart.de/forschung/project_en.php?pid=146), updated here for sulfur dioxide emission coefficients

⁹ Stated in the Presidency Conclusions of the Göteborg European Council (June 2001).

4.1. Sustainable Development Objectives in the Congestion/Transport Area

The analysis covers the following quantifiable SD objectives associated with the transport sector:

- *Passenger Transport Intensity* (passenger km/GDP)
- *Freight Transport Intensity* (tonne km/GDP)
- *Energy Intensity of Transport* (toe/GDP)
- *CO₂ emissions from Transport* (Mt)
- *Total emissions of air pollutants (NO_x, NMVOC, PM, SO₂, Lead)* in (kt)
- *Urban emissions of air pollutants (NO_x, NMVOC, PM, SO₂, Lead)* in(kt)
- *Urban Road Congestion* (total travel time in hours)
- *Noise Emissions* (db A)
- *Fatalities from Road Accidents* (thousands)

4.2. The Transport Policy Simulation Tool

For the purposes of the MINIMA-SUD project a full transport simulation and policy assessment tool has been developed specifically within the project. It covers the whole transport sector (road and rail transport, inland shipping and aviation) in the EU-15 region, identifying each country separately. It attempts to bridge the gap between top-down energy-economy models, which address the transport sector in an aggregate fashion, and bottom-up technological models, which provide sufficient technological coverage but often cannot simulate the effect of behavioural changes induced by changing costs and income. It covers the major sustainability issues associated with the transport sector and is designed so as to enable integrated policy exploration jointly with models addressing different aspects of sustainability such as economic imbalances, health concerns and security of energy supply. Its underlying database is consistent with those of EU institutions such as the European statistical service (Eurostat), the European Commission and the European Environment Agency (EEA).

The model links the choice of transport mode and technologies with economic variables such as income and generalised transport costs, but at the same time is technology-rich so as to simulate sustainability impacts in a sufficiently transparent manner. Depending on the values of exogenously set policy variables such as taxes, regulations or infrastructure investments, the demand and supply modules interact in order to reach an equilibrium, where generalised prices satisfy demand and supply for transport services. The outcome of this iterative process is the determination of the overall demand for passenger and freight transport, travelling speeds and associated costs. These variables are then fed in the other modules, where the vehicle stock is calculated and allocated into vintages, technology shares are assessed and the sustainability-related impacts are calculated.

Total expenditure on transport depends on private income (for passenger transport) or weighted industrial plus agricultural value added (for freight transport) and average user price of transport. A microeconomic optimisation framework is assumed for the allocation of total expenditure between transport modes involving the maximisation of consumer utility for passenger transport or the minimisation of transport costs for freight transport. Consumer and producer choices are described as a series of separable choices, which create a nesting structure (decision tree). Utility and cost functions at each level of the decision trees are Constant Elasticity of Substitution (CES) functions.

Central to the model is the Generalised price concept. Generalised price reflects monetary as well as time costs. It includes vehicle purchase costs, registration and circulation taxes, maintenance costs, insurance, fuel costs and public transport fares. Travel time costs depend on travel and waiting time, the average distance travelled and the value of time. Travel time depends on average speed while the value of Time (measured in Euros per passenger/tonne per hour) is different for each transport mode, road type and peak/off-peak travel.

Choice of technology in road transport is driven by emissions legislation (within the same fuel/size group) and relative user prices, determined from vehicle, maintenance and fuel costs. The model

includes the 113 technology classes of the COPERT III methodology as well as alternative vehicle technologies and fuels: CNG, methanol, ethanol, fuel cells, and electricity. A simpler approach has been adopted for non-road transport modes. The model calculates NO_x, NMVOC, SO₂, PM, Pb and CO₂ emissions.

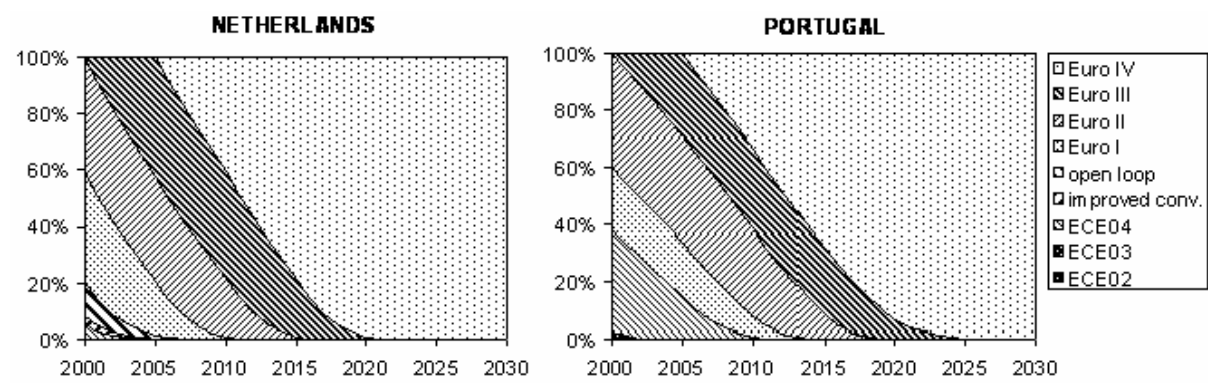
4.3. Baseline

In order to establish a benchmark against which the impacts of transport policy measures can be evaluated, the model has been used to build baseline projections over the 2030 horizon. Results on the EU-15 average indicate that vehicle costs per pkm decrease slightly (in real terms) because of the moderately rising average distance driven with each car. Fuel costs remain broadly unchanged, as a composite result of increasing congestion, improving fuel economy and slightly increasing fuel prices (after 2010). Time costs, however, are expected to rise considerably, because of both higher congestion levels and increasing value of time per pkm, the latter being a result of growth in private income. The time cost during urban peak driving is projected to double in 2030 relative to 2000 and to account for more than half the user price of transport, whereas for highways the increase is less pronounced (about 70%). Vehicle ownership and operating costs represent the largest fraction of total costs over the outlook.

Private transport activity is projected to grow less in urban than in non-urban areas, mainly due to increasing congestion levels. Big cars, heavy duty trucks and motorcycles are the fastest growing road modes, along with aviation and high-speed rail in non-road modes.

Significant differences are projected in the vehicle age distribution pattern among EU-15 Member States, which results in different penetration rates of new technologies. Taking the two extremes the baseline projects that in the Netherlands – a leading country in new car fleet with an average age of 6.8 years by 2000 – non-catalyst cars disappear by the beginning of the projection period, whereas in Portugal – where cars currently have an average age of more than 10.5 years – non-catalyst cars continue to circulate up to 2010. By 2015, the total car park in the Netherlands only consists of the most advanced technologies ‘Euro III’ and ‘Euro IV’, whereas ‘Euro II’ cars (of model years 1996-1999) will still account for about 10% of the Portuguese car stock. ‘Euro IV’ vehicles take over the whole car market by 2020 in the Netherlands and by 2025 in Portugal (Figure 3-1).

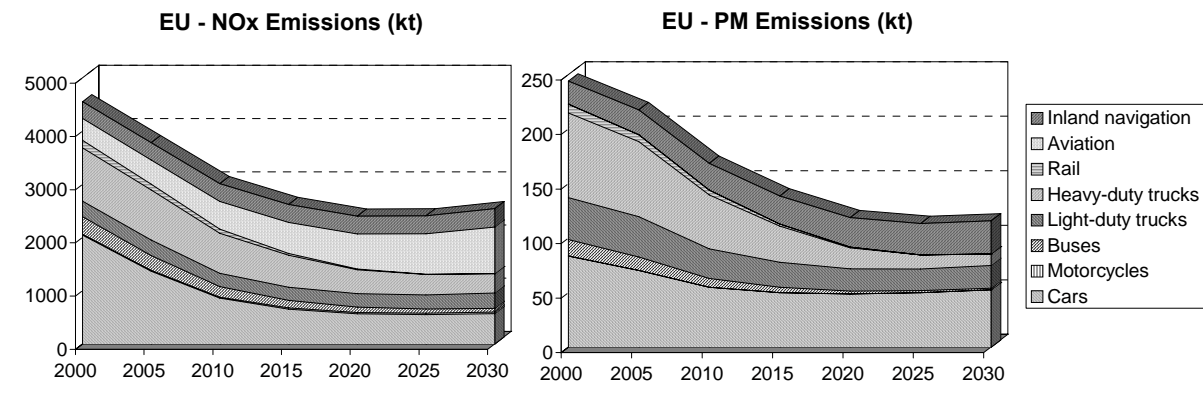
Figure 4-1: Evolution of technology shares for medium-sized (1400-2000 cc) gasoline passenger cars in the Netherlands and Portugal.



NO_x and NMVOC emissions are projected to fall significantly in the forecast, primarily as a result of the penetration of advanced technology (‘Euro III’ and ‘Euro IV’) cars and trucks. Conversely, the share of aviation in total emissions rises continuously under baseline conditions (unless additional abatement measures are taken for jet propulsion engines). PM emissions of heavy duty vehicles (trucks and buses) are projected to decline significantly up to 2025 (only 15% their respective 2000 value) because of the penetration of ‘Euro V’ technology, thus making inland navigation the second biggest PM emitter after passenger cars (Figure 4-2). CO₂ emissions are projected to grow by about 60% between 2000 and 2030; road freight transport and aviation (despite efficiency improvements up to 2020) account for the largest share in this increase, whereas cars follow with a relatively lower emissions growth rate (partly because of better fuel economy of cars entering the market up to about

2015 and partly because of an increase in the diesel car share). The market penetration of alternative fuelled vehicles (CNG, electric and fuel cells) remains modest throughout the reference.

Figure 4-2: Baseline development of transportation NOx and PM emissions in the EU (2000-2030).



Congestion levels and noise emissions still grow over the outlook but at a diminishing growth rate. A gradual decrease in accident rates is projected (ranging from -0.36% between 2000-2010 to -0.26% in 2020-2030) which is coupled with a remarkable decline in the number of road fatalities (50 percent reduction over the outlook).

4.4. Policy Scenarios

To assess the impact of policies on transport-related sustainability indicators, a number of transport-specific policy instruments have been determined, which go beyond the ones commonly retained within the project. The final selection has been based on the Commission’s White Paper on Transport and includes economic, technical and social instruments such as urban road pricing, incentives for using public transport, car scrapping schemes, accelerated introduction of clean transportation fuels and of alternative fuel vehicles, as well as expenditure on road infrastructure. All instruments selected were quantifiable, which renders them explicitly applicable to the transport model. The following scenarios have been evaluated using such instruments:

4.4.1. Diesel Fuel Taxation

This scenario assumes a doubling of the tax on diesel fuel used by private vehicles (cars and trucks). It results in a substantial increase in the costs for diesel vehicles which is however not reflected in significant increases in the total user costs for passenger cars (less than 2 percent increase). Increases in the user costs of trucks however, range from 2 to 10 percent. Passenger kilometers of diesel cars decrease by 3-14% (with the largest decline observed in fuel consuming urban peak driving conditions); yet, gasoline cars – rather than public transport modes – benefit most from this decline. Energy demand and CO₂ emissions decline slightly (1-2% over the 2010-2030 period) due to the somewhat higher transport price. The enhanced penetration of gasoline vehicles produces additional NMVOC and lead emissions, whereas emissions primarily originating from diesel vehicles (NO_x, PM and SO₂) decrease.

4.4.2. Investment on Transport Infrastructure

Investment on transport infrastructure primarily aims at alleviating road congestion. In this scenario investment expenditure on the road network (both urban and non-urban) doubles. Driving becomes cheaper (by 3-4% in urban areas and by 1% in motorways) and total time spent in urban driving declines by about 6% over the outlook. Some of the impacts are rather limited, an outcome mainly attributed to the ‘rebound effect’: improved congestion conditions reduce time and fuel costs and make car driving more attractive, thus leading to even higher passenger and freight transport intensity and energy demand. Accordingly, impacts on pollutant emissions vary depending on the functional form of emission factors and the relative change in urban and non-urban driving speeds; their variation however does not exceed ±3% from baseline levels. Despite higher driving speeds, which would normally lead to more road accidents and fatalities, better infrastructure improves road safety, so that

the number of deaths from road accidents remains effectively unchanged relative to the baseline. Finally, heavier traffic at higher speeds tends to increase average noise levels by 1.6% in 2030.

4.4.3. Subsidisation Schemes

Three alternative subsidising schemes have been assessed. First, vehicles powered with CNG and Fuel Cell vehicles are subsidised at a rate of 50% of their pre-tax purchase cost (this applies to cars, light and heavy trucks). Second, fares of all public transport modes (bus, tram, metro and train) are subsidised at a rate of 50%. Third, the pre-tax purchase cost of all new passenger cars that replace old ones is subsidised by 50% (in order to accelerate car scrapping).

Subsidising CNG and Fuel Cell vehicles causes negligible changes in generalised prices, aggregate transport activity and travelling speed. The most significant effects are exerted on the fuel mix, particularly after 2010, when CNG and fuel cell vehicles start to penetrate the market. The number of gasoline and diesel fuelled vehicles falls considerably by 2020. By 2030, alternative fuel vehicles account for about 7%, 30%, 20% and 44% of the total fleet of cars, buses, light trucks and heavy trucks respectively. This results in reduced consumption of conventional fuels and increased demand for CNG and methanol (13-fold and fivefold increase respectively in 2020). In 2030, CO₂ emissions decline by 2.8% and SO₂ emissions by 1.3%. NO_x emissions fall by 2% in 2020, with the urban portion decreasing more sharply (3.6% compared to 1.3% in non-urban areas). Impacts on emissions of other pollutants are stronger; over the 2030 horizon reductions in lead, PM and NMVOC emissions range from 5.3% to 8.1% and 8.6% respectively.

Heavy subsidies of public transport fares (by 50%) render these transport modes much more attractive, but this induces an overall increase in the use of trains and buses without affecting the use of cars significantly. Although pkm of buses and rail increase in total by 11-16% and 27-29% respectively over the outlook, pkm of cars decline only slightly (by approximately 1%). Here, the 'rebound effect' is again evident: improved congestion conditions encourage private car travel, so that the overall impact on car use is very small. Emissions remain essentially unchanged.

Subsidising the pre-tax purchase cost of all new passenger cars induces significant acceleration in the renewal of the car park, so that scrapping rates increase by 15-20% and the average age of the passenger car stock in 2010-2020 falls to 6.7-6.9 years (from 7.2-7.4 years in the reference). By the end of the projection, the population of cars less than 5 years old increases by 5-15% relative to the reference, whereas the number of old cars falls by up to 60%. The share of the most advanced 'Euro IV' technology in 2010 exceeds 50% (5% increase from baseline levels). As a result of the faster penetration of 'Euro IV' cars, energy use and pollutant emissions decrease particularly in the 2006-2015 period. The overall effect on total transportation, energy and emissions is limited though as the scrapping subsidies apply to passenger cars only: for example, NO_x emissions of cars are 5% below baseline levels in 2010, but total transportation NO_x emissions are only 1.5% lower because emission levels of trucks and aviation remain unchanged. Finally, there is no impact on congestion, noise and accident rates in this scenario.

4.4.4. Advanced Emission Standards

Earlier introduction of 'Euro V' emission standards in cars and light trucks is assumed (introduced in 2006 rather than beyond 2008 in the reference). 'Euro V' vehicles are expected to be on average 10% more fuel efficient and to emit 24% - 50% less NO_x, NMVOC and PM than the corresponding 'Euro IV' technologies, depending on vehicle type, fuel and size. Their 'premature' introduction implies that their purchase and maintenance costs are 40% higher.

The accelerated introduction of advanced 'Euro V' technology at higher purchase costs is projected to make car travel more expensive, particularly in non-urban areas, where capital costs account for the major part of total costs. This slightly alleviates congestion levels. Public transport becomes slightly more attractive to passengers, both for urban and non-urban travel. Buses and rail in urban areas are projected to gain about 5% and 4% in vkm respectively after 2020. In non-urban passenger transport, high-speed rail and aviation are expected to benefit most, their activity (in pkm) rising by over 4% and 3% respectively after 2020. Total energy consumption falls by 8.2% in 2020 and by 9.5% in 2030, with some switch from conventional to alternative fuels. The earlier introduction of Euro V emission standards and the shift towards public transport results in a significant reduction in air pollutant emissions, with that for NO_x and PM in urban areas being the most pronounced: -18% and -39% in

2030 respectively. A negative side effect is observed in road fatalities: higher driving speeds cause a 3% increase in injury accidents and a 4% increase in road fatalities in 2020-2030.

