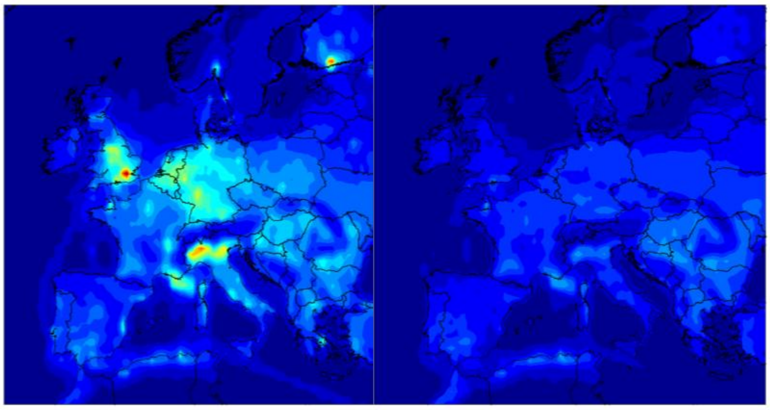
Cobenefits of climate and air pollution regulations

The context of the European Commission Roadmap for moving to a low carbon economy in 2050



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European Topic Centre on Air Pollution and Climate Change Mitigation

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Front page picture:
Change of annual mean surface NO_2 concentration modelled with the chemistry transport model CHIMERE between 2005 (left) and 2030 (right) according to the emissions of the Global Energy Assessment for a scenario accounting for the full implementation of air quality and climate policy (colour range : 0-26µg/m^3), see Section 4.3.1.

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Abstract

The objective of the European Union is to reduce the domestic emissions of greenhouse gases (GHG) by 80 percent by 2050 compared to 1990 levels, provided that other world regions also make a proportional contribution. A sketch of how such a reduction could be realized is outlined in the recently published 'Roadmap for moving to a low carbon economy in 2050' (EC, 2011b). By targeting the whole range of human activities having an impact on the atmospheric radiative forcing, these measures will have an indirect effect on the emissions of air pollutants. This effect is studied in this report.

First we present a comparison of the various emission inventories developed after 2007 taking into account both the reduction of greenhouse gases and air pollutants. A specific focus to the emissions related to the transport sector is then detailed because of its relatively small potential for the reduction of greenhouse gases compared to its important health impacts from air pollution. Last, the impacts of the reduction of emissions on air pollution levels at the 2030 milestone are assessed with an air quality model that accounts for the transport and transformation of secondary pollutants in the atmosphere.

The main highlights of this report are summarized below.

<u>Comparison of scenarios that address both air pollutants and greenhouse gas emissions:</u>

- A **review of the existing quantitative projections of climate and air pollution policies** highlighted the scarcity of air pollutant emission data that can be readily used for an impact assessment of air quality. The spatial and sectoral aggregation is often too coarse for their implementation in Chemistry Transport Models that are required to account for chemical and meteorological processes. Only the Representative Concentration Pathways (RCPs) and Global Energy Assessment (GEA) emission scenarios were found to provide appropriate data. Amongst them, only the GEA scenarios were based on explicit air quality measures. These scenarios were therefore compared in detail with the Commission Roadmap for moving to a low carbon economy in 2050.
- The **RCP2.6 and GEA-mitigation pathways have been designed to limit global warming to 2 degrees by the end of the 21st century. Hence, these projections are thus conceptually similar to the Commission Roadmap for the EU scenario** of global action effective technologies and shall thus reach similar targets in terms of global radiative forcing. Nevertheless, significant differences were found in terms of GHG emissions over Europe for 2050. For example because of the combined large-scale application of biomass and carbon capture and storage (CCS), the power sector becomes a net sink of GHG by 2050 in the RCP2.6 scenario. In the Commission Roadmap and GEA scenarios, GHG emissions in the power sector are also strongly reduced but remain positive in 2050.
- **Emissions of all primary air pollutants decrease because of climate policies, except for ammonia which** exhibit very little sensitivity to climate policies.
- **Cobenefits of climate policies on air pollution exist for all investigated emission scenarios**. No net trade-off (e.g. an increase of pollutant emission as a result of a decrease of GHG) was found in the raw emissions for the policy packages concerned. For the GEA scenario the co-benefits evolve linearly with GHG-reduction, while they level-off in the RCP2.6 and they are notably smaller for the RCP4.5.
- When aggregated over several pollutants, the **cobenefits of climate policies for air pollutant emissions are larger in the GEA scenario** than for the RCP and the Commission Roadmap for the EU. However, a detailed comparison with the Commission Roadmap could not be achieved because of lack of disaggregated information.
- The larger climate cobenefits found in the GEA mitigation scenario are likely to be due to the focus given to energy efficiency in this scenario, whereas the RCP2.6 prioritises measures such as CCS - that yields lower cobenefits for air pollution.

<u>Transport scenario analysis</u>

- Using GAINS emission factors, it was possible to compute air pollutant emissions for the CTS (Clean Transport System) study that provides energy consumption and activity data for the transport sector including the latest legislation.

- Except for gasoline heavy duty vehicles, emissions decrease sharply for all vehicle types and all scenarios, even though total energy consumption increases for the reference pathway. **The decrease for NOx, PM and VOC emissions ranges from 90 to 97% for all the mitigation scenarios** illustrating the larger potential of the transport sector for mitigation of air quality rather than GHG emissions.
- The dominant electrification scenario delivers the highest improvement for air quality, while the dominant biomass scenario is the least efficient. Differences among the various mitigation scenarios are small though. **The increase of NOx and VOC emissions brought about by the use of biofuels compared to the reference did not appear to be significant, given the dominating impact of the reduction of the total energy consumption induced by a better efficiency of the vehicles**. Similarly, the increased electricity demand in the electrification scenario is not expected to have a significant impact from the power sector, given the magnitude of the decarbonisation for the power sector.