4.4.5. Road Pricing

In this scenario a surcharge of 3€ per automobile trip in urban areas is implemented, which produces important increases in urban travel costs (more than 20% for cars and light trucks), thereby reducing congestion by more than 4% and increasing transport activity of urban buses and tram/metro by more than 25% and 15% respectively in the 2010-2020 period. Average urban driving speeds are remarkably improved, especially in peak hours (reaching close to 20% higher levels than in the baseline), which leads to fuel savings and hence to a reduction of 4.4% in CO₂ emissions by 2010. NO_x emissions fall by 5 to 6 percent in urban areas (and by less than 2% in total) over the outlook period; the corresponding figures for PM emissions are 9-10% in urban areas and 4-5% in total. Higher urban travel speeds however result in deterioration in road safety: fatalities in road accidents are increased by 15-22%.

4.4.6. Combination of instruments

The impact on transport sustainability indicators of applying not a single but rather a suite of policies has also been assessed. In particular, the following three policy combinations are examined:

Road pricing and Advanced Emission Standards

The combined application of road pricing and advanced emission standards results in stronger impacts on CO₂ emissions reductions (12.2 percent reduction in 2030) and pollutant emissions reductions (up to 25 percent reduction for urban PM and lead emissions). However, as average speed rises, the impact on accident rates is substantially increased: road fatalities are increased by 17.5 percent relative to the reference.

Road pricing, Advanced Emission Standards and Subsidies on CNG and Fuel Cell vehicles (assuming that revenue raised from charging road users is allocated to granting alternative propulsion systems and fuels).

This scenario leads to improvements in all sustainability indicators, with the exception of road fatalities. The enhanced penetration prospects of alternative fuels produce more than 20% lower energy demand and CO₂ emissions. The most noticeable impacts are observed on other pollutants emissions (PM, SO₂ and lead) which display reductions of more than 30% relative to the reference. Lower congestion levels however are also expected to give rise to fatalities from road accidents (over 20% from baseline levels).

Road pricing, Advanced Emission Standards and Subsidies on bus and rail fares (assuming that revenue collected by discouraging private vehicle use is directly utilised to support public transport modes).

The application of this suite of instruments is less efficient than the previous case examined because in this case the 'rebound effect' operates to mitigate the benefits of the reduced use of passenger cars.

A broad conclusion from this analysis can be drawn: the application of individual policy measures cannot respond sufficiently to the diverse sustainability concerns associated with transportation; a suite of policies combining promotion of advanced 'conventional' technologies and alternative fuels with interventions to reduce demand for transport would be most suitable to address the variety of sustainability issues.

5. Economy

This section deals with the macro-economic and sectoral input to the MINIMA-SUD project. It concentrates both on issues touching social exclusion and regional imbalances – as sustainable development concerns in themselves – as well as more straightforward economic objectives like productivity, competitiveness and economic growth. Clearly such objectives are of prime interest in the area of sustainable development. For the instrument to impact analytical chain this section draws heavily on the use of General Equilibrium models and notably on a version of the GEM-E3 model

incorporating endogenous economic growth and on a much smaller in terms of regional and sectoral coverage core CGE model best suitable for handling dynamic aspects.

5.1. Analysis using the GEM-E3 World Model

The GEM-E3 model is an applied multi-regional, multi-sectoral general equilibrium model used in the present context to accommodate the analysis on sustainable development issues from a macro-economic point of view.

5.1.1. Sustainable Development Objectives and Policy Instruments examined

An important task undertaken within this section of work has been the development of a methodology to introduce social indicators, in particular Gini coefficients and poverty lines indicators into the GEM-E3 World Model. This task has entailed a considerable amount of effort given that the social dimension of GEM-E3 is very limited. The collection and harmonisation of data for the 21 geographical areas considered in GEM-E3 world, at national level, proved to be particularly arduous as information came only in domestic units and in different nomenclatures (depending on the statistical systems of the different countries). The data obtained had to be re-aggregated in the GEM-E3 World nomenclatures, in order to calculate, for each of the 21 regions of the model the level of sectoral wage rates. The introduction of sector wage rates has allowed the calculation of a GINI index for wage earnings (which also includes transfer earnings). The United Nation Development Program dataset was subsequently utilised to calculate GINI indexes for total earnings, i.e. wage, transfer and capital earnings. The latter task has also proved cumbersome due to scarcity of information on capital earnings. To overcome this information shortfall, the value of the GINI for capital earnings is calibrated for the base year of the GEM-E3 world model and then assumed to remain constant. The model then calculates endogenously the GINI for total incomes for the years beyond 1995.

Concerning economic indicators, two broad categories of indicators have been considered:

- Situation indicators referring to welfare attainable by present generations (GDP per Capita, Final Consumption per Capita, Utility per Capita, Employment)
- Dynamic indicators, assessing the welfare attainable by future generations (Capital and R&D stocks per capita, Public Debt per Capita)

Even though these economic indicators are well suited for characterising the situation emerging in a given country (or group of countries) due to the imposition of a policy measure, they do not give any insight as to the efficiency/equity trade-off which follows its implementation. In an effort to overcome this, the analysis has been supplemented by two generic synthetic measures of inter-country equity, or convergence, which can be applied for any group of countries:

- The Absolute Convergence for Indicator i , which allows to measure if the implementation of the policy increases the discrepancy between the countries with the lower and higher level for this indicator
- The Relative Convergence for Indicator i , which evaluates if the average discrepancies for indicator i , inside a group of countries tends to decrease following the introduction of the policy

These synthetic indicators are particularly useful when emphasis is given to cross-country equity of policy application, but do not provide any insight as to the impact of policies on inequalities between groups of households.

Policy Instruments

GEM-E3 World allows, from its great level of detail, the implementation of numerous policy instruments, at different geographical and sectoral levels. However, the present analysis assumes that all policies are only exercised within Europe. The policy instruments considered are:

- Tradable permits for CO₂
- CO₂ taxation
- Reduction of employers' social contribution rate
- R&D subsidies

The combined application of these policy instruments is also assessed in order to examine more realistic scenarios. For example, CO₂ taxation can provide an Employment-Environment double dividend, when the tax income is allocated to reduce the employers' social contribution rate, or triple dividend when part of the taxation revenue is used to subsidise R&D, thus stimulating long term growth.

5.1.2. Model Extensions

A crucial task undertaken within the MINIMA-SUD project has entailed the development and incorporation into the GEM-E3 World Model of an endogenous growth module. In most applied economic models, technical change is assumed to be exogenous, meaning that the response of economic sectors to a sustainable development policy is limited to factor (or product) substitution. The endogenous technical change mechanism implemented in GEM-E3 widens the scope of responses to R&D decisions, new technologies adoption and a series of interlinked issues, including factor productivity, product quality, innovation, knowledge diffusion between economic sectors and over countries. It thus opens the way to in-depth sustainable development analysis, where productivity and quality play a major role in increasing welfare in the context of accelerated de-materialisation.

5.1.3. Shocks on Instruments to Obtain Normalised Impacts

The results of policy simulations undertaken with the GEME-E3 World model have been aggregated into three world areas in order to correspond to the geographical specification of the stochastic model: OECD Europe, Rest of OECD and Developing Countries. Table 5-1 gives an overview of the shocks introduced to the policy instruments (all shocks were introduced from 1995 to 2030). The results presented below are aggregates for the European region.

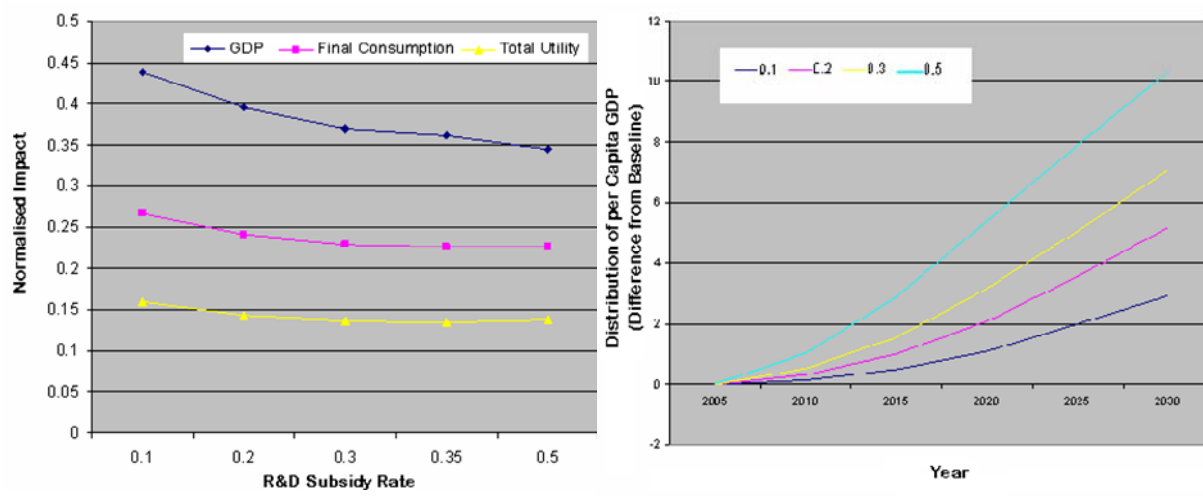
Table 5-1: Synthetic list of policy runs with the GEM-E3 World Model

Single Policies:					
	Required Emissions Reduction:				
CO ₂ taxation on Firms to reduce emissions by:	5%	10%	15%	20%	
CO ₂ taxation on Firms and Households to reduce emissions by:	5%	10%	15%	20%	
Tradable permits for firms (grandfathering) to reduce emissions by:	5%	10%	15%	20%	
	Subvention by:				
Employers' Social Contribution Rate	5%	10%	15%	20%	
R&D Subsidies	10%	15%	20%	35%	50%
Combined Policies:					
	Required Emissions Reduction:				
Tradable permits for firms (grandfathering), CO ₂ taxation for Households, to reduce emissions by:	5%	10%	15%	20%	
Tradable permits for firms (grandfathering), CO ₂ taxation for Households, recycled by ESC rate reduction, to reduce emissions by:	5%	10%	15%	20%	
Tradable permits for firms (grandfathering), CO ₂ taxation for Households, recycled by ESC rate reduction and 30% subsidies to R&D, to reduce emissions by:	5%	10%	15%	20%	

As illustrated in Figure 5-1 on the left, the impact of R&D subsidies in terms of GDP gains and final consumption decreases with the level of subsidy rate. Impacts on total utility decline for shocks up to 35%, but increase thereafter. Two factors explain this result: first the further reduction of pollutants emitted, resulting from productivity gains accruing from enhanced R&D activity and second the increased labour productivity, which exerts a positive impact on economic utility of households. This example illustrates the non-linear response of economic indicators to the level of instrument used.

Figure 5-1 on the right illustrates the impact of R&D subsidies on the Relative Convergence Indicator. Taking the 30% subsidy level as an example, it can be seen that the average deviation of GDP per capita in European countries increases by approximately 7000 \$95 in 2030, indicating an important increase of earnings discrepancies inside European countries.

Figure 5-1: Impacts of R&D Subsidies on GDP, Final Consumption and Total per capita Welfare in 2030 (left) and on the Distribution of GDP per Capita (differences from Baseline-right)



As regards the impacts on GDP, final household consumption and total welfare of carbon taxation on firms and households, the results indicate increasing macroeconomic costs with the level of the CO₂ constraint which clearly reflect the increasing marginal emission reduction costs.

A final case examined has considered the imposition of a CO₂ emissions constraint (20% reduction), recycled through a reduction of employers' social contribution rate and a 30% R&D subsidy. The results on the main macroeconomic indicators are presented in Table 5-2 below:

Table 5-2: Macro-Economics Indicators For Europe (% deviation from Baseline)

	2005	2010	2015	2020	2025	2030
Gross. Dom. Pro./Capita	-0.5	1.5	3.8	6.6	8.7	11.3
Total Consumption/Capita	-1.3	0.2	1.9	4.2	5.9	8.4
Final Cons. Energy/GDP	-6.4	-9.0	-12.4	-16.1	-18.7	-21.7
Employment	0.1	0.1	0.0	0.0	-0.1	-0.1
Household Disposal Income	-1.1	0.4	2.0	4.2	5.8	8.2

Compared to the baseline, this case leads to significant improvement in the competitiveness of the European economy, while stabilising the employment level. GDP per capita rises by 11% in 2030. However, the GINI coefficient for total incomes is considerably higher (8% increase in 2030) indicating that growth grounded on R&D and productivity improvements may lead to considerable increases in social inequalities, unevenly favouring returns to capital over labour incomes.

Table 5-3: GINI Index for Total Incomes (% deviation from Baseline)

	2005	2010	2015	2020	2025	2030
Europe OECD	2.7	3.0	4.3	5.5	6.5	7.9

5.2. A reduced CGE Model with Dynamic Characteristics

The present Computable General Equilibrium (CGE) analysis also draws from the use of a smaller in terms of regional and sectoral coverage CGE model. The analytical framework is based on an existing multi-sector, multi-region CGE model (the core CGE model) which, in the present context, has been further developed and considerably enhanced with a view to specifically serve the research needs of the MINIMA-SUD project. The model extensions include an update of the underlying database for global trade from GTAP5 to GTAP6, the incorporation of most recent baseline projections on regional developments up to 2030 (based on the International Energy Outlook), the incorporation of various analytical chains from policy instruments to impacts on sustainable development indicators and the integration into the model of non-CO₂ greenhouse gases.

A major task has also involved the development of a dynamic intertemporal specification of the core CGE model. This has been an essential task, as key issues in Sustainable Development policy involve

applications over longer time periods. A dynamic framework is essential to capture the adjustment path of economies during the transition towards some SD targets in the future. On the consumption side, dynamics involve the representation of the savings behaviour of households. On the production side, dynamics involve the description of investment decisions (including resource exploration and extraction strategies) of firms. There are two basic approaches to handle dynamics: (i) the dynamic-recursive framework based on myopic expectations, and (ii) the fully intertemporal setting with perfect foresight. Adopting a dynamic-recursive approach the static core model is solved for a sequence of temporary equilibria with consumers allocating income between present and future consumption (through savings) at each point in time. Savings is based on the expected return assuming myopic predictions (i.e. the households assume prices to remain constant). Myopic expectations are also assumed on the production side of the economy. Equilibrium ensures the saving-investment equality. The path for the economy is a set of connected equilibria where the current period's savings augment capital in the next period. Following the intertemporal approach the static model is cast into an intertemporal setting where consumption and investment decisions are based on rational expectations of future prices (Lau et al., 2002). This assures that the effects of policy interference on savings and investments are consistently taken into account. The intertemporal framework reveals effects of policy changes on intertemporal consumption and investment (savings) decisions, permits measurement of transition costs (inter-sectoral adjustments) and rates of resource depletion as well as long-term growth effects, which can be significant relative to long-term gains.

5.2.1. Baseline

A business-as-usual scenario has been developed against which the impacts of alternative policies on sustainable development indicators can be measured. For the quantification of this scenario, official projections on country/region specific development of GDP, fossil fuel production, international fuel prices and carbon emissions have been taken into account, as derived from the International Energy Outlook (IEO – DOE 2005). The calibration has been based on the most recent version 6 of the GTAP database which provides detailed input-output tables and bilateral trade flows for 57 commodities and 87 regions for the base year 2001.

Following the GTAP dataset and IEO projections, the regions have been ranked (using a weighted average) on the basis of their GDP, population and carbon emissions. Table 5-4 below indicates the countries/regions that might be of major importance for targeting sustainable policies over the next three decades.

Table 5-4: Key Regions in terms of GDP, population and CO₂ emissions*

	GDP	Population	CO₂ emissions
China	6.6	19.1	19.5
Japan	9.8	1.7	4
India	2.5	16.5	4.8
United States	34.5	4.2	21.2
Germany	4.4	1.1	2.8
Russia	1.1	1.9	5.2
Rest of Middle East	2.6	3.6	4.9
Total	61.5	48.1	62.4

in % of world total (averaged between 2000-2030)

In order to warrant coherence with the regional dimension of the stochastic module developed within MINIMA-SUD, the 87 countries/regions of GTAP6 have been aggregated to 3 major regions: Europe OECD (EUR), Non-Europe OECD (OEC) and Rest of World (ROW). The regional, sectoral and factor aggregation of the model are summarized in the following table:

Table 5-5: Model dimensions

Production sectors		Regions and primary factors	
Energy	Non-Energy	Regions	Primary factors
Coal	Energy-intensive sectors	Europe OECD (EUR)	Labor
Crude oil	Other manufactures and services	Other OECD (OEC)	Capital
Natural gas	Savings good	Rest of World (ROW)	Fixed factor resources for coal, oil and gas
Refined oil products			
Electricity			

5.2.2. Climate Policy Scenario

The intertemporal CGE model has been applied to examine the implications of the implementation of a unilateral carbon tax policy within the EUR region. The carbon tax is levied from 2010 onwards at a constant real value throughout the time horizon (i.e. until 2030). A large number of carbon tax scenarios have been assessed, augmenting the tax rate in discrete steps. The tax simulations yield associated changes in selected sustainable development indicators establishing reduced form representations of policy instrument dose to indicator response.