Air quality modelling for 2030

- The **impact on air quality of the projected emission reduction was assessed by implementing the chemistry transport model CHIMERE**. The 2030 milestones of the GEA reference and mitigation pathways were chosen because they constitute the only available scenarios based on explicit air quality legislation measures.
- **Important differences are identified between the reference simulation with GEA emissions for the 2000's and a reference based on the EMEP official inventory** (all other simulation parameters being equal). The projections are matched with existing inventory for the present-day condition ('handshake process') but this matching is performed on an aggregated basis, so that spatial differences are not unexpected.
- The estimate of **the cobenefit brought about by the climate policy (in the GEA data) on nitrogen oxides is very similar (50%) when quantified either from the raw emissions or from the modelled NO_2 concentrations** because primary emissions dominate for this compound.
- The average ozone concentrations differ over the reference period (2005 emissions) between the GEA and EMEP emissions: the titration effect (reduced ozone over the high-NOx emission areas over Central and Northern Europe) is lower with the GEA dataset because of different spatialisation algorithms (hence, higher ozone concentrations result using GEA data for the control period).
- **Ozone is found to decrease substantially over Europe by 2030** in the GEA scenarios, except above the NOx emission hotspots where an increase of annual mean ozone is found. Again, this increase of the annual mean is induced by the titration effect which has an impact on low O_3 levels and does not reflect changes in exposure to ozone pollution that would be depicted by other statistical indicators.
- The comparison between the reference and climate mitigation GEA scenarios shows that **the cobenefit of climate policy for ozone concentrations is about 125%, i.e. twice as large as the reduction of nitrogenous precursors**.
- For the concentration of Particulate Matter of diameter larger than 10µm (PM10), the enforcement of the climate policy (as depicted in the GEA scenarios) yields a 30% decrease, whereas the cobenefit estimated for PM emissions was about 20%. **Using only the primary emissions to quantify the cobenefit leads to an underestimation because the secondary production of PM** (from gaseous anthropogenic precursors) is neglected.
- A radiative transfer model, implemented in the post-processing of the CHIMERE chemistry-transport model showed that a strong reduction of the radiative forcing brought about by particulate pollution could be expected from the reduction of PM concentrations. This reduction of the radiative forcing yields a reduction of the net cooling effect of aerosols over Europe.
- The radiative forcing from aerosols decreases by 20% in the reference and 30% in the mitigation scenario. There is thus a **more than 40% cobenefit of the climate policy between the two GEA scenarios for the radiative forcing** although, since aerosols have a net cooling effect, it will yield a penalty in terms of warming.

1 Introduction

1.1 Policy Context

In March 2011, the European Commission published its Roadmap for moving to a low carbon economy in 2050 (EC, 2011b), here after referred to as 'Commission Roadmap for the EU'. In this Roadmap, the Commission lays down the ambition to reduce domestic greenhouse gas emissions by 80% in 2050 (compared to 1990), in the context that also other developed and developing countries reduce their emissions such that global emission are reduced by 50% by 2050. The Commission's ambition is in line with positions taken by world leaders within UNFCCC negotiations - most notably, the Copenhagen Accord in March 2010, followed by decisions at COP16 (Cancun) and COP17 (Durban) - and the position of the European Council (EC, 2009), aiming to agree upon limiting global temperature rise to 2 degrees Celsius, to reduce global emissions to at least 50% and to reduce greenhouse gas emissions of developed countries by 80-95% by 2050. A global greenhouse gas (GHG) emission reduction by some 50% or more in 2050 will be needed to achieve this (Moss et al., 2010; van Vuuren et al., 2007). With its climate Roadmap, the European Commission sketches a long term perspective towards a low carbon economy in 2050, with ambitions that look beyond the current climate and energy targets for 2020. The climate Roadmap builds upon the overall EU strategy 'Europe 2020, A strategy for a smart, sustainable and inclusive growth' (EC, 2010a), in particular its flagship initiative for a resource efficient Europe, and many other more specific policy strategies, including the energy efficiency plan for 2020, the 2020 energy strategy, and the white paper on the future of transport. The Commission has also presented an Energy Commission Roadmap for the EU for 2050 in December 2011. Since greenhouse gas emissions result to a large extent from energy use, the two Roadmaps are tightly linked.

In the past years, many studies have addressed what technical options exist to realise a drastic GHG emission reduction, globally or within Europe (ECF, 2010; IEA, 2010). In general, these studies show that it is technically feasible to meet very substantial GHG emissions reductions by 2050, but that this requires dramatic changes within the energy system. Options considered in such studies include the reduction of energy demand, increased use of biomass to replace fossil fuels, the application of carbon capture and storage (CCS) in industry and the power sector, and other low carbon electricity technologies (solar, wind, hydro, geothermal, as well as nuclear), accompanied by an increased share of electricity in final energy consumption (e.g., by electrification of transport or the use of heat pumps in the built environment).

It is important to investigate the effects of such an energy transition on air pollution as well. While air pollution has been reduced substantially within Europe since the 1980s, still large areas of sensitive ecosystem in Europe suffer from excess nitrogen deposition thereby deteriorating species abundance. Human health is still significantly affected by exposure to particulate matter, ozone and nitrogen dioxide (EEA, 2010). The thematic strategy on Clean Air for Europe (EC, 2005) and, more recently, the Roadmap to a Resource Efficient Europe express the ultimate goal of achieving levels of air quality that do not cause significant impacts on health and the environment. It is questionable whether current policies are sufficient to deliver this long term objective. A revised Gothenburg

Protocol (UNECE, 1999) aims at setting interim objectives, which will be an important step towards reducing air pollution. Also, the 2020-milestone objective of the EU-strategy is to be seen as an interim objective. Therefore, attaining levels that do not significantly damage human health and the environment will require further reductions of air pollutant emissions. The question is to what extent measures taken to reduce GHG emissions could contribute to this objective.

1.2 Effects of climate policies on air pollution

Many studies have highlighted the positive effects of climate policies on air pollution (ApSimon et al., 2009; EEA, 2004a; van Aardenne et al., 2010; van Vuuren et al., 2006a; van Vuuren et al., 2007; van Vuuren et al., 2006b). (Amann et al., 2008) concluded that climate policies in the EU needed to meet the 2020 targets also reduce the costs of air pollution control, and these cost savings can be substantial compared to those of climate mitigation measures in Europe (several tens of percents). A similar conclusion was drawn when analyzing efforts to comply with the Kyoto target (EEA, 2004b; van Vuuren et al., 2006a), and if the EU would increase its climate policy target from 20% to 30% CO_2 reduction by 2020 (EC, 2010b). (van Aardenne et al., 2010) quantified the improvement on life expectancy, crop yield loss and nitrogen deposition from various policies, and confirmed that climate policies alone are not sufficient to solve air pollution problems, especially in Asia (van Aardenne et al., 2010).

1.3 Effects of air pollution on the climate system

While climate policies affect air pollution, air pollution policies also affect the climate system. Air pollutants significantly affect the Earth's radiation budget (IPCC, 2007). Tropospheric ozone (O_3), resulting from emissions of methane (CH_4), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), and nitrogen oxides (NOx), is the third greenhouse gas in terms of radiative forcing potential, after carbon dioxide and methane. Black Carbon (BC) also contributes to global warming (IPCC, 2007; HTAP, 2010), by absorbing solar radiation in the atmosphere and at the surface (particularly after deposition on snow). In contrast, most other aerosols (resulting from emission of sulphur dioxide, nitrogen oxides, ammonia and organic carbon) enhance the planetary albedo and partly mask global warming, either directly or indirectly through their impact on cloud reflectivity and lifetime. Estimates indicate that air pollutants have currently a net cooling effect (IPCC, 2007).

The effect of fossil fuel combustion on the radiative forcing is actually limited at relatively short timescales (decades) through the offsetting effects of CO_2 and aerosol emissions at these timescales (Hansen et al., 2000; Wigley, 1991). (Hansen et al., 2000) therefore argued that the rapid warming in the past decades is largely due to non-CO_2 GHGs. Shindell and co-workers argued that multi-gas climate mitigation strategies should account for the effect of short-lived air pollutants (Shindell et al., 2012; Shindell et al., 2009). Reducing emissions of air pollution by end-of-pipe technologies may negatively impact net radiative forcing in the coming decades (Kloster et al., 2010; Raes and Seinfeld, 2009). Several studies have therefore argued that air quality policies should also consider the effects on radiative forcing, more attention should be given to air pollution policies and their effect on ozone precursors and black carbon (HTAP, 2010; Rypdal et al., 2009).

1.4 Contents of this report

To date, however, only few studies have investigated the consequences of drastic GHG emission reductions in 2050 on air pollution in Europe in detail, e.g. accounting for effects of current EU air pollution control and looking at higher spatial resolution than global studies.

The EEA has asked the ETC-ACM to support the evaluation of the Commission Roadmap for the EU 2050 and other low carbon scenarios in terms of their effect on air pollution and its impacts on human health and vegetation, and radiative forcing. This report is the first outcome of this task.

The goal of this report is to present an overview of existing climate mitigation scenarios with the view to examine their suitability for Chemistry Transport Model (CTM) calculations (Chapter 2), to investigate this in particular for the transport sector (Chapter 3), and to present results of initial analyses based on simulations with the CHIMERE model for 2030 (Chapter 4). The report ends with suggestions for future work (Chapter 5).

2 Review of available scenarios

2.1 Overview of scenarios published since 2007

Over the past years, many studies have addressed the future development of GHG emissions. We have prepared a comprehensive, however non-exhaustive, overview of existing global and European scenarios that were published since 2007, with the aim to identify whether these scenarios can be used as an input to calculate the effect of stringent climate change policies on the European air quality in 2050 (see Table 1). For reports that appear on a multi-annual basis, only the most recent report is included. Some general observations are summarised below.

2.1.1 Type of scenario and target year of study

In Table 1 we have distinguished two categories of scenario. Firstly, there are studies that explore a plausible development, without trying to reach a pre-specified emission reduction or climate target. We refer to these as forecasting scenarios (denoted by F in the table). These scenarios may account for effects of current or future air and/or climate mitigation policies. Secondly, there are studies that aim to meet a certain target specified beforehand (e.g. an 80% emission reduction in Europe), and investigate the technical feasibility. These we refer to as backcasting scenarios (denoted by B). Often backcasting studies also consider a baseline development (in fact a forecast-scenario, denoted by BSL). Some studies contain both forecasting as well as backcasting scenarios. Most studies considered multiple scenario variants. Backcasting studies often have target years 2050 or 2100, while forecasting studies often consider the period up to 2030-2050.