The results on welfare changes – as an intertemporal measure of changes in lifetime income for the representative agent in region EUR – indicate that despite the possibly highly non-linear technological and behavioral relationships reflected in the CGE framework, there is a rather stable (linear) relationship between the level of the carbon tax and the induced loss in economic welfare.

The results suggest that carbon taxes as high as 100€ per ton of carbon are necessary to effect emission reductions of more than 20% *vis-à-vis* the baseline scenario. It should be noted that these results refer to effective emissions reductions in the EU without accounting for partially offsetting leakage in the two remaining world regions which do not undertake equivalent carbon tax policies. Neglecting the benefits of emission reductions, emission taxes restrict the “free” use of energy, thereby reducing aggregate productivity of primary factors and real income of the EU economy. The loss in real income is reflected in a decline of GDP and its components – consumption and investment – over the time horizon. The higher the carbon tax, the more pronounced the decline in these macroeconomic indicators. As regards sectoral competitiveness aspects, carbon taxes aim at a structural change towards less carbon intensity. Consequently, production of energy-intensive industries is negatively affected. These adverse effects for the EU energy-intensive industry are further amplified, as important trading partners face a cost advantage in energy-intensive production since they do not levy equivalent domestic carbon taxes. This has a negative effect on the competitiveness of the European economy, in terms of changes in its RCA (Revealed Comparative Advantage, measured as the ratio of exports and imports for the EU energy-intensive industry over the ratio of exports and imports for all EU industries).

5.2.3. Monte-Carlo Sensitivity Analysis

The extent to which policy instruments alter sustainable development indicators depends crucially on the responsiveness of supply and demand with respect to price changes (i.e. elasticities). In order to evaluate the sensitivity of the CGE estimates with respect to uncertainties in the elasticity space, Monte Carlo simulations for core elasticity parameters were conducted. In each randomised simulation values for critical trade and fossil fuel supply elasticities (which determine the economic adjustment costs to emission constraints) were drawn from uniform probability distributions around the model central values. Table 5-6 below provides a statistical summary of results for key model responses for the EU region at a carbon tax level of 100 US\$ per ton of carbon. The results – which are representative for other tax levels as well – confirm robustness of the dose-response-relation with respect to major changes in the parameterisation of elasticities.

Table 5-6: Monte Carlo sensitivity analysis (EU carbon tax of 100€ per ton of carbon)

Indicator	25% quantile	50% quantile	75% quantile	mean
Welfare (in % HEV of income)	-0.23	-0.23	-0.22	-0.22
CO ₂ (in % from BaU)	-18.70	-18.60	-18.40	-18.56
GDP (in % from BaU)	-0.41	-0.39	-0.38	-0.39
Investment (in % from BaU)	-1.11	-1.09	-1.08	-1.09
Consumption (in % from BaU)	-0.05	-0.05	-0.04	-0.05
Production of EIS (in % from BaU)	-1.06	-0.91	-0.75	-0.90
RCA of EIS (in % from BaU)	-1.71	-1.39	-1.04	-1.38

6. Stochastic Modelling

6.1. Introduction

Policy integration has been carried out in a non-deterministic environment and therefore a considerable amount of effort has been devoted to assessing the risks associated with the whole chain from policy instrument to impact on the objective. This effort involved the development of a stochastic model which contains reduced form stochastic versions of the path from instrument to objective as modelled in the large scale deterministic analytical tools. The stochastic model contains relations and exogenous variables for all the main quantities that are of interest in the MINIMA-SUD project. These include demographic and economic activity indicators, energy consumption by main fuel, fuel resources and prices, greenhouse gas emissions and concentrations, average temperature change, health impacts as well as impacts on buildings and agriculture, congestion indices, technology uptake and two factor learning curves. In short it contains most of the salient features of the models/analytical chains used in the deterministic modelling process. Naturally these are represented in reduced form, but specific effort has been made to retain the key structural elements as these are the main vehicles through which stochastic dependence of the impacts is established.

By necessity the stochastic model is highly aggregate, especially in terms of regional coverage. It covers the following regions: OECD Europe, Rest of OECD and Less Developed Countries¹⁰.

Since for the integration process it is important to consider the total cost of a measure (direct “private” costs as well as indirect costs through secondary impacts to the economy) and in order to fulfil the requirements of providing the stochastic dimension to the economic analysis, a more aggregate stochastic version of the GEM-E3 model has been developed. This is summarily presented in the following section. The chapter proceeds with a brief description of a summary stochastic climate module, developed in the context of the MINIMA-SUD project to provide stochastic evaluation of the impacts of policy instruments on global temperature change (section 6.3). It ends with the analysis of the stochastic outlook, which assesses the likelihood and ranges of key variables of interest in the MINIMA-SUD project.

6.2. Stochastic CGE Model

Most of the policies proposed in the MINIMA-SUD project involve economic instruments and at any rate, whatever the instrument, there are clear macro-economic implications regarding the cost of their application. General equilibrium models (and notably GEM-E3 World) have already been applied in the present project to serve the deterministic analysis of these issues. The stochastic dimension of the economic analysis is covered by the development of a more aggregate stochastic version of GEM-E3. Such a model is used to establish joint distributions of main economic aggregates allowing probability statements on results of GEM-E3 to be made i.e. derive variances and co-variances of impacts of policies on key economic indicators and the cost of applying them. This provided essential input for the TIPA policy exploration tool (see chapter 9).

In attempting the development of such a model, it soon became apparent that research was being directed into essentially uncharted territory as no stochastic GE models exist. In fact there are very few econometrically estimated GE models developed in the US taking the form of one sector models with one productive sector (GDP and no intermediate consumption). The main reason for this state of affairs is the difficulty encountered in obtaining consistent and sufficiently long time series data at a more detailed level (Social Accounting Matrices). In fact mere econometric estimation is not enough to build an operational stochastic model. It is also necessary to obtain good statistical properties of the estimators and overall robustness of specification to ensure that the stochastic model will perform under “extreme” conditions as well as improve on mere “random walk” type of distributions (keep variances sufficiently low and co-variances sufficiently significant to retain some usefulness in the results).

¹⁰ OECD Europe includes the EU-15 member states plus Norway and Switzerland, the Rest of OECD includes USA, Canada, Japan, Australia and New Zealand and LDCs include all non-OECD countries plus the Czech Republic, Hungary, Korea, Poland, Slovak Republic, Mexico and Turkey, which have joined OECD after 1990

Considerable difficulty has been encountered in constructing the full data series, justifying the paucity of econometric work on full CGE models. To begin with, input-output tables are available every 5 years in the best of cases. Intermediate years were computed through a RAS method. Data concerning output, intermediate consumption and final uses was only available at an aggregate level, therefore a considerable effort was devoted to their disaggregation using information from various detailed surveys (Industrial, Agricultural, Energy). For EU Countries, data for the period before 1995 was incompatible with the more recently compiled data (ESA 79/ESA 95 differences) and hence had to be translated to the ESA95 format. Published tables are expressed usually in value terms while the model necessitates separately price and volume data; to calculate consistent time series a procedure similar to the ESA95/ESA79 case has been followed. Finally, some countries like the USA, France and Canada (especially after 1995) publish Supply and Use tables which had to be transformed into Symmetric Input-Output tables utilised GEM-E3.

The stochastic model specification identifies four productive sectors (agriculture, energy, industry and services) and assumes perfect competition in output and factor markets. It uses nested CES production functions, involving intermediate goods, labour and capital. Demand for production factors is derived from profit maximisation behaviour while the comparison of the available stock of capital in the current year with the desired one determines the volume of investment decided by the firms. Concerning trade it is assumed that commodities by origin are not perfect substitutes and an Armington assumption is made involving a composite good: combination of domestic and imported goods. A nested CES allocation demand to commodities by origin is obtained from Shephard's lemma (cost minimising mix and endogenous bilateral trade flows). Household behaviour involves maximisation of consumer's utility. A representative Household is assumed allowing for the derivation of consumer demands by product. The parameters are established by econometric estimation of the Linear Expenditure System derived from utility maximisation.

The model has been estimated using the Three Stages Least Squares method, which produced more "robust" estimates relative to alternative methods tested. Within the MINIMA-SUD project the main purpose of the estimation is to provide input in the form of distribution characteristics for the parameters and residuals that are used in the stochastic model, which is subsequently used to produce Monte-Carlo sets on the economic variables of interest. Under this light obtaining the characteristics from the estimation of the static version (levels) results in very large variability (connected to the variability of key parameters) in the early years of the run of the stochastic model, which tends to increase very modestly over time (due to white noise factors). This is clearly counterintuitive since it violates the generally accepted and highly reasonable hypothesis that the uncertainty surrounding the outcome on economic variables increases steadily and markedly the further the projection recedes into the future. The problem with the time profile of variability is virtually eliminated if a dynamic set of equations is used in the estimation and subsequently introduced into the stochastic model despite the fact that the conventional statistics of such dynamic equations generally turn out to be inferior to those obtained when estimating the static (level) version. The dynamic set of equations however presents another problem, as some shift parameters are eliminated in its derivation. The stochastic model has an annual frequency. On the other hand adjustments of the economy to given conditions and especially some of the policy instruments considered in MINIMA-SUD may take longer to be completed as they involve changes in the capital stock. As a result, one period time-lag is often inadequate to reveal the long term properties of the estimated parameters. The solution to this problem arising in the estimation of the equations and their implementation in the stochastic model has been the introduction of Polynomial Distributed Lags (PDL), which are characterised by considerable flexibility regarding the depth of the lag and the time profile of lagged effects without a big loss in degrees of freedom that – given the relatively short samples used for the estimation – could result in poor statistics of the estimated parameters.

To tackle the problems mentioned above and maintain a stochastic model with the desired properties a two stage approach has been adopted where the most suitable PDL structure is established in the first stage while in the second stage the dynamic equations are estimated jointly with a set of equations expressed in levels allowing for the identification and estimation of the shift parameters.

The construction of the stochastic CGE model constitutes an innovative task. However, the models' relatively simple structure, especially in terms of sectoral coverage, has meant that it has not been possible to evaluate stochastically all the policy instruments considered within the project and in particular policies that operate within a fairly narrow part of economic activity (e.g. urban transport,

electricity production etc). Still, the model has provided broad reduced form indications of the joint probability distributions of the impacts of some generic instruments such as consumption or business taxation direct government investment etc. Such information was useful in constructing the impact on welfare constraints used in the integrated policy analysis using the TIPA Decision Tool (see chapter 9).

The model itself has a much wider scope for applications in policy analysis where notions of risk play an important role. It has also become a new reference for estimates of key elasticities for Computable General Equilibrium models particularly since, unlike most econometric studies providing such estimates that are based on partial equilibrium specifications the current work was based on a General Equilibrium specification from the outset.

6.3. Stochastic Modelling of Climate Change Processes

The majority of existing climate models are essentially deterministic in character: although their projections provide interesting insights as to the course of climate change variables (such as temperature) they do not give any quantitative information as to how likely some occurrences may be (for example the probability of observing an increase in temperature more than 1°C in the next 50 years). Moreover, the uncertainty underlying the chaotic and non-linear climate system is underestimated.

The stochastic module developed in the context of the MINIMA-SUD project belongs to a relatively new family of simplified stochastic climate models. The module includes reduced, parameterised forms of atmospheric dynamics and recognises uncertainties arising from imperfect knowledge of the climate system and notably the parameters included in the module. All exogenous variables, parameters and error terms are stochastic and there is explicit representation of their distribution including terms of covariance. This means that all endogenous variables are also stochastic. The output of the model is the distribution of emissions, concentrations and global temperature.

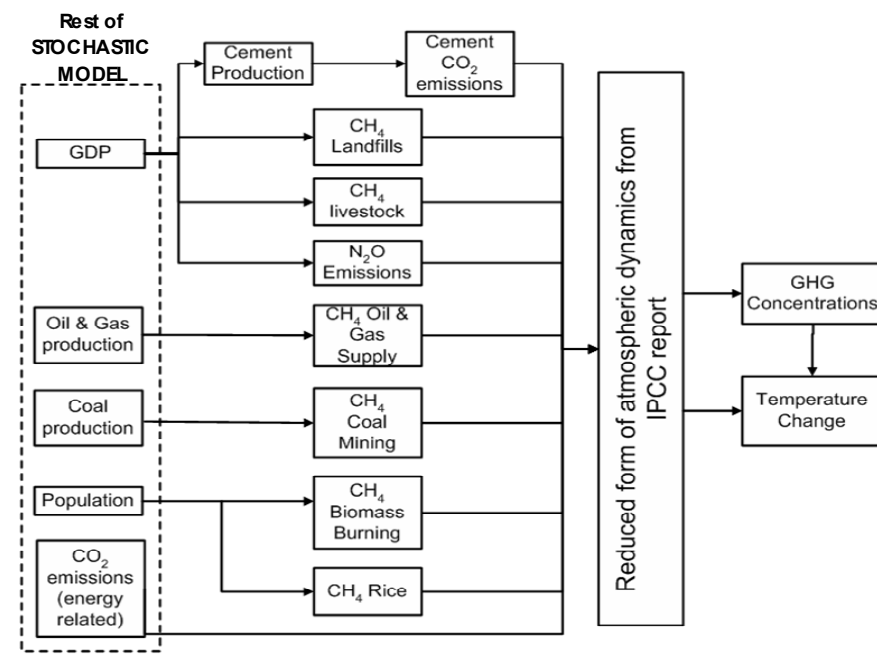
The module's forecast horizon is the 2003-2050 period, plus 15 years for "additional warming commitment". According to IPCC TAR the climate system requires some years to come into equilibrium with a change in forcing (a change in greenhouse gas emissions/concentrations). The "additional warming commitment" is the further increase in temperature, over and above the increase that has already been experienced, that will occur before the system reaches a new equilibrium with radiative forcing stabilised at the current value.

The model calculates CO₂ emissions from fossil fuel combustion and industrial processes, N₂O emissions from industrial and land uses, CH₄ emissions from biomass burning, landfills, livestock, rice farms, oil & gas supply and coal mining, their atmospheric concentrations and global temperature.

Figure 6-1 presents an overview of the stochastic climate change module and its interaction with the rest of the stochastic model. The required input to the module is a set of key drivers, which determine the anthropogenic emissions from processes other than fossil fuel combustion since the latter are provided by the stochastic energy model. This set of drivers consists of economic activity, population and fossil fuels production. Economic activity is the main driver for cement production, which drives CO₂ emissions from industrial processes, for CH₄ emissions from landfills and livestock and for N₂O emissions. The production of fossil fuels determines the CH₄ emissions from energy-related processes, while population affects the CH₄ emissions from biomass burning and rice farms.

Based on IPCC TAR reduced form equations of the atmospheric dynamics were estimated, which take into account the uncertainty underlying the interaction of the main components of the climate system (atmosphere, hydrosphere, cryosphere, land surface and biosphere). The anthropogenic emissions constitute the main input to equations enabling the calculation of the atmospheric concentrations and the estimation of global temperature.

Figure 6-1: Overview of the stochastic climate change module



6.3.1. Methodological considerations

The stochastic climate change module relies heavily on the use of extensive econometric techniques in order to obtain the detailed stochastic information required for as complete a representation of the interaction of climate system components as possible. One of the main advantages of this methodology is that it provides an element of objectivity. Moreover, it is amenable to the analysis of co-variance both in terms of statistical dependence of the parameters and in terms of the simultaneous solution of sets of econometrically estimated equations. It also tends to force the analyst to investigate the nature and extent of stochastic elements (why past variability occurred). On the negative side however, this implies an excessive reliance on the evidence from history. However, it is not clear whether this reliance leads to exaggeration or under-estimation of variability – therefore the method does not in itself produce systematic bias.

Econometric estimation has been in many cases supplemented with risk assessment provided by scientific expertise particular to the uncertainties associated with knowledge of greenhouse gases accumulation in the atmosphere and its effects on climate change. The IPCC Third Assessment Report was the main source of such scientific expertise.

6.3.2. Estimation and calibration of the stochastic climate change module

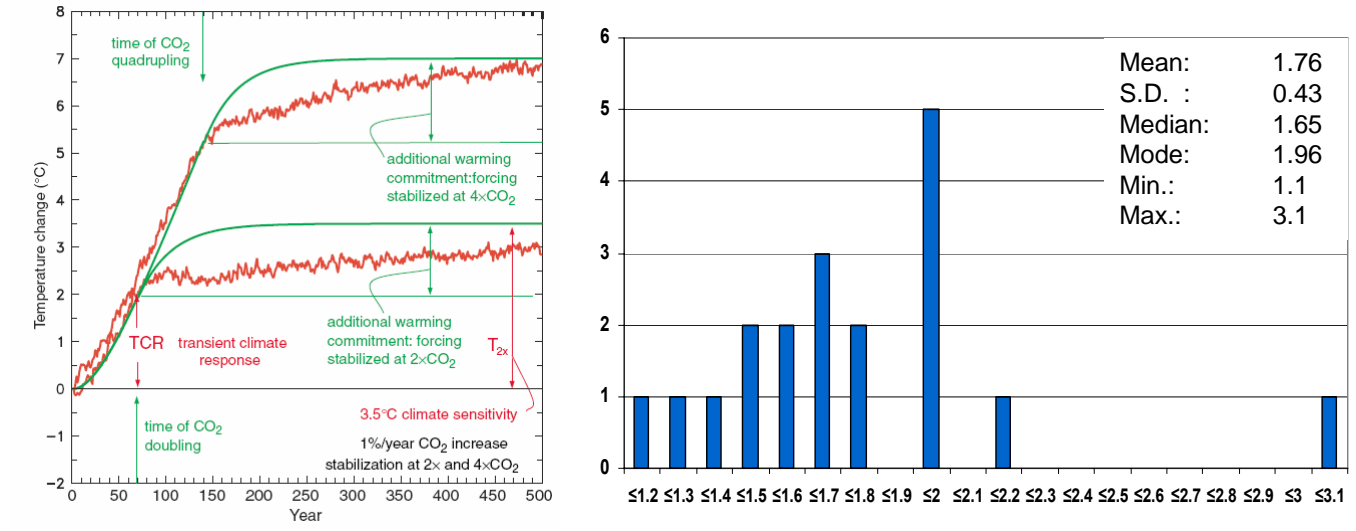
To estimate the stochastic climate change module, time series regarding the anthropogenic greenhouse gas emissions by source, their atmospheric concentrations and the global average temperature change were needed. This has necessitated taking into account different data sources, which cover different time periods. Data validation was performed in the overlapping years of the various sources in order to reconcile their differences.

The module calculates the emissions, concentrations and temperature for a set of at least 1000 scenarios using the Monte-Carlo approach. However, since the module is a simplified climate model it is necessary to adjust the mean of each distribution in order to be compatible with the results of more detailed, and complex, models. The calibration process was performed for anthropogenic emissions and temperature. The former was based on the results of POLES and IMAGE2.2 world models. For the mean of the temperature variable a standardised climate change scenario needed to be taken into account. According to IPCC TAR, a common standardised “forcing” scenario is the “1%/yr increasing CO₂” scenario, which specifies atmospheric CO₂ to increase at a rate of 1%/year compound until the concentration doubles (or quadruples) and then is held constant. The global mean temperature change which occurs at the time of CO₂ doubling for this scenario is termed the “transient climate response”

(TCR) of the system. The range of TCR value serves to illustrate and calibrate differences in model response to the same standardised forcing.

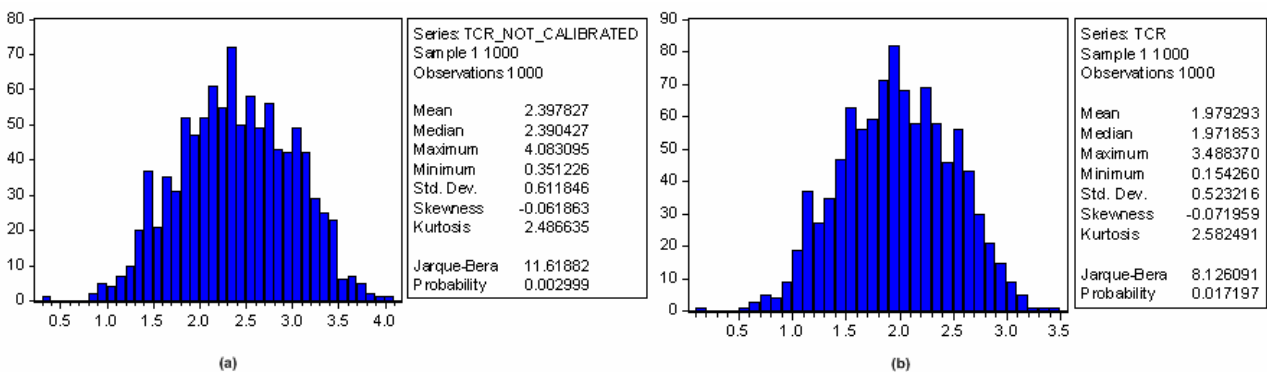
Figure 6-2, taken from IPCC, illustrates the global mean temperature evolution for this standardised forcing in a simple illustrative example with no exchange with the deep ocean (the green curves) and for a full coupled AOGCM¹¹ (the red curves). The diagram also illustrates the TCR, climate sensitivity and warming commitment. The figure illustrates the idealised case of instantaneous stabilisation at 2x and 4x CO₂.

Figure 6-2: Global mean temperature change for 1%/yr CO₂ increase with subsequent stabilisation of CO₂(left) and the distribution of the TCR results from the 19 models that have simulated the “1%/yr increasing CO₂) exercise in IPCC TAR (20-year average 61-81 global mean) on the right



Implementing the “1%/yr increasing CO₂” in the stochastic climate change module resulted in a mean TCR higher than the mean TCR of the results reported in IPCC TAR (2.4°C instead of 1.8°C). Figure 6-3a below presents the distribution of TCR from the stochastic climate change module without adjusting the mean. Although the non-calibrated mean TCR resulting from the stochastic climate change module lies inside the range of the results from the models participating in IPCC TAR, it was decided to adjust the mean to reproduce the mode (i.e. the value that occurs most often) of the IPCC TAR transient climate response distribution. Figure 6-3b presents the distribution of TCR after adjusting the mean.

Figure 6-3: Distribution of TCR from stochastic climate change module: a) without calibration of the mean, b) calibrating the mean to the mode of IPCC TAR transient climate response distribution



In order to test and evaluate the stochastic climate change module an exercise was performed by increasing the baseline abatement effort by 30€/99/tn of CO₂ (case CV+30). Despite the strong policy assumptions suggested by the CV+30 scenario summary temperature statistics are not affected

¹¹ Three-dimensional Climate Models or coupled Atmosphere-Ocean General Circulation Models

significantly (the mean and median are decreased by barely over 0.1°C) and extremes are little affected. However, as shown in Table 6-1 the stronger policy has substantially reduced the probabilities of exceeding some key thresholds beyond which considerable damages are supposed to occur.

Table 6-1: Change in probabilities

	Baseline	CV+30
Probability of more than 2°C increase (relative to pre-industrial levels)	22.1	11.4
Probability of observing more than 0.3°C highest temperature increase in any decade	46.8	34.3

6.4. Stochastic Outlook

This section presents the baseline stochastic outlook of the sustainable development indicators considered in the stochastic model. The demographic and macroeconomic outlook is presented first, due to the fact that population growth and economic activity influence most of the indicators. Then for each sustainable development indicator a brief uncertainty analysis is given, which focuses not only on the indicator *per se* but also on the main drivers affecting the specific indicator.

6.4.1. Demographic and macroeconomic outlook

World population is expected to increase in the next 50 years, but at lower rates compared to the period 1970-2000 (hereinafter referred to as the historical period). It is unlikely to observe a higher average annual growth rate in 2000-2030 than the historical one in all regions considered in the model. Moreover, a deceleration in the period 2030-2050 is expected. This deceleration, which in stochastic analysis takes the form of low probabilities of attaining historical growth, is predicated on secular trends (evident over a number of years) suggesting an aging of the world population and a natural decline in fertility rates in the less developed regions.

Concerning economic activity, the expected average annual growth rate in all regions considered is lower than the historically observed. The above is consistent with a general trend of diminishing marginal productivity of capital, labour and knowledge. Over the whole period the probability that LDCs as a group will start diverging from European GDP per capita is less than 1%. On the other hand, there is a negligible probability that their GDP per capita will have reached the European levels in 2050. Europe is gradually converging to North America and Japan. The probability that the GDP per capita in Europe will still be lower than the GDP per capita in the Rest of OECD in 2050 is around 70%.

6.4.2. Depletable resources

High uncertainty surrounds the amount of oil and gas that is yet to be discovered and this uncertainty has been incorporated into the stochastic model. The rate of discovery as well as the rate of recovery for oil and gas are endogenous in the stochastic model, depend on fuel prices and are subject to their own specific uncertainties. For gas it is assumed that often oil is sought and gas is found. The oil and gas resources to production ratios incorporate both discovered and undiscovered reserves (as emerging from the stochastic model), since it was found that the conventional definition of the reserves to production ratio depends heavily on projected discoveries.

In 2001 the oil resources to production ratio (including conventional and non-conventional oil) was 234 years. This high ratio is mainly attributed to non-conventional oil resources, which are not fully exploited due to their high extraction costs compared to the oil price in 2001. According to the stochastic model results, the probability of exceeding the 2001 figure in 2050 is only 0.5%, while the same probability in 2010 is 11.6%. This implies that non-conventional oil increases its share in world oil production, because of high oil prices. Non-conventional oil compensates for the continuous decline in non-Gulf oil production and there is 5% probability that almost 70% of world oil production in 2050 comes from non conventional oil.

Considering gas resources to production ratio, the probability to exceed the 2001 figure (which was estimated at 230 years) is 0%; the same probability in 2010 is 3%. This suggests a higher rate of depletion than that which pertains for oil.

6.4.3. Energy

Final consumption (Europe)

It is expected that final consumption in European industry will be reduced in the next 50 years, due to continuing de-industrialisation, continuing improvements in efficiency and de-materialisation of industrial production. Electricity plays an important role in industrial final consumption for the next 50 years, however its average annual growth rate in the period 2000-2030 is unlikely to exceed its historical growth rate (equal to 2% on average). Coal consumption is expected to decrease due to secular trends away from coal but also to ever intensifying climate policies. However, there is 19% probability that coal actually grows in industry as a result of high oil and gas prices. Oil consumption is also expected to decrease from its 2000 levels. Natural gas consumption has zero probability to exceed its historical growth rate (3.5%).

In the residential, services and agricultural sector, a reduction in total final consumption from its current levels is expected and it is unlikely to observe the historical growth rate. Gas consumption is affected by high, on average, gas prices; in 2050 there is a 99% probability that gas consumption in Europe will be lower from its 2000 levels. Electricity is and it is expected to remain a dynamic part within the residential, services and agriculture final consumption.

In the transport sector, a reduction in oil consumption is expected, due to saturation effects in human mobility, the improvement of car efficiency and the penetration of the more efficient (in terms of oil consumption) hybrid car.

Energy cost to the European consumer

In 2050 on average 74% (down from 78% in 2000) of the energy cost to the consumer is attributed to mobility costs and electricity consumption costs. There is 62% probability that the electricity price to industrial consumers in 2050 will be higher than in 2000; the same probability for residential consumers is 30%. On the other hand the probability that the gasoline price will be higher in 2050 than in 2000 is almost 100%.

The energy cost to consumer indicator is correlated with GDP, international fuel prices and fuel consumption. The strongest positive correlations occur between GDP, final consumption and fossil fuel prices. Economic activity drives final consumption, which in turn leads to higher prices and consequently to higher energy costs. The strong correlations between energy cost and oil price reflects the significant share of mobility cost to the total consumer cost. In addition, the strong correlation between energy cost and gas price reflects the significant share of electricity cost (electricity is mainly produced from gas) in energy cost as well as the significant share of gas in final consumption. The correlation with coal price is small due to the small share of coal (relative to other fuels) in final consumption.

6.4.4. Climate change indicators

Assuming no policy response in the stochastic model baseline would be equivalent to stating that there is no probability of such policy anywhere in the World for the next 50 years. Such an assumption alters the stochastic model results from “maximum likelihood” to conditional distributions. It was therefore necessary to construct joint distributions for carbon values in the different world regions using data obtained from questionnaires addressed to experts. It is assumed that the EU leads the world climate abatement effort, followed by lesser efforts in other industrialized regions. Developing regions undertake abatement efforts only after industrialised regions do and their efforts are smaller or equal to those in industrialized regions.

The main drivers of greenhouse gas emissions are economic activity, population growth and primary consumption of fossil fuels. Regarding the latter – and despite rising carbon values – coal consumption is expected to increase faster than oil and gas. This occurs in all regions except Europe, where the carbon values are on average high enough to prevent it. Two reasons explain this: the first is high oil and gas prices; the second is that China and India have large coal resources and – according to the stochastic model results – it is unlikely that they will desist from their exploitation in view of paucity of large scale alternative energy sources. Increasing gas scarcity results in progressively increasing gas prices, leading to a gradual decrease in gas consumption which is particularly evident after 2030. Oil consumption decreases in developed countries due to higher oil prices.

The high likelihood of a strong climate policy in the developed world, the reduction of energy demand, the increased contribution of non-fossil fuel technologies in power generation and the penetration of CO₂ capture and storage technologies lead to a marked deceleration in energy related CO₂ emissions growth, which however remains positive with a probability of over 99%. The probabilities to exceed the historical average annual growth rate are 9% for energy related CO₂ (historical: 1.8%) and 14.1% for CH₄ (historical: 1.3%), while for N₂O and non-energy related CO₂ they are zero (historical: 2% and 3.4% respectively).

The mean projected temperature increase in 2065 from 2003 levels is approximately 1°C. The probability of a temperature increase of more than 2°C from pre-industrial levels (average of 1861-1890) is 22.1%.

6.4.5. Transport related indicators

Transport activity (vehicle kilometres) per capita increases on average in the next 30 years at a rate of 0.1%/yr. It is also surrounded by considerable uncertainty, reflected in the high probability (41.5%) that transport activity in 2030 will be lower than in 2002. The above results point to saturation phenomena in human mobility in Europe.

The expected average annual growth rate of traffic congestion (measured as total hours spent in driving) is 0.74% whereas the probability that traffic congestion in 2030 will be reduced relative to 2000 is less than 2%.

In 2030, in Europe, the probability that the noise emissions from transport activity will be higher than in 2000 (estimated at 86.4 dbA) is 99.5%. The uncertainty surrounding noise emissions is small.

Road accidents are affected by transport activity and cumulative road infrastructure investments. According to the stochastic outlook in Europe, on average a slight decrease in road accidents is expected by 2030. This decrease can be attributed to saturation in transport mobility, increased infrastructure investments and improvements in car safety. The expected average annual growth rate is -0.3%/yr for the period 2000-2030. However, the distribution of the average annual growth rate of road accidents points to large uncertainty. There is a 45% probability that road accidents may increase in the next 30 years.

6.4.6. Health, buildings, agriculture and ecosystems

All indicators related to human health (except asthma) are expected to improve in 2020 relative to 2000, due to the penetration of more efficient technologies (vehicles and electricity production technologies), the reduction of the share of coal in electricity generation and the introduction of filters for capturing SO₂, PM₁₀ and NO_x emissions.

The expected average annual growth rate of mortality from air pollution is -2.8%/yr while the probability that the mortality rate in 2020 will be higher than in 2000 is only 8%. The expected average annual growth rate of congestive heart failure cases among adults above 65 years of age is -1.06%/yr over the 2000-2020 period. However, there is a 30% probability that the cases will be increased in 2020 from their 2000 levels. The expected average annual growth rate of asthma cases among children is 2.8%/yr and the probability to observe a decrease in children asthma by 2020 is 8% (relative to 2000). Concerning restricted activity days from air pollution, their expected average annual growth rate is -2.8%/yr, while the probability that the indicator will deteriorate in 2020 is 15%. Finally, the expected average annual growth rate of respiratory hospital admissions from air pollution is -2.9%/yr, while the probability that these admissions will increase in 2020 compared to their 2000 levels is almost 7%.