2.1.2 Geographical and sectoral coverage

Various scenario studies focus on global developments; others have a European focus, of which some have an explicit global context. All global studies considered zoom-in upon large country groups. For Europe, global studies often consider slightly different country groups (OECD-Europe[1], EU27[2], EU27+). In Table 1, the spatial detail of emission data is indicated. The emissions can be given only for the total of the country group considered, or can be at higher spatial resolution (gridded, or at country level). Several studies consider energy related sources in detail, but do not or only very briefly consider non-energy related emissions (EREC, 2010; Eurelectric, 2009); in Table 1 this is denoted by *Energy*. Other studies also consider non-energy related emissions (like methane and nitrous oxide emissions in agriculture and waste and (sometimes) emissions/sinks of land-use, land-use change and forestry); this is denoted by *All.* Some studies consider all these non-energy related emissions, but for instance LULUCF emissions (Land Use, Land-Use Change and Forestry) are not always considered. Depending on the study, LULUCF emissions have been included in the total emission reduction listed in Table 1.

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[1] OECD-Europe is EU15 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom) plus the Czech Republic, Hungary, Iceland, Norway, Poland, Slovak Republic, Switzerland, Turkey.

[2] European Union (Austria, Belgium, Bulgaria, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom).

Study				Scenario characteristics			Coverage and detail			Emisisons					
Reference	Title	year of publication	Institution[1]	target year of study	Scenario type	Number of scenarios	Geographical coverage	Spatial detail of European emissions	Sectoral coverage	metric for emission change given in this table (Region / Baseyear)	scenario variant for which emisson changes are given in this table	% change GHG emission[2]	% change CO2 emission	Emissions of air pollutants quantified for	Numerical emission data publically available
Multi-sectoral backcasting scenarios															
Clarke et al., 2007	Scenarios of greenhouse gas emissions and ...	2007	R	2100	B+BSL	5	Global	Annex I	All	Europe / 2005	RCP 4.5 (Minicam)	-20		Yes	Yes
EC, 2011	Roadmap for a low carbon economy by 2050	2011	G	2050	B+BSL	11	EU27	Country	All	EU27 / 1990	Glob. Act. E-Tech.	-78		Yes	No
ECF, 2010	Roadmap 2050: a practical guide to a prosperous...	2010	N	2050	B+BSL	5	EU27	EU27	All	EU27 / 1990		-80		No	No
EREC, 2010	RE-Thinking 2050 - A 100% Renewable Energy ...	2010	I	2050	B	2	EU27	EU27	Energy	EU27 / 1990			-94	No	No
Eurelectric, 2009	Power choices: pathways to carbon-neutral ...	2009	I	2050	B+BSL	5	EU27	EU27	Energy	EU27 / 1990	Power Choices	-75		Yes	No
Greenpeace/EREC, 2010	Energy [R]evolution: A sustainable energy outlook ...	2010	N	2050	B+BSL	3	Global	OECD-Europe	Energy	Global / 1990	Adv. Energy Rev.		-89	No	No
Greens/EFA, 2011	The Vision Scenario for the European Union 2011	2011	N	2050	B+BSL	2	EU27	EU27	All	EU27 / 1990	Vision	-91		No	No
Grübler et al., 2007	Greenhouse Gas Initiative (GGI) database	2007	R	2100	F+B	20	Global	0.5x0.5 deg	All	Global / 2000	B1-450	-60		Yes	Yes
Hiljioka et al., 2008	Gloal GHG emission scenarios under GHG ...	2008	R	2100	B+BSL		Global	0.5x0.5 deg	All	Europe / 2005	RCP 6.0 (Aim)	5		Yes	Yes
IEA, 2010a	Energy technology perspectives 2010	2010	G	2050	B+BSL	14	Global	OECD-Europe	Energy	Global / 2005	Blue Map		-50	Yes	No
IEA, 2010b	World energy outlook 2010	2010	G	2035	F+B	3	Global	EU27	Energy	Global / 2008	450 scenario		-25	Yes	No
Naturvardsverket, 2007	Low emission scenarios for the European Union	2007	R	2050	B	6	EU25	Country	Energy	EU25 / 1990	EU30pc20N		-70	No	No
PBL/SRC/SU, 2009	Getting into the right lane for 2050	2009	R	2050	B+BSL	2	EU27	EU27	All	Europe / 1990	Vision	-79		No	No
Riahi et al., 2012	Global Energy Assessment (GEA)	2011	R	2100	B+BSL	4	Global	0.5x0.5 deg	All	Europe / 2005	Low CLE (mitigation	-57		Yes	No
Schade et al., 2009	ADAM 2-degree scenario for Europe – policies and ...	2009	R	2050	B+BSL	3	EU27	Country	Energy	EU27 / 2010	400 ppm		-80	No	No
van Vuuren et al., 2007	Stabilizing greenhouse gas emissions at low levels ...	2007	R	2100	B+BSL	2	Global	0.5x0.5 deg	All	Europe / 2005	RCP 2.6 (Image)	-77		Yes	Yes
Multi-sectoral forecasting scenarios															
EC, 2010	EU energy trends to 2030, update 2009	2010	G	2030	F	2	EU27	Country	Energy	EU27 / 1990	Reference	-24		No	Yes
Royal Society, 2008	Ground-level ozone in the 21st century: future ...	2008	R	2050	F+BSL	4	Global	EU27	All	Global / 2000	Revised B1 + CLE		15	Yes	No
Riahi et al., 2007	Scenarios of long-term socio-economic and ...	2007	R	2100	BSL		Global	0.5x0.5 deg	All	Europe / 2005	RCP 8.5 (Message)	22		Yes	Yes
Shell, 2011	Shell Energy Scenarios to 2050 - Signals and signposts	2011	I	2050	F	2	Global	Global	Energy	Global / 2000	Blueprints		-20	No	No
van Aardenne et al., 2010	Climate and air quality impacts of combined climate ...	2010	R	2050	F	6	Global	EU27	All	Global / 2000	CAP		-20	Yes	No
Transport backcasting scenarios															
Schade et al., 2010a	A transport scenario for Europe until 2050 ...	2010	R	2050	B+BSL	2	EU27	4 regions	Transport	EU27 / 2010	450 scenario		-30		Yes
TRL, 2010	Policies ro decarbonise transport in Europe: 80 by 50	2010	R	2050	B	2	EU27	EU27	Transport	EU / 1990			-80	No	No
E3MLab	Clean Technology Systems	2011	R	2050	B+BSL	4	EU27	EU27	Transport	EU27 / 2005	Electrification scenario		-77	No[3]	No
IEA, 2009	Transport, Energy and CO2 - Moving toward ...	2009	G	2050	F	5	Global	OECD-Europe	Transport	Global / 2005	Blue Shifts		-40	No	Yes
Transport forecasting scenarios															
Petersen, 2009	Transport Scenarios with a 20 and 40 Year Horizon	2009	R	2050	F+BSL	5	EU27	EU27	Transport	EU27 / 2005	Reduced Mobility		-61	No	Yes
Schade et al., 2010b	The iTREN-2030 Reference Scenario until 2030	2010	R	2030	F	2	EU27	Country	Transport	EU27 / 2005	Integrated		-12	Yes	Yes

[1] G=Governmental organisation; R=Research institution; N=NGO or political party; I=Industry association

[2] The % change refers to the region and baseyear listed in this table. In this table, Europe includes EU27 countries as well as several other European countries, depending on specific study

[3] In this study, air pollutant emissions corresponding to these scenarios have been derived (see chapter 3)

Table 1 : ***Overview of the GHG emission scenarios published since 2007 for Europe.***

2.1.3 Assumed drivers and policies

We have analysed population, economic growth assumptions, and assumed policies, but we have not attempted to summarise this in Table 1. For three studies, these issues are further described in some detail in Section 2.2. We observed that all global scenario studies use the United Nations population forecast, often using the medium forecast in which global population increases to slightly above 9 billion in 2050 (UN, 2007, 2009). For Europe, various sources are used. In general they assume a slightly declining (after reaching a peak by 2030) to stable population. Global GDP is expected to increase between 350-500%, with Europe somewhat lagging behind (180-300%, mostly 200%).

2.1.4 Resulting emissions and availability of data

Greenhouse gas emission reductions (or sometimes only CO_2 emission reduction in case only energy related emissions were considered) are listed in Table 1. The emission reduction may pertain to the global scale, or European country groups, and can be with respect to different base years, as indicated in the table. In case more scenarios were considered in the study, the scenario name is given that pertains to the emission reductions quoted. Generally we have presented the most stringent emission reduction scenario in the study. Also we have indicated whether or not air pollutant emissions are presented, and whether or not data are available for further analysis and modelling by third parties.

We may observe that it is not straightforward to compare the scenarios in terms of their GHG emission reduction for a certain geographical area (e.g., EU-27). This is because the scenarios differ with respect to the aggregation of countries, the base year and future years concerned, the inclusion or not of certain emission sources (international transport, non-energy related sources, land-use).

While the literature review revealed many examples of stringent greenhouse gas mitigation scenarios, the impact on air polluting emissions was often not presented, and if so, often limited to a limited set of species and/or sectors. For instance, in the IEA Energy Technology Perspectives and the Eurelectric-study only impacts on NOx and SO_2 are presented for low-carbon electricity production. The Commission Roadmap for the EU's Impact Assessment briefly describes some results for NOx, SO_2 and primary PM2.5 emissions for various scenario variants, as well as impacts on costs, health, and vegetation. Also for the GEA (Global Energy Assessment) scenarios, health impacts of air pollutants are assessed (Riahi et al., 2012). The Naturvardsverket-study describes emission changes for NOx and SO_2, but only up to 2030 (Naturvårdsverket, 2007). Emissions of air pollutants are, if present, sometimes only presented as the total of all sectors. Scenarios for 2050 with stringent air pollution mitigation only (and not at the same time considering stringent climate policy) were almost absent.

Availability of data – at the level of detail necessary for CTM calculations - is often problematic. For instance, at the time of writing this report, the data of the Commission Roadmap for the EU were not available. The GGI (Greenhouse Gases Initiative) and RCP (Representative Concentration Pathways) data are publicly available on the IIASA website, but are presented as aggregated totals per country group and per sector. Upon request, gridded sector specific air pollutant emissions of GEA were made available by IIASA for years up to 2050, and also RCP2.6 sectoral data were made available by PBL for years up to 2100, but for selected country groups only. In section 2.2 we present a more detailed comparison between the Commission Roadmap for the EU, GEA and RCP2.6 scenarios.