The expected average growth rates of all indicators related to buildings, agriculture and ecosystems are negative due to the expected reduction in the contribution of coal in power generation, the penetration of the more efficient and less polluting gas turbine combined cycle plants and the introduction of filters for removing SO₂ and NO_x emissions in power plants. The expected average annual growth rate of the monetary damage to buildings for the period 2000-2020 is -0.9%/yr. Despite the fact that a strong reduction in the pollutants causing the damage is projected, the probability that this indicator will deteriorate in 2020 is still 40%, mostly due to increases in the costs of restoring such damage. The expected average annual growth rate of the monetary damage to crops is -2.4%/yr, whereas the

expected average annual growth rate of the area (in km²) of ecosystems for which the critical loads for acidification or eutrophication are exceeded is -6.2%/yr.

Correlations between human health, buildings, agriculture and ecosystems indicators

The correlations between the human health indicators are very strong and positive (correlation coefficients range from 0.7 to 0.95). Correlations between the indicators related to environment are stronger for those indicators which are mostly affected by the same pollutant; for example the correlation between monetary damage to materials and monetary damage to crops is 0.91 due to the fact that both are affected by SO₂ emissions and dispersion. Correlations between damage to ecosystems and all health indicators are significantly lower (between 0.4 and 0.5) as the former indicators are primarily affected by SO₂ and NO_x emissions and not by PM₁₀ emissions, which display the heaviest impact on human health.

6.4.7. General remarks on the stochastic outlook

An analysis of correlations between some key variables and the sustainable development indicators reveals a key feature of the outlook as derived from the stochastic model: the uncertainty concerning sustainable development lies mostly along an axis dominated by economic activity. High growth in economic activity is associated with:

- Fast fossil fuel resource depletion resulting in slower reserves addition, tighter fuel supply and ultimately high or even very high international prices
- Higher emissions of CO₂ and other GHGs leading to high concentrations and increasing the risk of damaging climate change
- High R&D investments both because of the higher availability of funds generated from the higher activity levels but also as result of the urgency created by the higher fossil fuel prices
- Higher transport activity leading to higher traffic congestion and noise
- Higher emissions leading to higher mortality and morbidity.
- Higher damage to ecosystems due to acidification and eutrophication

7. Standardised Policy Shocks using the Stochastic Models

The standardised policy shocks provide essential input to the TIPA meta-model, which carries out exploration of sustainable development policy options in the context of multiple objectives in a non-deterministic environment (presence of risks). Since TIPA is specified as a policy exploration tool involving hedging, the stochastic properties of exercising a policy instrument had to be examined alongside its expected impacts. The provision of essential input to the TIPA tool apart, the standardised policy shock exercises provide useful insights on the comparative productivity of different policy options on the given policy objectives retained in MINIMA-SUD, as it emerges from the stochastic model results. The required stochastic input for TIPA is the expectation and the co-variance of the impact variables.

The sustainable development policy objectives considered in the present analysis (and in turn incorporated in the TIPA tool) are those presented in chapter 1. In the following, the selected sustainable development policy instruments are presented alongside issues related to the measurement of the impact of policies and problems associated with the measurement of policy costs; finally some key results on the standardised shocks performed with the stochastic model are given.

7.1. Policy instruments and sustainable development objectives

In accordance to the identification of possible instruments in chapter 1, a more precise set has been singled out for performing policy shocks and obtaining standardised impacts. This comprises of:

Government investment:

- R&D expenditure on renewable technologies (wind, solar, small hydro and biomass)
- R&D expenditure on nuclear technologies
- R&D expenditure on clean vehicles (hybrid, electric, fuel cells and hydrogen internal combustion engine cars)
- Investment in road infrastructure

Taxation policies:

- Carbon tax
- Internalisation of environmental external costs of electricity generation
- Taxation of oil in transport

Subsidies:

- Subsidies in fares for public transport

It is assumed that all policies are implemented within the European Union only.

7.2. Shocks setup in the stochastic model

The shocks were orthogonally applied on each sustainable development policy instrument at a time. In order to obtain quantitative information on possible non-linearities pertaining to the impact of policies on objectives (increasing or decreasing average impacts), three to five shocks were performed per policy instrument. All shocks were applied at the beginning of the forecast horizon (2006) and over the whole forecast period for which each objective is evaluated.

R&D expenditures: The R&D shocks were applied in three doses: doubling, tripling and quintupling the baseline annual R&D expenditures on renewables, nuclear and clean vehicles for the whole period 2006-2050.

Investment in road infrastructure: Four shocks were performed by increasing the baseline annual infrastructure investments by 1.5, 2.0, 3.0 and 5.0 times. This policy was applied over the period 2006-2030.

Additional carbon tax policy: Three shocks were implemented by imposing additional carbon tax in Europe by adding +10, +50 and +100 €/tn of CO₂ to the mean of the carbon tax distribution in Europe. The policy was applied over the period 2006-2050.

Internalisation of environmental external costs of electricity generation: Shocks were equal to the internalisation of 30%, 60% and 100% of the external costs, as derived from Case Study 4 of the ACROPOLIS project. The external costs were introduced as an additional tax on electricity. The policy was applied over the period 2006-2050.

Taxation of oil in transport: The oil taxation in road transport was assumed to be applied on all passenger and freight transport affecting all oil-based transport modes and not only private cars and trucks. Four shocks were performed by increasing the baseline gasoline and diesel tax by 50%, 100%, 200% and 400%. The policy was applied over the period 2006-2030.

Subsidies in fares for public transport: Three shocks were introduced as subsidies to the bus, train and tram fares equivalent to 30%, 60% and 90% of the values in the baseline. The policy was applied over the period 2006-2030.

7.3. Measurement of the impacts

The term “standardised impact” refers to the impact on an objective per unit of policy cost. The general formulation used for measuring the standardised impacts is:

$$\text{Standardised impact on objective } k \text{ of policy } i = (\text{Cumulative impact on objective } k \text{ measured in specific units}) / (\text{Discounted cost of policy } i)$$

In the following paragraphs a brief presentation of the specific measurement for each of the fourteen objectives retained for integrated policy assessment is given.

i. Temperature change

A 15-year “commitment” period is considered meaning that in order to measure the temperature change due to 2050 greenhouse gases concentrations the climate module is run forward to 2065. Changes in temperature are measured relative to 2000:

$$\text{Std. Impact} = (\text{Shock 2065 temperature} - \text{Baseline 2065 temperature}) / (\text{Disc. cost of policy shock})$$

ii. Cumulative world CO₂ emissions

The formula for the measurement of the impacts on cumulative world CO₂ emissions is:

$$\text{Std. Impact} = (\text{Shock induced cumulative CO}_2 \text{ emissions} - \text{Baseline cumulative CO}_2 \text{ emissions}) / (\text{Disc. cost of policy shock})$$

iii. Oil and gas resources to production ratio

The impact on this objective is given by the following formula:

$$\text{Std. Impact} = (\text{Shock Modified R/P ratio} - \text{Baseline Modified R/P ratio}) / (\text{Disc. cost of policy shock})$$

The modified R/P ratio is a measure incorporating both discovered and undiscovered reserves as emerging from the stochastic model results. In the case of oil, both conventional and non-conventional oil is considered. All quantities are calculated for the year 2050.

iv. Energy cost and electricity cost reduction to European consumer

The impact formula is given by:

$$\text{Std. Impact} = (\text{Shock induced disc. energy/electricity cost} - \text{Baseline disc. energy/electricity cost}) / (\text{Disc. cost of policy shock})$$

All final energy consumers (households and firms) are considered in the calculation. Attention was paid to avoid double counting (i.e. costs of inputs to power generation or hydrogen production should not be included as they would be properly reflected in electricity and hydrogen prices to final consumers).

v. Road congestion

The index for road congestion is based on the total hours spent in driving. The impact is discounted by using a social discount factor of 4% since the hours spent in urban traffic is mostly lost working hours, which in turn can be expressed in money. Under this perspective, a time preference rate is introduced as is the common practice in economic evaluations. The formula used to calculate the standardised impact is:

$$\text{Std. Impact} = (\text{Shock disc. time spent in driving} - \text{Baseline disc. time spent in driving}) / (\text{Disc. cost associated to policy shock})$$

The impact is measured up to the year 2030.

vi. Road safety

The road safety is measured in terms of road accidents involving injuries and fatalities. The cumulative impact in 2030 is measured according to the following formula:

$$\text{Std. Impact} = (\text{Shock cum. road accidents} - \text{Baseline cum. road accidents}) / (\text{Disc. cost associated to policy shock})$$

vii. Noise emissions

For the assessment of policy impacts on road transport noise a similar approach to air pollution is followed; the noise annoyance is addressed through ‘vehicle emissions’ (i.e. emitted sonar energy). The most commonly used indicator is the A-weighted equivalent noise level Leq, expressed in db(A). The impact of policies on noise emissions is measured up to 2030:

$$\text{Standardised Impact} = (\text{Shock cumulative noise emissions} - \text{Baseline cumulative noise emissions}) / (\text{Discounted cost of policy shock})$$

viii. Impacts on Human Health / Environment Objectives

All impacts on human health and environment objectives are cumulative and they are measured up to 2020 according to the general formulation described in the beginning of this section.

7.4. Measurement of policy costs

From the public expenditure perspective investment policies and subsidies are expenditures, while all taxation policies are revenues. The term “policy cost” is used in this text to define the amount spent or received by the government when applying a specific policy instrument.

R&D expenditure is assumed to take the form of additional subsidies to R&D. They are expressed in terms of percentage of subsidy to R&D effort that is undertaken by the private sector. To the extent that such R&D outlays by the private sector are endogenous, there also subject to uncertainties arising from the uncertainty surrounding future funding of R&D on specific technology groups by the private sectors.

In addition, the costs of taxation and subsidies policies are also endogenous and subject to uncertainty surrounding the demand evolution and their costs are also considered as stochastic. On the other hand, investment in road infrastructure is a policy in which a public body decides in advance their cost before applying it and its cost is deterministic.

As an expedient for obtaining distributions of linear functions of random variables and via the justification provided by the Central Limit Theorem, TIPA assumes that the distribution of the standardised impacts is normal. According to results obtained using the stochastic models this assumption is not valid for all impacts. As mentioned above, most policy measures involve stochastic costs. This introduces an additional difficulty in establishing a distribution for the standardised impacts, since the ratio of two normal variates is basically unknown and certainly not normal. However, looking at the results from the stochastic model the ratio of the distribution of impact to the distribution of policy cost tends to approach the normal distribution better than either the numerator or the denominator of this ratio does.

Figure 7-1: Impact of additional carbon tax of 50€/tn of CO₂ on Energy cost reduction to consumer: a) stochastic policy cost, b) deterministic policy cost

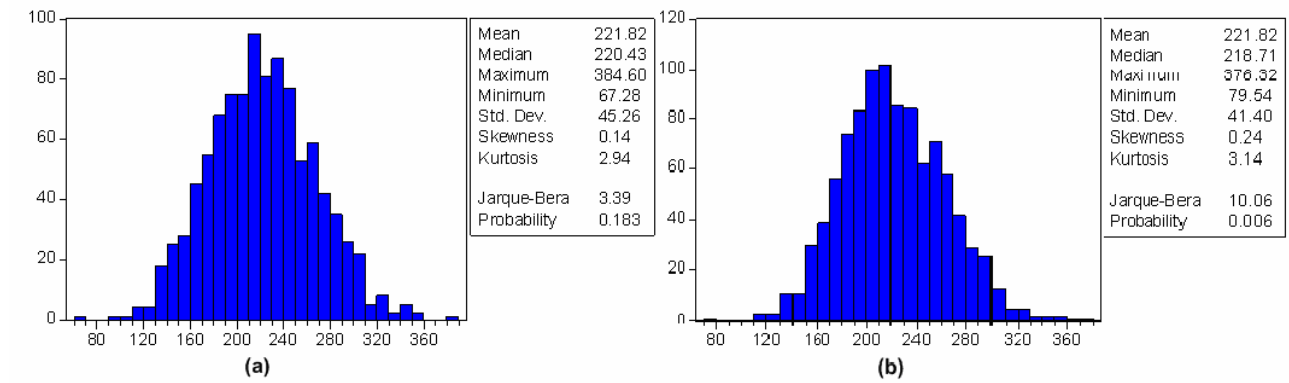


Figure 7-1 presents an example in which the distribution of the standardised impact is closer to the normal distribution when stochastic costs are considered. The policy instrument is oil tax in road transport and the sustainable development objective is road congestion. The distribution (a) is the distribution of the standardised impact taking into account a stochastic policy cost, while the distribution (b) is the distribution of the standardised impact when a deterministic policy cost is considered. The positive sign of the mean of distributions implies that this policy has positive impact on the objective, i.e. it alleviates road congestion. The expected impact is the same in both distributions, but the Jarque-Bera criterion is smaller in the first distribution which in turn leads to higher probability that the first distribution is derived from a normal sample (18% instead of 0.6%)

This phenomenon has been observed in 70% of all standardised impact distributions of policies with stochastic costs.

7.5. Stochastic model results on the impacts of SD Objectives

Table 7-1 summarises some key results on the impacts of policy instrument shocks applied on the set of sustainable development objectives considered in the MINIMA-SUD project. The expected impacts have been modified so that a desirable impact is always presented with a positive sign.

Table 7-1: Key statistics for the standardised impacts on the sustainable development objectives in the MINIMA-SUD project

Sustainable Development Objective	Unit		Policy instrument							
			R&D on renewables	R&D on nuclear	R&D on clean vehicles	Investment in road infrastructure	Carbon tax	Oil tax in transport	Internalisation of external costs for electricity generation	Subsidies in fares for public transport
Energy cost reduction to European Consumer	Euro saved per Euro spent	Mean	0.17	1.07	4.24	0.00	-1.20	-10.99	-1.24	4.69
		Std. Dev	0.43	0.68	2.98	0.00	0.07	1.34	0.24	0.43
Electricity cost reduction to European Consumer	Euro saved per Euro spent	Mean	0.10	0.96	0.09	0.00	-0.25	-0.03	-1.23	-0.01
		Std. Dev	0.34	0.53	0.13	0.00	0.05	0.03	0.23	0.01
Temperature change	oC per Trillion Euro	Mean	0.07	0.11	0.05	0.00000	0.00314	0.00429	0.00880	0.00361
		Std. Dev	0.05	0.12	0.07	0.00000	0.00121	0.00153	0.00430	0.00108
Cumulative world CO2 emissions	Mtn of CO2 avoided per Trillion euro	Mean	192.79	265.68	213.14	0.00	9.61	0.00	0.00	0.00
		Std. Dev	66.85	103.89	87.24	0.00	32.40	20.27	48.13	8.77
Oil resources to production ratio	Years per Trillion euro	Mean	2.02	7.19	260.37	0.00	0.16	9.42	0.02	7.17
		Std. Dev	4.748	17.48	365.85	0.00	0.34	10.37	4.44	6.81
Gas resources to production ratio	Years per Trillion euro	Mean	18.03	83.25	-116.95	0.00	0.05	-1.94	0.07	-1.42
		Std. Dev	234.91	373.14	104.64	0.00	0.39	0.63	3.26	0.44
Road congestion	000hours saved per billion euro spent	Mean	0.00	0.00	0.00	16.14	5.38	330.40	0.00	36.77
		Std. Dev	0.00	0.00	0.00	3.04	1.17	66.58	0.00	4.46
Road safety	Accidents avoided per billion euro spent	Mean	0.00	0.00	0.00	4836.67	132.95	8864.95	0.00	574.28
		Std. Dev	0.00	0.00	0.00	16344.41	223.63	15058.11	0.00	927.36
Noise emissions	Decibels avoided per Trillion euro spent	Mean	0.00	0.00	0.00	-16.26	0.72	51.31	0.00	0.00205
		Std. Dev	0.00	0.00	0.00	3.00	0.56	40.40	0.00	0.00149
Mortality	Years of lifetime saved per billion euro	Mean	33.78	-23.53	1.26	3.44	53.45	970.61	314.53	7.70
		Std. Dev	31.56	50.98	1.05	0.65	23.36	470.07	220.85	3.59
Congestive heart failure	Cases avoided per billion euro	Mean	0.76	-0.12	0.47	0.00	0.91	19.39	4.73	0.70
		Std. Dev	0.61	0.80	0.39	0.00	0.38	9.24	3.20	0.32
Days of restricted activity	Days saved per billion euro	Mean	4768.95	-817.67	2812.46	11.10	5891.67	127131.11	30282.27	4631.92
		Std. Dev	4109.38	4844.12	2436.85	2.11	2760.89	67559.15	22457.21	2361.63
Asthma	Cases avoided per billion euro	Mean	382.91	-56.77	251.23	-6.02	433.29	8974.32	2302.36	321.96
		Std. Dev	315.93	416.91	198.50	1.14	180.86	4167.60	1614.57	139.01
Respiratory hospital admissions	Cases avoided per billion euro	Mean	0.99	-0.16	0.25	0.00	0.97	12.89	6.51	0.46
		Std. Dev	0.92	0.91	0.20	0.00	0.45	6.12	5.28	0.20
Monetary damage to materials	Million Euro of maintenance saved per billion euro spent	Mean	0.02	0.00	0.00	0.00	0.01	0.00	0.11	0.00
		Std. Dev	0.01	0.01	0.00	0.00	0.01	0.00	0.09	0.00
Monetary damage to crops	Million euros avoided per billion euro spent	Mean	0.07	-0.01	0.00	0.00	0.06	0.00	0.53	0.00
		Std. Dev	0.07	0.06	0.01	0.00	0.05	0.00	0.44	0.00
Damage to ecosystems	km2 avoided per billion euro spent	Mean	64.10	-14.20	8.77	-3.28	65.35	653.75	415.36	14.70
		Std. Dev	56.81	54.05	8.46	0.62	40.15	443.04	309.86	9.55

Starting with the energy cost reduction to the European consumer objective, the policies associated with the highest expected impacts are those aiming at reducing oil consumption in the transport sector, namely subsidies in public transport and R&D on clean vehicles (hybrid, electric and hydrogen-powered cars). The latter policy however displays half the impact at higher uncertainty (as measured in terms of standard deviation) a pattern attributed to two factors: first, the efficiency improvement of hybrid cars is not sufficiently high to significantly reduce oil consumption and second the hydrogen

price still remains high. R&D on nuclear and R&D on renewables also register significant positive impacts as they produce energy cost savings to the consumers by reducing the cost of electricity.

Looking at global temperature change, all R&D policies display positive expected impacts, as the increased R&D effort undertaken in Europe activates cost reductions that spillover throughout the world resulting in increased global technology uptake. On the other hand the effects of carbon tax, oil tax and internalisation of external costs policies are limited to Europe. Given the small weight of Europe in total GHG emissions and some carbon leakage effects (reductions in consumption in Europe resulting in lower prices and higher consumption elsewhere), the impact of these policies on the climate targets is very small compared to the R&D impacts (the share of EU-15 in total CO₂ emissions is 14% in 2000, and on average 6% in 2050). R&D on nuclear has the highest expected standardised impact among the R&D policies although it also displays the highest relative variance.

All other sustainable objectives of global interest examined in MINIMA-SUD (CO₂ emissions, oil resources to production ratio and gas resources to production ratio) are only affected by policies with worldwide spillovers. For all these objectives the R&D policies show significant impacts. The general observation that high expected impact is associated with relatively high uncertainty also holds for these objectives.

Considering the road congestion sustainable development objective, the oil tax in road transport was found to be very productive but with highly uncertain prospects. Subsidies in public transport and investment in road infrastructure also exhibit significant positive impacts. The impact of the latter is mitigated by the “rebound effect”: improved infrastructure reduces congestion in the early years but by making car travel more attractive it causes partial regression in the longer term.

Impacts on road safety appear very volatile. The oil tax in road transport has the highest expected impact, followed by the investments on road infrastructure, subsidies in public transport and the carbon tax. This set of policies manages to achieve positive impacts through different mechanisms: reducing the whole transport activity through taxes, reducing the activity of private cars through subsidies in public transport and improving the infrastructure by building safer roads.

Only policies aiming at reducing the whole transport activity (i.e. the oil tax in transport and the carbon tax), appear effective in reducing noise emissions. Oil taxation presents the highest expected impact but with the highest variability. Investment in road infrastructure appears to produce increased noise emissions, as besides making car travelling more attractive it also enables high-speed driving. Subsidies in public transport result in a negligible positive impact.

It should be noted that the mortality objective is affected mainly by SO_x and PM₁₀ emissions. Thus, the oil tax in road transport, which reduces PM₁₀ emissions and the internalisation of external costs, which reduces SO₂ and SO_x emissions from power generation, show the highest expected standardised impact, followed by the carbon tax and R&D on renewables. However, the most certain policy to reduce mortality is investment in road infrastructure, which results in one of the lowest but least uncertain impact. The negative expected impact of R&D on nuclear policy (which is not very significant) is mostly a result of crowding-out of renewables. This also holds for the impacts on the rest of the objectives related to human health.

Only policies that induce lower SO₂ and SO_x emissions have positive impacts on crops and materials. Since the main source of these emissions is the power generation sector, all policies related to transport have almost zero impacts. The internalisation of external costs presents the largest (albeit very uncertain) positive impact, followed by R&D on renewables and the carbon tax.

Oil taxation displays the largest positive impact on ecosystems followed by the internalisation of external costs and the carbon tax. R&D on renewables is found to be very productive but with highly uncertain impacts. Investing in road infrastructure displays negative impacts as it increases the average speed of driving and hence emissions. Research on nuclear also produces adverse impacts on ecosystems.

As a broad conclusion of the preceding analysis, it can be argued that policies which exhibit strong mean expected standardised impacts are not necessarily the optimal candidates for funding, as these prospects may be surrounded by higher uncertainty.

Covariance of the standardised impacts

A key element for the integrated policy exploration is the co-variance of the standardised impacts, as it greatly modifies hedging characteristics in terms of maximising probabilities of attaining given thresholds or satisfying specific probability constraints.

The main source of covariance of impacts is the (dis)similarity of unknown future conditions favouring the impacts of policy instruments. For example, the impact on mortality is affected by the emissions of specific pollutants. Maximising the probability that the impact on mortality exceeds a specific threshold tends to increase the budget share of policies that have positive expected impacts and of those policies whose impacts positively co-vary. However, the TIPA model also takes compensatory measures so as to counterbalance possible loss due to the uncertainty underlying the conditions (i.e. the pollutant emissions, demand elasticities, climate policies, etc.). These measures involve budget allocation to policies whose impacts are negatively correlated.

Table 7-2: Example of correlation matrix between the impacts of different policy instruments

Objective: Energy cost reduction to European consumer - Correlation matrix						
	Additional carbon tax	Internalisation of external costs for electricity generation	Oil tax in transport	R&D on nuclear	R&D on renewables	R&D on clean vehicles
Internalisation of external costs for electricity generation	0.53					
Oil tax in transport	0.59	0.06				
R&D on nuclear	-0.41	-0.42	-0.03			
R&D on renewables	-0.11	0.03	0.00	0.24		
R&D on clean vehicles	-0.07	0.05	-0.08	0.00	0.04	
Subsidies in public transport	0.61	0.02	0.27	-0.01	-0.01	-0.12

Table 7-2 gives the correlation matrix for the impacts on energy cost reduction to European consumer as an example of how co-variances affect the decision under the presence of risks. An inspection of the table indicates that there is strong positive correlation between the standardised impact of internalisation of external costs in power generation and the carbon tax. These policies affect the energy cost by increasing the electricity cost through the same mechanism, taxation, implying that the uncertainty regarding the price elasticity of electricity demand is in fact the source of their covariance. A similar case arises for the carbon tax and the oil tax in transport policy instruments.

Impacts of R&D on nuclear and R&D on renewables are positively correlated and negatively correlated to those of a carbon tax. The source of covariance between these policies is the electricity price elasticity in final demand. However, the former two policies affect energy costs in the same direction (i.e. reduce costs) whereas the latter policy produces adverse impacts.

Subsidies in public transport are positively correlated with both carbon taxes and oil taxes in transport. The source of this covariance is the oil price elasticity (all policies reduce oil demand in transport). However, the impact on energy cost reduction is positive in the case of subsidies and negative in the case of taxes.

The analysis suggests a negative correlation between R&D on clean vehicles and subsidies in public transport. The combined application of these instruments constitutes a candidate for hedging, as both policies produce energy cost reductions but the unknown conditions that favour their impacts differ: the effect of subsidies depends on the oil price elasticity in transport final demand, while the effect of R&D on clean vehicles depends on both the oil and hydrogen price elasticities and the learning by research elasticity of the clean vehicles capital cost. The TIPA model can use this negative correlation as a compensatory measure in order to counterbalance possible loss due to the uncertainty underlying these elasticities.

Based on the above remarks, the significant role of the covariance can be illustrated with a simple example. Assuming that the only objective is to minimise the probability that the energy cost to consumer increases and that there is 1 bn € budget for the costs of policies, the TIPA meta-model is run first ignoring the covariance and next taking it into account. In the first exercise, the budget share of R&D on clean vehicles is 2.6%. The TIPA meta-model allocates the budget by considering each

policy independently taking into account only the variability of the impact of the specific policy. As a result R&D on clean vehicles – being the most uncertain policy – has the lowest share among the policies with positive impacts. Taking into account covariance, the budget share of R&D on clean vehicles increases to 5%. The negative correlation of -0.12 between subsidies and R&D on clean vehicles has given TIPA the opportunity to reduce the probability of failure by doubling the share of R&D on clean vehicles in the total budget, hedging against cases where the other policies may fail.

Looking at the correlation matrices of the impacts of all policies on all sustainable development objectives, it can be observed that:

- The correlations between the impacts of policies on the sustainable development objectives of global interest are very small. This is due to the fact that the variability of the impacts on these objectives is very large and it is attributed to global factors and hence lies outside the scope of the policies, which, as it has been mentioned before, are applied within the EU only.
- The carbon tax policy has positive correlations with almost all policies in all objectives. The source of covariance between the carbon tax and R&D policies is the uncertainty in climate policy. On the other hand, the source of covariance between the carbon tax and subsidies in public transport, the carbon tax and oil tax in road transport and the carbon tax and the internalisation of external costs is the uncertainty regarding the fuel price elasticities in final demand.

7.5.1. Examination of non-linearities of Impacts

If large “policy budgets” are considered the possibility of non-linearities in the impacts must be taken into account. This allows for the exploration of the role of diminishing (or even increasing) returns to policy intensity for the various options. In addition, in this way “budget” size becomes a possible policy parameter. In order to model these non-linearities shocks of different intensity (as described in section 7.2) have been applied to each policy instrument using the stochastic model. To examine the impact of each policy on each sustainable development objective, a relatively simple equation was estimated using the model generated results. This function was specified to be continuously differentiable to ensure convergence of TIPA which in mathematical terms is a non-linear optimisation problem:

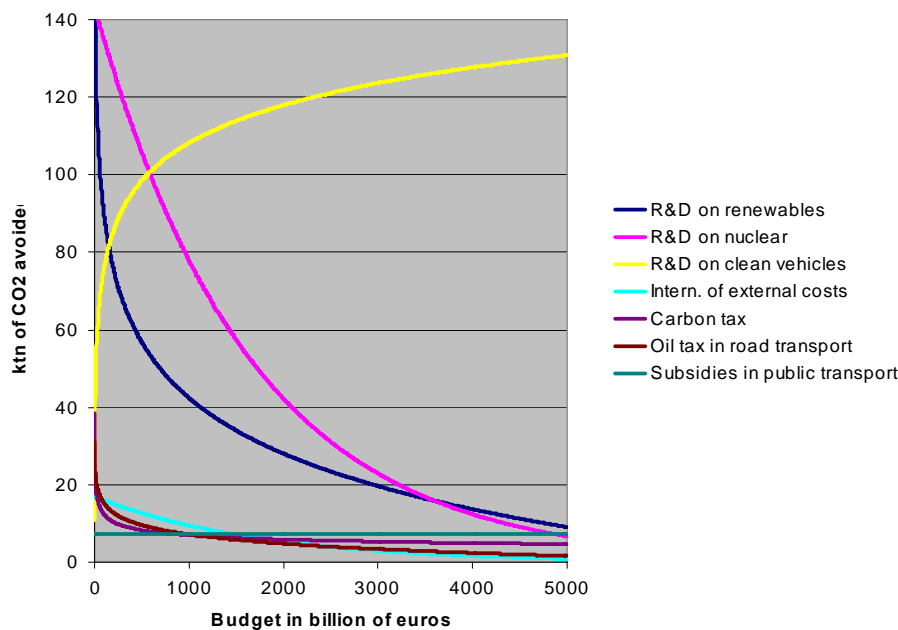
$$\text{Standardised Impact} = f(\text{policy budget})$$

Various functional form types were tested to measure the impact per unit of policy intensity. These exercises have revealed a highly diversified (depending on policy instrument and objective) modulation of policy impacts to budget size. The introduction of non-linearities into TIPA, while increasing the capabilities of the tool also results in considerable increase in its complexity. However, no numerical problems arise and the convexity of both the objective function and the feasible set is retained. In general, results are defensible but impacts appear sensitive to budget size.

The graph below gives an indication of the non-linearities encountered and the way they have been treated.

The graph presents the variation of the expected impact per unit of policy cost on the cumulative world CO₂ emissions for the sustainable development policy instruments considered in TIPA. The graph shows that R&D budgeting in terms of expectations seems to be the most effective policy. However as already has been shown in Table 7-1 it also exhibits high uncertainty on the efficacy of R&D actions. The graph also shows that most policies exhibit strongly diminishing returns to policy intensity. An exception is R&D on clean vehicles where learning by experience implies an acceleration of vehicle stock renovation (snowball effect). Even so the average impact of this policy tends to stabilise for very large budget due to diminishing returns in terms of the efficacy of R&D spending (i.e. the ability of spending on R&D to produce technical innovation).

Figure 7-2: Non linearities in cumulative CO₂ emissions objective



8. Dynamic Receding Horizon Module

Earlier work on Sustainable Development devised a policy assessment tool (ISPA-Integrating System for Priority Assessment¹²) which was used to perform integrated R&D policy exploration. ISPA took the form of an optimisation tool maximising the probability that a given threshold on a policy objective is attained while specifying minimum probabilities of attaining thresholds on other policy objectives. This was essentially a static optimisation formulation. This work pioneered a quantitative approach to policy assessment in connection with allocation of public research and development budgets between alternative technologies for electrical power generation. However, the optimization allowed only for one policy adjustment (i.e., in model predictive control (MPC) terms the input prediction horizon was 1), and both the constraints (on the budget and on indicators measuring cost) and the objective function (based on indicators measuring benefit) placed all emphasis on cumulative effects at the end of a prediction horizon. More crucially, no consideration was given to the closed-loop effects of the receding horizon application of the open-loop optimization. Discounting and the effect of constraints dictated by the problem often avert the onset of instability, but closed-loop performance can be far from optimal. Still, this approach is a step forward in that it poses the problem in a strongly stochastic formulation and casts it in a multiobjective setting. The latter is made possible through a probabilistic formulation for both the objective function and the constraints which allows for the objective function to be interchanged with any one of the constraints. The purpose of this work section is to preserve these attributes but introduce dynamics and give guarantees of closed loop stability. This is achieved by deploying MPC ideas while retaining the stochastic and multi-objective nature of the problem.