We conclude that, in general, only few climate mitigation scenario studies or databases also present air pollutant emissions. Among these are the scenarios of the Commission Roadmap for the EU, the GEA scenarios and the RCP scenarios, which are described in more detail below. If emissions of air pollutants are quantified, this often concerns total emissions of all sectors combined. Only few studies or databases also present sectoral emission trends for air pollutants (RCP, GEA). For this reason these scenarios have been considered in more detail in the next section.

2.2 *A focus on the Commission Roadmap for the EU, RCP and GEA scenarios*

In this section, we make a more detailed comparison between the Commission Roadmap for the EU, GEA and RCP scenarios, to show to what degree assumptions and results of the Commission Roadmap for the EU are similar to, or different from, other scenarios.

2.2.1 Commission Roadmap for the EU

The impact assessment of the Commission Roadmap for the EU describes a baseline (reference) scenario and 10 different mitigation variants (EC, 2011a). These scenarios are based on modelling with POLES and PRIMES (energy system), and CAPRI, GLOBIOM, and GM4 (agriculture, forestry, and land-use). POLES, GLOBIOM and GM4 are used for the global scale, while PRIMES and CAPRI are used to zoom-in on Europe. The GAINS model is used to identify cost-effective emission control options for Europe for the activity levels provided by the models previously mentioned. In all scenario variants, global population is assumed to increase to 9 billion inhabitants in 2050, while the EU27 population is expected to stay at about 500 million in 2050. Global GDP is assumed to increase by 2.8% per year between 2005 and 2050. Economic growth within the EU27 is 1.5% per year on average.

In the reference scenario of the Commission Roadmap for the EU, the Primes 2010 reference scenario (EC, 2010c), which goes to 2030, is extended to 2050. An important element of the reference scenario is that the ETS (Emission Trading System) cap is assumed to continue to decline linearly after 2020 by 1.74% per year. In principle, this would result in ETS emissions in 2050 70% below 2005 levels. However, given the agreed review of this linear factor after 2025 as well as the unspecified possibilities for emission trading with countries or companies outside the EU, it is assumed in the Commission Roadmap for the EU's impact assessment to result in a domestic emission reduction of 50% in the ETS-sector by 2050 compared to 1990. In the Commission Roadmap for the EU scenarios, current EU air pollution control policies are taken into account through the GAINS model.

The mitigation scenarios considered in the Commission Roadmap for the EU fall into two groups: (1) global action scenarios, in which concerted global climate action is assumed, and (2) fragmented action scenarios, in which for the rest of the world more limited climate policies are assumed, while for EU27 climate policies are the same as in the global action scenarios (see Table 2).

Scenario	Key assumption	Scenario variant	Key assumption
Reference	Current trends and policies		
Global climate action	-80% GHG reduction in EU. Global action results in reduced energy import prices compared to the reference	Effective technology	All technologies are effectively enabled
		Delayed CCS	Lower contribution of CCS
		Delayed electrification	Lower contribution electrification of transport
		Delayed climate action	Reinforced action only from 2030 onward
Fragmented climate action	Only fragmented action globally, not resulting in reduced energy import prices compared to the reference	Effective technology	All technologies are effectively enabled
		Specific measures for exposed sectors, (variant a)	Society compensates additional costs for energy intensive industries
		Specific measures for exposed sectors, (variant b)	Carbon prices for energy intensive industries are as in the reference scenario, thus resulting in lower emission reductions in this sector
		High fossil fuel price (variant: oil shock)	Oil prices increase sharply in 2030, after which prices return close to reference levels
		High fossil fuel price (variant: structural high prices)	Structural increase of fossil fuel prices from 2030 onwards
		Delayed climate action	Reinforced action only from 2030 onward

Table 2 : Overview of scenarios considered in the Commission Roadmap for the EU impact assessment (EC, 2011b)

Both the global and the fragmented action scenarios have a variant with effective technology development, in which all key low-carbon technologies (energy efficiency, renewables, nuclear, CCS, electric cars) are successfully enabled. The global action scenario in addition has two variants that consider less optimistic technology developments (delayed Carbon Capture and Storage, CCS, delayed electrification). The fragmented action scenario has two variants with higher fossil fuel prices (resulting from a higher global demand for fossil fuels in these scenarios), and two variants in which additional measures are taken to protect sectors exposed to global competition. Also, both the global and fragmented action scenarios have delayed climate action variants, in which EU27 climate action is the same as in the reference scenario up to 2030 and then quickly accelerates such that EU27 cumulative GHG emissions over the 2005-2050 period equal those of the effective technology scenarios.

2.2.2 Global Energy Assessment

In the Global Energy Assessment (GEA[3]), a set of four scenarios was constructed (Riahi et al., 2012), which differ with respect to levels of future air quality legislation and with respect to levels of policies towards climate change and energy efficiency and access. It is one of the stated aims of the GEA

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[3] http://www.iiasa.ac.at/Research/ENE/GEA/index_gea.html

modelling exercise to identify the impact of the different scenarios in terms of air quality and human health.

The scenarios are based on modelling by IIASA with MESSAGE (energy system) and GAINS (air quality). Information about air pollutant inventories and air quality legislation (control options) from GAINS was linked with the MESSAGE energy scenarios to derive sector based estimates of air pollutant emissions.

MESSAGE distinguishes 11 world regions, amongst which Western Europe (WEUR[4]) and Central & Eastern Europe (CEEUR[5]). The emission trajectories were developed for the period from 2005 up to 2100. The main focus of the scenarios, however, is on 2030. The sectoral coverage includes power plants, industry (combustion and processes), domestic (residential/commercial), road transport, international shipping and aviation, waste, agriculture (fertilizer application), agricultural waste burning, and biomass burning (deforestation, savannah burning and forest fires). The following greenhouse gases and air pollutants are included in the scenarios, of which all but CO_2 were gridded: CO_2, CH_4, SO_2, NOx, CO, VOCs, BC, OC, PM2.5. In all four scenario variants, global population is assumed to increase to 9.2 billion inhabitants in 2050. The European population is expected to amount to 623 million in 2050, following a stabilisation after 2030 and a decline after 2040. For the period from 2005 to 2050 the scenarios assume an annual average GDP growth rate of 2.8% for the world and of 1.6% for Europe. The major policy assumptions behind the four GEA scenarios are summarised in Table 3, note that there is no scenario representing a climate policy enforcement without air pollution legislation.

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[4] Western Europe (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom).

[5] Central and Eastern Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, The former Yugoslav Rep. of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia).

Scenario	Policies			
	Air pollution	Climate Change	Energy efficiency	Energy access
Frozen Legislation (FLE)	No improvement in air quality legislation beyond 2005	No climate policy	Annual energy intensity reduction of 1.5% until 2050	No specific energy access policy; slow improvement in quality of cooking fuels
Reference Case with Current Legislation (CLE) [Reference]	All current and planned air quality legislations until 2030	No climate policy	Annual energy intensity reduction of 1.5% until 2050	No specific energy access policy; medium improvement in quality of cooking fuels
Sustainable Policy with CLE [mitigation]	All current and planned air quality legislations until 2030	Limit on temperature change to $2^{o}C$ in 2100	Annual energy intensity reduction of 2.6% until 2050	Policies to ensure global access to clean energy by 2060
Sustainable Policy with Stringent Legislation (SLE)	Stringent air quality legislations globally	Limit on temperature change to $2^{o}C$ in 2100	Annual energy intensity reduction of 2.6% until 2050	Policies to ensure global access to clean energy by 2060

Table 3 : Scenario Policy Matrix. Source: (Riahi et al., 2012).

In later sections of this paper the second and third scenarios are referred to as 'reference' and 'mitigation' scenarios respectively. These two scenarios make equal assumptions about policies and measures assumed for air pollution control: the application of current legislation by 2030 (cf. Table 4) and improvements of emission factors occurring with technology improvements, as well as a convergence of emission factors across regions as welfare increases (environmental Kuznets curve theory) in later years. The scenarios differ however in their assumptions about policies towards climate change. Whereas the reference scenario assumes no climate policy at all, the mitigation scenario assumes policies leading to a stabilisation of global warming (2°C target) in 2100. The two underlying energy trajectories are fundamentally different. Compared to the reference scenario, the mitigation scenario is characterised by a distinctly lower energy demand and shifts in the energy mix (less coal/oil and more renewables). Energy demand increases globally until 2100 across all the scenarios, although in the climate mitigation scenarios demand growth is very limited and almost stable by the end of the century. For specific regions, however, demand declines in the mitigation scenario because of the much larger emission intensity improvements compared to the rest of the world. For Europe this is the case from 2010 onwards.

	Transport	**Industry and power plants**	**International shipping**	**Other**
SO_2	OECD: directives on the sulphur content in liquid fuels; directives on quality of petrol and diesel fuels. Non-OECD: national directives on the sulphur content in liquid fuels	OECD: emission standards for new plants from the Large Combustion Plant Directive (LCPD) Non-OECD: increased use of low sulphur coal, increasing penetration of FGD after 2005 in new and existing plants	MARPOL Annex VI regulations	Reduction in gas flaring, reduction in agricultural waste burning
NOx	OECD: emission controls for vehicles and off-road sources up to the Euro-VI and Euro-V standard; penetration of three-way catalysts Non-OECD: national emission standards equivalent to up to Euro III-IV standards	OECD: Emission limits according to the EU LCPD; national emission standards if stricter that LCPD Non-OECD: primary measures for controlling NOx	Revised MARPOL Annex VI regulations	Reduction in gas flaring, reduction in agricultural waste burning
CO	OECD: emission controls for vehicles and off-road sources up to the Euro-VI and Euro-V standard; penetration of three-way catalysts			Reduction in gas flaring, reduction in agricultural waste burning
VOC	Stage-I measures	Solvent directive of the EU (COM(96), 538, 1997); 1994 VOC protocol of the LRTAP convention		Reduction in gas flaring, reduction in agricultural waste burning
NH_3		End of pipe controls in industry (fertilizer manufacturing)		

Table 4 : Specific policies and measures for air pollution control in the CLE scenarios. Source: (Riahi et al., 2012).

Assumptions about air pollutant emission factors up to 2030 are in principle the same in GEA and Commission Roadmap for the EU, as both are based on GAINS. However, since the underlying energy models differ (PRIMES for the Commission Roadmap for the EU and MESSAGE for GEA), and as MESSAGE energy flows are too highly aggregated to be directly computable in GAINS, for GEA implied emission factors that are compatible with the sector-fuel combinations in MESSAGE were derived from GAINS. Computing GAINS emission factors thus required some aggregation for application to the GEA scenarios. This aggregation applies to fuel sectors but also to the granularity of the air quality legislation. The country-scale GAINS information (emission factors, technological and economic information, control measures, etc.) had to be aggregated to match the granularity of MESSAGE (Rafaj et al., 2010). Finally, while in the Commission Roadmap for the EU scenarios, emission factors are kept fix after 2030 (no extrapolation is performed with regard to a hypothetical improvement of the technologies), GEA scenarios apply the environmental Kuznets theory to extrapolate improvements in emission factors after 2030. Hence, any air pollutant emission reductions in the Commission Roadmap for the EU after 2030 are due to changes in total energy use or changes in the energy mix, while in GEA they are additionally due to assumed improvements in emission reduction technologies.