This section explores the benefits of dynamic modelling in policy assessment for sustainable development problems relating to Research & Development budget allocation between alternative technologies. The “system” is defined by a detailed multiplicative stochastic energy-economic model, PROMETHEUS (developed by ICCS-NTUA for the SAPIENT project) comprising variables that relate to demographic and economic indicators, energy (fuel) consumption, fuel resources and prices, CO₂ emissions, technology uptake, and two-factor learning curves describing technology improvement in terms of research and experience gained through application. Attention was focused on the response of two indicators, Energy Cost and CO₂ emissions, to shocks being applied to the R&D budget

¹² The TIPA meta-model employed within the MINIMA-SUD project is the advanced version of the ISPA tool (developed within the European Commission SAPIENT project, Contract No. ENG2-CT1999-0003)

allocation to two technologies, Wind and Combined Cycle Gas Turbines. For brevity, the latter two will be referred to as “inputs” and the two indicators as “outputs”. As a first step, pseudo-random binary sequence (PRBS) that met budgetary constraints were applied to the two inputs and the responses of the two outputs were recorded. Least squares procedures were then used to derive linear Weighting Sequence (WS) model representations of the dynamics from the two inputs to the two outputs. A set of different PRBS were applied to the derived models and to PROMETHEUS and the results showed good agreement, thereby providing the necessary validation of the WS models. These models were then used to predict the cumulative effects of the two inputs on the two outputs. Unlike the earlier work, the predicted inputs were allowed to assume different values at each of the first 10 instants (years) of the 30-year prediction horizon. The last twenty values were constrained to be the same so that the two indicators would reach steady state values at the end of the prediction horizon. This restriction was imposed in order to narrow the gap between open-loop optimal predictions and closed-loop (actual) responses. It is assumed that the overall strategy will be implemented in a receding horizon manner: (i) predictions over the current horizon (say from 2000 to 2030) would be optimised, producing optimal open-loop input trajectories (and the respective open-loop output trajectories); (ii) the first element of the optimal input trajectories only would be implemented, (iii) steps i and ii would be repeated at the next and subsequent years with horizons from (2001 to 2031), (2002 to 2032) ... (2030 to 2060). The actual output responses obtained in this manner are referred to as closed-loop responses and in general may bear little relation to any of the open-loop optimal predictions. Invoking the constraint that the open-loop output predictions reaches steady state at the end of the prediction horizon, narrows the gap between open- and closed-loop responses. This development enables the determination of extra degrees of freedom that are introduced through the use of dynamics. The earlier assumption concerning the validity of finite length linear time invariant WS models is tested by means of Monte Carlo simulations on PROMETHEUS. The end product of these simulations is the computation of the expected values and covariance matrices for the distributions of such WS models (which were assumed normal). From this point on, it is possible to apply the procedure to maximise the probability that a given threshold on the first policy objective is attained while specifying minimum probabilities of attaining thresholds on the second policy objective. In this formulation optimisation concerns the first indicator, which therefore will be referred to as “primary”, whereas the second is involved in a probabilistic constraint and will be referred as “secondary”. It is noted that reversal of the roles of primary and secondary provides a means of exploring the multi-objective nature of the problem under consideration. The optimal results using the dynamic WS models over the earlier static models showed up to 12% improvements. It is noted that it is possible to show rigorously that the optimisation deployed in this approach is convex; this can be achieved by showing that the relevant Hessian matrix (matrix of second partial derivatives) is positive semi-definite (for completeness the relevant details are included in the MINIMA-SUD Final Technical Report).

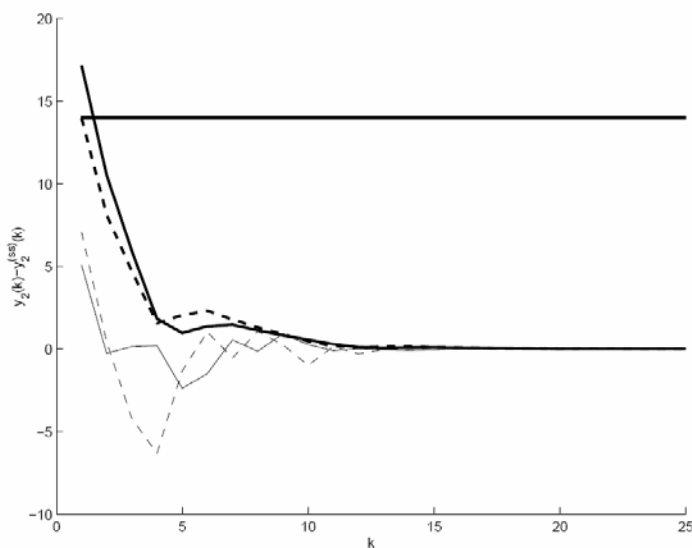
The work thus far considered only the aspect of open-loop optimisation. It was explained earlier that in a receding horizon application open- and closed-loop results may be quite different and this, in conjunction with consideration of cumulative effects only, could have serious consequences. To illustrate the point consider the hypothetical case where a satisfactory optimal cumulative effect on the primary is achieved by a trajectory whose behaviour is poor during the initial prediction years but improves dramatically in the later years. If this trend were to persist at subsequent years, then benefit of the later prediction years will never materialise but will forever recede with the prediction horizon. The same situation could arise in connection with the secondary indicator in such a way that, whereas the predicted cumulative effect is within bounds due to exceptionally good behaviour in the later prediction years, the actual cumulative effect would violate (by far) the relevant constraints. These significant problems were overcome through the derivation of a fully dynamic formulation, and the imposition of an artificial stability constraint which ensures a monotonic decrease in predicted cost and the recursive guarantee of feasibility. Use of the WS models enables the determination of the best steady state value for the primary indicator and this in turn enables the development of a fully dynamic formulation through the use of probabilistic bounds, defined on predicted actual (not cumulative) primary values at each individual prediction time (not just the end of the prediction horizon). The receding horizon application of this 2-phase optimisation strategy can be shown to guarantee the closed-loop (actual) asymptotic convergence of the primary indicator to the interval while respecting the probabilistic constraints on the secondary indicators and the budgetary constraints.

Typical results of closed-loop responses for a numerical example indicate improvements of up to 300% in the closed-loop cost over the earlier static approach. It is noted that the optimisation used in this

approach can be shown to be a Second Order Cone Program (SOCP) that is convex whose unique solution can be computed efficiently. The convex nature of the problem arises from the fact that if the vectors of coefficients of the WS models are normally distributed, then so will the vectors of indicator predictions. However PROMETHEUS, for anything other than limited shock adjustments (up to 10% of baseline) exhibit nonlinear behaviour. It turns out that the predictions remain normal even when use is made of nonlinear representations so long as these representations are linear in the parameters. One such representation is possible through Neural Network models deploying Gaussian Radial Basis Functions (GRBF). The improvement in goodness of fit over the linear WS models is illustrated by the response to 35 random validating sequences. Application of a suitably adapted receding horizon optimisation strategy, similar to that described above, gave closed-loop results which improved the agreement in the computation of the relevant probabilities using the model and PROMETHEUS results by a factor of 5. Further improvements are also possible through the use of models which are linear but time-varying (LTV), so tuned to better capture the salient features of the PROMETHEUS responses. Improvements (over the Neural Network representations) in goodness of fit are possible for both the primary and secondary indicator. Linear time varying models afforded improvements in the optimality of the closed-loop PROMETHEUS results; thus the lower steady state probabilistic lower bound for the primary indicator using GRBFs was 2.61, whereas the corresponding value obtained through the LTV models was 3.43 (31% better).

A final task undertaken under this work section considered the generation of extra design freedom through the relaxation of the artificial equality stability constraint invoked in the previous formulations. It was possible to replace these constraints by inequality constraints through the adoption of predictive control tools such as feasible and invariant terminal ellipsoidal sets and terminal penalty terms. Rather than formulate the problem in terms of Moving Average (MA) models, here use was made of a state space description. The distinctive feature of this formulation is that the predicted steady state value for the primary indicator is not a deterministic constant (assumed in previous work) but a random variable. The monotonic decrease property for the predicted cost was achieved through thresholding which was defined so that the cost-to-go for a release condition from anywhere inside the terminal set can be computed on the basis of expected values. It is possible to show that, subject to a mild condition (which can always be met through a suitable choice of the probabilities used in the definition of the secondary bounds), the design of the terminal set can be implemented through the use of Linear Matrix Inequalities as a convex problem. Once again the constrained optimisation of the predicted indicator behaviour turns out to be a SOCP convex optimisation problem. Typical closed responses for a numerical example where the probabilistic threshold was chosen to have two different values indicate that the use of inequality stability constraints (as opposed to the earlier equality constraints) expanded the range of achievable steady state values by 13% (Figure 3-1).

Figure 8-1: Error (from steady state) in secondary output. Heavy lines show the 95% threshold levels (above) while light lines show one simulated output realisation for $L=50$ (solid) and $L=14$ (dashed). The heavy horizontal line show the constraint $L=14$.



9. Integrated Policy Exploration with TIPA

TIPA lies at the heart of the MINIMA-SUD approach since it constitutes the decision tool through which policy integration incorporating hedging on a large number of objectives is performed. Hedging, naturally, is not a novel notion in decision analysis. It has been practiced by insurance and financial institutions for a long time indeed. However, this kind of “financial” hedging analysis is usually carried out by processing very large numbers of time series data in view of limited and well defined objectives and an extensive menu of options. In general, such analysis by-passes the “structural” considerations and through such lack of analytical transparency would have been unsuitable for policy makers, especially those attempting to tackle highly politically sensitive issues like those posed by sustainable development. The alternative approach of using exclusively deterministic analytical tools at worse gives a false impression of “exact” knowledge of mechanisms or at best leads to a limited set of contrasting alternatives with no indication on how probable they may be.

The approach adopted in MINIMA-SUD consists of a combination of structural and risk analysis, painstakingly building-up from detailed analytical tools and transparent statistical analysis (see chapters 6 and 7) to construct a hedging integrating tool (TIPA) condensing expectation and risk information and capable of multiple runs necessary for policy exploration.

The main features of the tool are:

- A single horizon, i.e. policy decisions are supposed to occur in the near term (the next 15 years) in order to obtain desired effects on a fixed future horizon ranging from 2020 to 2050. In general, cumulative impacts are considered.
- The impact of policy decisions is treated stochastically giving the possibility to make probabilistic statements on the efficacy of these decisions in achieving given results on the different objectives.
- The statistical dependence of impacts is incorporated. Such dependence arises from the fact that these impacts are influenced (albeit differently) by the same variables, themselves subject to specific or interlinked risks.
- Expected impacts as well as the joint distributions (essentially the variance and covariance) depend on the policy dosage. This feature enables the incorporation of diminishing returns or critical mass effects to policy intensity (for the analysis of these effects see chapter 7).

9.1. Specification of TIPA

9.1.1. General characteristics of TIPA

In order to incorporate fully the stochastic characteristics of the problem (enable the analysis of different risk averse stances) and at the same time treat the different objectives symmetrically TIPA is specified as an optimization problem where:

- The probability that an objective exceeds a given threshold is maximized;
- subject to the condition that the probability that the other objectives exceed given thresholds is greater than a certain level;
- also subject to a “notional budget” limiting the overall “cost” of the policies, as well as non-negativity constraints on the various instruments used.

Alternative specifications are of course possible, as for example setting the goal as the maximization of the expectation or alternatively the constraints as inequalities on the expectation of the different objectives. Such specifications would result in asymmetric treatment of the objectives, rendering the discussion of the presentation of the results somewhat ambiguous. Replacing both the goal and the objective in terms of expectations would effectively destroy the stochastic character of the exercise rendering meaningful risk analysis impossible.

The “notional budget” concept is necessary in order to limit the total policy intensity and avoid unbounded, i.e. infinite, solutions. It is also a constraint of specific analytical interest in itself since it

provides indications as to the cost of the policies as well as the marginal cost of improving on a specific sustainable development objective. According to economic theory, a proper if somewhat abstract measure of the cost of policies would be welfare loss arising from their adoption. In the integrated policy assessment exercises carried out within the MINIMA-SUD project, welfare loss has been approximated by a reduction in discounted household consumption of goods and services over the horizon 2006 to 2030. In order to establish impacts of the different instruments on this welfare measure, extensive use of the General Equilibrium models involved in the project has been made (see chapter 5). The costs are stochastic. The sources of uncertainty concerning them relate to the risks associated with the primary impact of the policy as well as the mechanisms and modalities of their diffusion throughout the economy. To the extent that some of the impacts depend on similar mechanisms (i.e. the impact of different types of tax and to some extent subsidies may partly depend on the same elasticities subject to specific uncertainties) they will also exhibit co-variance. The stochastic model was used as a reduced form to establish the magnitude of such variances and co-variances. A special problem has arisen with some of the policy instruments (mainly R&D expenditures) which, in conformity with macro-economic analysis, in some exercises (depending on the recycling rule) have exhibited positive impacts on welfare. The inclusion of such expectations in the welfare “budget” constraint would have clearly resulted in unbalanced and unrealistic solutions (in the best of cases favouring excessively such measures, in the worst producing unboundedness). In order to avoid such effects only those exercises that produced expected reductions in welfare have been retained. The general assumption has been that the reference case from which the impacts have been calculated was in some way “optimal” and any deviation from this optimal solution arising from the introduction of whatever measure would result in some loss of welfare. This assumption notwithstanding, R&D measures tended to display the lowest average (per euro intensity) impacts on welfare somewhat balanced by much higher uncertainty surrounding them (encompassing non-negligible probabilities of positive impact as well as non-negligible probabilities for relatively serious negative impacts).

Apart from this “notional budget” constraint in terms of economic welfare it was thought useful to introduce a second “notional budget” adopting the point of view of the public authority deciding on the policy mix. In terms of this constraint any tax or revenue producing instrument would appear with a negative sign (revenue) while any expenditure would be incurred as a cost. The reason for the introduction of this constraint was to take into account public finance realities: public bodies operate under restrictions on the amount of additional debt they can incur and solutions suggesting massive increases in expenditures (such as R&D, infrastructure, subsidies etc.) without at least some compensation in terms of additional revenues (e.g. from taxes) could be politically unrealistic. The quantities appearing in this constraint are related but by no means identical to those figuring in the welfare constraint. A policy has a fiscal cost and produces an impact on welfare. In general the impact on welfare of a particular measure is inferior to its fiscal cost since economic adjustment involves compensatory mechanisms through substitution away from penalised goods, services or activities. The fiscal cost of a policy is also a stochastic variable since tax revenues, demand for subsidies to R&D or to public transport, also depend on uncertain factors concerning demand reactions and uptake.

The two “notional budget” constraints take the form of probability inequalities like the rest of the objectives considered in the integrated policy analysis and they operate jointly to constrain the options available to the notional policy maker. The fiscal budget constraint was also introduced in terms of expectations in order to better control the implied total magnitude of the policy effort.

The TIPA model has been programmed in the GAMS software as a non-linear programming problem. It has performed robustly and efficiently enabling the execution of a very large number of exploratory exercises.

9.2. Integrated policy exploration using TIPA

The stated final aim of the MINIMA-SUD project has been all along to demonstrate a methodology for integrated policy assessment in a “real world” context. It was recognised at an early stage that no more than a demonstration of the methodology was possible but the ambition was to go beyond constructing a theoretical paradigm, to use the results from all the operational models involved in the project (together with the new ones constructed specifically within) and to provide insights on the specific

characteristics of the decision process proposed via examples of current policies and current sustainable development concerns.

In the absence of real policy analysts a major challenge has been to position a notional analyst exploring possibilities for a policy mix that would influence a set of objectives towards sustainability. The choice of objectives and especially of policy instruments capable of influencing them has been to a large extent dictated by the model coverage and specific expertise of the partners involved in the MINIMA-SUD project. In this sense there is a definite bias on policy instruments from the general domain of energy, transport, environment and the economy while the sustainable development objectives are also closely linked to this domain. In this sense for example, although a number of health objectives have been included the instruments chosen and the analytical tools for describing the path from instruments to impact on the objectives retained have meant that the only means for the policy analyst to influence such health objectives have been connected to energy and transport policies. Clearly health is a much broader issue and other means for achieving health objectives with much greater effectiveness exist. However, including them would shift the domain of the policy analyst to a much broader area and anyway well beyond the analytical capabilities of the quantitative tools used in the project. This limitation may appear at times awkward. On the other hand, such an analyst is not necessarily completely fictional. It can be envisaged that a public body is mainly concerned with energy, transport and their environmental implications but at the same time must consider possible impacts on health as secondary objectives without pretending that through the policies proposed, the whole issue of the health of the population is being handled.

TIPA allows for a wide selection of positions for the policy analyst: very specific and local concerns may be combined with global considerations. For the purposes of the current set of exercises the notional analyst was assumed to explore possibilities of European-wide policies in the domain of energy and transport aimed primarily at environmental impacts in Europe while maintaining a certain interest on global implications. The policies and measures included in the analysis, the impacts on the objectives and the way both policies and impacts are measured have been presented in (chapter 7.3).

Some broad assumptions had to be made in order to limit the total intensity of the policies to be applied. In the exploration exercises a total intensity (value of expenditures plus receipts) equivalent to around 0.2% of discounted GDP (2006-2020) was assumed to be available for additional sustainable development policies on the instruments and objectives as outlined in the previous paragraphs. Given that the sectors covered (mostly energy and road transport) represent approximately 10% of total activity, this intensity corresponds to devoting approximately 2% of GDP on additional sustainability objectives economy-wide. As mentioned earlier the impact of a particular measure on welfare is inferior to its fiscal intensity since economic adjustment involves compensatory mechanisms through substitution away from penalised goods, services or activities. As a consequence the impacts on welfare turn out to be around 0.1% of GDP (around half the total fiscal intensity of the measures).

9.2.1. Methodology for integrated policy exploration using TIPA

TIPA is a multiple criteria modelling tool and is essentially used for exploring policy mixes and compromises between different and often conflicting objectives. A characteristic of the literature on multiple criteria analysis is that no unique method for exploring the pay-offs and establishing compromises exist. Methods usually consist in heuristic rules designed to enable the communication of the modeller with the non-technical policy analyst in order to enable the incorporation of the choices of the latter in the exploration process efficiently and, to the extent that this may be possible, transparently. In the absence of real life policy analysts the co-ordinators of the project have had to play the role of surrogate ones while being at the same time the modellers.

The exploration was divided into essentially three parts:

1. The elaboration of a feasible set satisfying minimal requirements on all objectives at the same time.
2. Placing priority on a given objective and examining the implication of the limitations imposed by the restrictions elaborated in 1 above, in restricting improvements on the chosen priority objective.
3. In the light of the analysis carried out in 2 above relaxing the constraints on some objectives in order to promote a better performance on the priority objective.

In this way a set of alternative solutions have been obtained promoting different objectives and representing efficient compromises with regard to the rest of the objectives. Concerning the first part a trial-and-error procedure has been adopted involving successive tightening of constraints (equations 11, 12, 13) until a set of possibilities was obtained satisfying “reasonably” all the objectives. This exploration was done in a rather ad-hoc manner and had to take into account the specific characteristics of the version of TIPA as implemented: ambition on some objectives had to be adjusted to the possibilities offered given expected impacts and their joint probability distributions.

The reference feasible set elaborated is presented below. The probability that the policies adopted result in:

An increase in cumulative discounted energy cost to the European consumer in 2050 smaller than 500€ per capita should be greater than 90%¹³.

An increase in cumulative discounted electricity cost to the European consumer in 2050 smaller than 600€ per capita should be greater than 99%¹³.

A reduction in cumulative discounted household consumption in 2030 of more than 300 billion € should be less than 0.3%¹³.

A reduction in temperature in 2065 of more than 2 mills °C should be higher than 90%.

An increase of 2.5 years in oil resources to production ratio in 2050 should be greater than 70%.

A deterioration in the gas resources to production ratio in 2050 should be less than 50%.

A reduction in cumulative world CO₂ emissions in 2050 by 7.3Mtn should be at least 95%.

A reduction in traffic congestion in 2030 by more than 1.3 million cumulative discounted hours of driving should be higher than 60%.

An increase in noise from transport in 2030 should be at least 50%.

A reduction in cumulative road accidents in 2030 by at least 83 million accidents should exceed 70%.

A reduction in cumulative human mortality from air pollution in 2020 by at least 24.2 thousands of years of life should be higher than 95%.

A reduction in cumulative days of restricted activity due to air pollution in 2020 by at least 2.45 million days should be higher than 95%.

A reduction in cases of bronchodilator usage (asthma) due to air pollution in 2020 by at least 320 thousands should be higher than 90%.

A reduction in cumulative cases of congestive heart failures due to air pollution in 2020 by at least 650 cases should be higher than 90%.

A reduction in cumulative respiratory hospital admissions due to air pollution in 2020 by at least 660 cases should exceed 85%.

A reduction in cumulative discounted maintenance cost of buildings due to air pollution in 2020 by more than 1.5% is at least 80%.

A reduction in damage to ecosystems due to acidification and eutrophication in 2020 over at least 3600km² should be higher than 95%.

A reduction in damage to crops in 2020 by more than 1% must be higher than 85%.

¹³ No threshold for a positive impact on these objectives has been set. It is being well understood that sustainability would require sacrifices both in terms of traditional welfare and energy cost to consumer. The role of the thresholds imposed is to avoid solutions that would involve either big loses in welfare or will transfer the bulk of the cost of meeting sustainability targets onto energy consumers and particularly electricity consumers (on the understanding that electricity consumption constitutes a necessity in modern living)

A public budget deficit exceeding 700M€ is less than 10%.

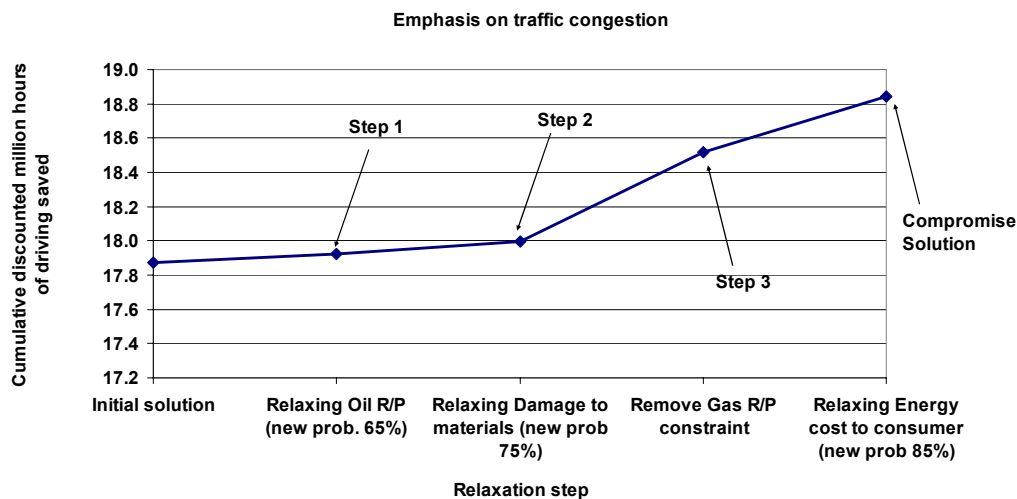
Having obtained this feasible solution the different objectives in turn have been placed at the position of the main objective. This has provided a set of “initial” solutions one for each objective considered. In general such solutions gave only mediocre improvements in terms of the objective focused upon. The reason for this was that as has been mentioned earlier the feasible set was constructed to provide a fairly satisfactory state for **all objectives at the same time**. In order to obtain further improvements some of the constraints had to be relaxed by reducing the probability requirement p_i . The dual values of the “initial” solution have provided guidance for this relaxation. The dual values are an indication of the improvement in terms of the objective that can be expected by relaxing a small amount of the requirement of the constraint. Relaxations were performed successively, one constraint at a time, while the impact of this relaxation in terms of the expectation on the main objective was mapped in a graph. A point on the graph was eventually chosen representing a situation where a considerable improvement on the main objective was obtained, while further improvements could only be achieved by making major sacrifices in terms of other objectives.

To illustrate the process an example is presented below concerning the traffic congestion objective. When the probability that the policies adopted will reduce the traffic congestion by 2030 by more than 1.3 million cumulative discounted hours of driving was placed as the main objective the initial solution gave an expected impact of 17.87 million cumulative discounted hours of driving. For this solution the following constraints were found to be binding: energy cost to the consumer, oil R/P ratio, cumulative world CO₂ emissions, road accidents, mortality due to air pollution and damage to crops.

Of all these, the constraint on the oil R/P ratio registered the highest dual value. Therefore, for Step 1, this constraint was relaxed: the requirement that the threshold should be exceeded with a 70% probability was reduced to 65%. In Step 1 the requirement on oil R/P ratio is no longer binding, but the damage to materials requirement registers the highest dual. In Step 2 the constraint on this objective has been relaxed by allowing the probability of exceeding the threshold to go from 80% to 75%. In Step 2 the highest dual relates to the gas R/P ratio. Since the probability of exceeding the threshold was already only 50% and in order to avoid a non-convex set with its attendant problems (both numerical and substantial) the constraint was dropped altogether at this stage.

In Step 3 the energy cost to the consumer constraint which has been operative throughout the exercise (due to the intensity of the taxation instruments included in the solutions) registers the highest dual value and the requirement concerning it was relaxed from a probability of 90% to 85%. In Step 4 the highest dual value concerned the temperature change requirement. However, improvements in the expectation of the main objective beyond Step 4 proved to be very modest implying increasing sacrifices for little gain. Therefore solution 4 was retained as the suitable compromise when traffic congestion was placed in the main objective position. The evolution of the expectation in cumulative discounted hours of driving saved in the different steps of exploration is given in Figure 9-1.

Figure 9-1: Expected impact on traffic congestion



9.2.2. General remarks

The systematic policy exploration using TIPA outlined above has revealed some persistent patterns which are arising from the definition of the problem as well as the causal and stochastic interconnections of different policy impacts on the objectives considered.

Concerning the objectives/constraints the following broad remarks can be made:

- The methodology adopted for the construction of the feasible set and for the successive relaxation of the probability constraints of the different objectives has resulted in solutions where on average around 6 of the objective constraints out of 19 were binding for a given solution. This is clear evidence of the existence of pay-offs between these objectives and has contributed to a large extent to the relatively balanced mix in the intensity of policy instruments obtained irrespective of the priorities attached on different concerns.
- The probability constraint on the budget deficit has been a factor limiting the ambition in all cases. This is particularly remarkable especially in view of the fact that the constraint on the expected budget deficit has been largely inoperative and the expected fiscal budget in general was more or less balanced. This means that the uncertainties associated with the fiscal implications of policies and measures constitute a crucial element if policy makers are concerned with the risk of overshooting public indebtedness limits.
- The constraint on the increase in the energy cost to the European consumer has also been binding in all cases despite successive relaxations that were necessary in order to obtain better performance with regard to the different objectives. This is not very surprising since many of the instruments involved taxation of energy use. This cost constraint has been a key factor in favouring the use of R&D instruments as well as, occasionally, subsidies despite the fiscal implications. The energy cost to the consumer is not strictly speaking a sustainable development objective and it can be argued that policies aimed at sustainability of the energy system are bound to create burdens on energy consumption. On the other hand, this constraint limits the extent to which such burdens are unevenly born by this category of consumption which after all includes essential services that are essential for modern living.
- When priority was given to any objective except road accidents and damage to ecosystems, the constraint on natural gas resource to production ratio became a highly restrictive element in the attempt to obtain better performance. This was the case even though the reference constraint on natural gas depletion was very modest in that it only required an improvement with a 50% probability. This suggests that in the medium term a deterioration in natural gas resource availability is an essential by-product of the pursuit of other sustainable development objectives like the ones included in the MINIMA-SUD analysis. Under this light this constraint has been dropped in most of the cases considered.
- Concerning the transport related objectives, accidents emerged persistently as a binding consideration in all cases where the ambition on the different objectives was raised (with the exception of climate change). On the other hand, by inspecting the marginal cost of the accident constraints it becomes evident that such constraints did not have a major influence in limiting the ambition and were generally adequately handled by relatively small increases in subsidies to public transport, infrastructure investments and, to a lesser extent, increases in oil taxation for road transport.
- Concerning the health objectives the mortality constraint emerged as the dominant limiting factor. It was binding in almost all cases at the initial solution stage. However, with modest relaxation it ceased being binding, constraints on other non health objectives becoming dominant.

Table 9-1: Policy mixes depending on priority given on alternative objectives

	R&D on renewables	R&D on nuclear	R&D on vehicles	Intern. Of external costs	Additional subsidies to public transport	Additional carbon value	Additional Oil tax in road transport	Additional road infrastructure expenditures
	Subvention %	Subvention %	Subvention %	% of total external costs	% on fares	Euro/tn of CO ₂	Euro/lt	Billion euro
Reduction in temperature	75.1	53.0	88.4	12.0	53.3	0.71	0.27	0.0
Increase in Oil Resource to Production ratio	44.4	40.6	117.5	11.0	59.7	0.34	0.26	0.0
Reduction in mortality due to air pollution	42.1	37.8	112.8	13.8	53.4	0.17	0.28	3.2
Reduction in cases of congestive heart failure	42.5	36.8	102.3	18.6	70.3	0.00	0.29	10.3
Reduction in respiratory hospital admissions	43.5	55.3	85.0	12.9	59.0	0.45	0.25	0.8
Reduction in cases of bronchodilator usage (asthma)	37.7	52.2	108.4	13.9	56.3	0.31	0.26	0.0
Reduction in days of restricted activity	44.7	48.3	94.1	15.5	54.8	0.08	0.27	3.6
Reduction in road accidents	54.7	54.0	65.7	13.6	61.5	0.15	0.25	4.2
Reduction in traffic congestion	53.6	31.4	64.6	11.8	66.7	0.36	0.25	1.0
Reduction in damage to ecosystems	50.6	59.5	70.3	15.1	57.2	0.25	0.24	2.7

The multiple criteria nature of the TIPA exploration process together with the stochastic nature of the constraints on the objectives has produced diversified and fairly robust policy mixes in spite of the fact that different and even conflicting objectives were given priority at different stages (Table 9-1).

This general remark notwithstanding there have been some general tendencies concerning specific instruments in conjunction with the objectives sought:

- All solutions display a certain emphasis on R&D expenditures, despite the fiscal implications and the high risk associated with the impacts. This is mainly due to the high expected impacts, the relative independence or even negative correlations between these impacts and the impacts of other policies and the small average implications in terms of welfare loss. R&D subventions on clean vehicles appear to be strongest irrespective of the objective prioritised. In many cases, notably when the health concerns are given priority, this instrument registers large increases primarily due to its impacts on urban pollution. Large increases in the application of R&D on clean vehicles are also obtained when the conservation of oil resources is given priority. R&D on renewable energy forms is favoured particularly when the reduction in temperature risks is given priority. On the other hand, it is little affected when transport related activities are prioritised and registers marked reductions when health concerns become more important. The latter is due to the importance of urban pollution on health, renewable energy playing a minor role in avoiding such pollution. Similarly R&D support on renewables drops when oil resources become a concern because of the relatively small savings in cumulative oil consumption resulting from an additional penetration of renewables in the power generation sector. R&D support at substantial level for nuclear is a characteristic of the initial solution and is due to the relative independence of its impacts with respect to the impacts of other R&D actions. This results in R&D support for nuclear power becoming an important hedging tool. On the other hand, placing priorities on almost all objectives results in a decline of the intensity of this instrument with the exception of prioritisation of the reduction in damage to ecosystems.
- The policy instruments involving taxation have also figured in all the solutions obtained. This is particularly the case for the additional oil tax for road transport, which is applied intensively and with small variability (from 24 to 29 eurocent per litre) throughout the solutions considered. The highest increase (29 eurocent per litre) is obtained when reduction in cases of congestive heart failure is given priority although it should be noted that this constitutes a “by-product” objective in TIPA exploration. Internalisation of external costs of power generation also features in all solutions. However, the percentage of external costs internalised ranges from 11-19% only. This is mainly due to the impact of this measure on the energy cost to the consumer. Via the probability constraint on energy cost, internalisation comes into conflict with the additional oil tax in road transport, which has a strong impact on costs but also helps in meeting requirements on a variety of objectives and

particularity those concerning road congestion, accidents and health damages from urban pollution. All the same internalisation increases when priority is given on some health concerns like heart failure and days of restricted activity as well as damage to ecosystems. A rather surprising result of the policy exploration has been the low additional carbon values emerging in the different solutions. They range from 0 Euro/tn of CO₂ when heart failure is given priority to 0.71 Euro/tn of CO₂ when the emphasis is given on temperature change. Clearly such carbon taxes are very low (though even 70 cents/tn of CO₂ still imply significant costs both in terms of welfare and the burden on the energy consumer). The main reason for the feeble uptake of this policy instrument is its limitation to the EU-15 countries, which given the small share of Europe in future world CO₂ emissions and carbon leakage effects results in low productivity of the measure even in terms of climate change. Another reason for these low values is the strong correlation of impacts of carbon taxes with the impacts of internalisation of external costs in power generation which reduce the value of the former instrument even as a hedging tool.

- Subsidies to public transport also figure at high intensities (ranging from 53% to 70% of fares) in all solutions. As could be expected this instrument is used intensely when the reduction in traffic congestion is given priority. The persistence of high levels of support in all solutions is to a large extent due to the need to counterbalance the effects of the taxation instruments on the energy cost to consumer probability constraint. In effect, TIPA is recommending the utilisation of tax instruments, especially fuel taxes in road transport, and the use of a part of the revenues generated to subsidise fares, thus enabling the attainment of objectives such as reduction in road accidents and traffic congestion without placing an excessive burden on energy consumers.
- Additional road infrastructure expenditures has been the policy instrument that was taken-up at the lowest relative intensities and most erratically across solutions (up to above 10 billion euro over the period 2006-2020). In fact, it is almost completely absent from all initial solutions and emerges only when the ambition on objectives such as reduction in road accidents, congestion, most of the health objectives and damage to ecosystems are given priority. This is not surprising since of all the measures considered infrastructure investments is characterised by the narrowest scope of its impacts.