2.2.3 Representative Concentration Pathways

The Representative Concentration Pathways (RCPs) are a set of four scenarios that were selected to span the range of radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W/m^2 in the year 2100 (Moss et al., 2010). The RCPs prescribe emission and concentration developments of atmospheric constituents that affect the Earths' radiation budget, and serve as a basis for climate and atmospheric chemistry modelling experiments, that may contribute to the 5th Assessment Report of the IPCC. The emission and concentration trends of the RCPs may result from different socio-economic and policy assumptions. In this sense, the RCPs are not a new fully integrated set of scenarios based on a common set of socio-economic assumptions (this in contrast to the SRES-scenarios (Nakicenovic et al., 2000)).

The four RCPs were selected from an analysis of the peer reviewed literature. The selection process relied on previous assessment of the literature – considering several hundreds of publications – conducted by the IPCC Working Group III during development of the Fourth Assessment Report. An individual scenario was then selected for each RCP (Table 5). The selected RCP scenarios (RCP8.5, RCP6.0, RCP4.5, and RCP2.6) are scenarios from the teams/models NIES/AIM, IIASA/MESSAGE, PNNL/MiniCAM, and PBL/IMAGE, respectively. Each of the RCPs was produced by a different integrated assessment model; therefore, each has its own reference scenario (Thomson et al., 2011). The baseline scenarios were kindly made available by the RCP research groups upon request.

For Europe, the RCP2.6 scenario leads to an almost 80% GHG emission reduction by 2050 (see Table 1). For the RCP4.5 scenario, this is only a 20% emission reduction, while GHG emissions actually increase for Europe in the RCP6.0 and RCP8.5 scenarios until 2050. As we are interested in mitigation scenarios in this study, we have only considered the RCP2.6 and RCP4.5 scenarios in more detail.

The RCP2.6 scenario (also called RCP3-PD, where PD stands for a Peak in a radiative forcing to 3 W/m^2 in 2050 followed by a Decline to 2.6 W/m^2 in 2100) is the most stringent climate mitigation scenario in the RCPs. It assumes drastic emission reductions necessary to limit global temperature increase to below 2 degrees. In the study selected to represent the RCP2.6 scenario (van Vuuren et al., 2007; van Vuuren et al., 2006b), global population grows to 9 billion in 2050, and slightly declines in Western and Eastern Europe (to 490 million, including Norway, Switzerland, Iceland and non-EU Balkan countries; this is a -0.1% per year decrease averaged over 2000-2050). Global GDP increases by 2.8% per year, resulting in almost a factor 4 increase between 2000 and 2050. For Western and Eastern Europe, GDP increases by 1.7% per year over this period, resulting in more than a factor 2 increase between 2000 and 2050.

In the RCP4.5 scenario, global radiative forcing reaches about 4 W/m^2 in 2050 and only slightly increases to 4.5 W/m^2 until 2065 and stabilizes thereafter. Global population reaches a maximum of more than 9 billion in 2065 and then declines to 8.7 billion in 2100. European population (including Turkey) remains more or less stable at 575 million. Global GDP is assumed to increase by a factor of 3, and almost doubles for Europe between 2005 and 2050 (Clarke et al., 2007; Thomson et al., 2011).

Unlike the GEA projections, in the RCP2.6 and RCP4.5 scenarios, air pollution policies are not explicitly taken into account. Here, it is assumed for the whole period under investigation that increasing income will lead to more stringent emission standards (environmental Kuznets curve theory), while for the GEA scenarios this assumption is applied only for the years after 2030 as information on air pollution legislation beyond this date is not available. The improvement of emission factors is differentiated between country groups, sectors and fuel types.

Description		**Publication – IA Model**
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	(Rao and Riahi, 2006; Riahi et al., 2007) – MESSAGE
RCP6.0	Stabilisation without overshoot pathway to 6 W/m^2 at stabilisation after 2100	(Fujino et al., 2006; Hijioka et al., 2008) – AIM
RCP4.5	Stabilisation without overshoot pathway to 4.5 W/m^2 at stabilisation after 2100	(Clarke et al., 2007; Smith and Wigley, 2006; Thomson et al., 2011) – MiniCAM
RCP2.6 (RCP-3PD)	Peak in radiative forcing at around 3.1 W/m^2 by 2050, then returning to 2.6 W/m^2 by 2100	(van Vuuren et al., 2011b; van Vuuren et al., 2007; van Vuuren et al., 2006b) – IMAGE

Table 5 : Overview of Representative Concentration Pathways. Source: (Moss et al., 2010).

2.2.4 Comparison of GHG emissions

The Commission Roadmap for the EU reference scenario exhibits declining greenhouse gas emissions (almost -30% in 2050 compared to 2005), which results from taking into account a continuing decrease of the EU-ETS emission ceiling (Figure 1). The GEA reference scenario does not account for any ETS emission cap. The RCP4.5 and 2.6 references are between that of GEA and the Commission Roadmap for the EU.

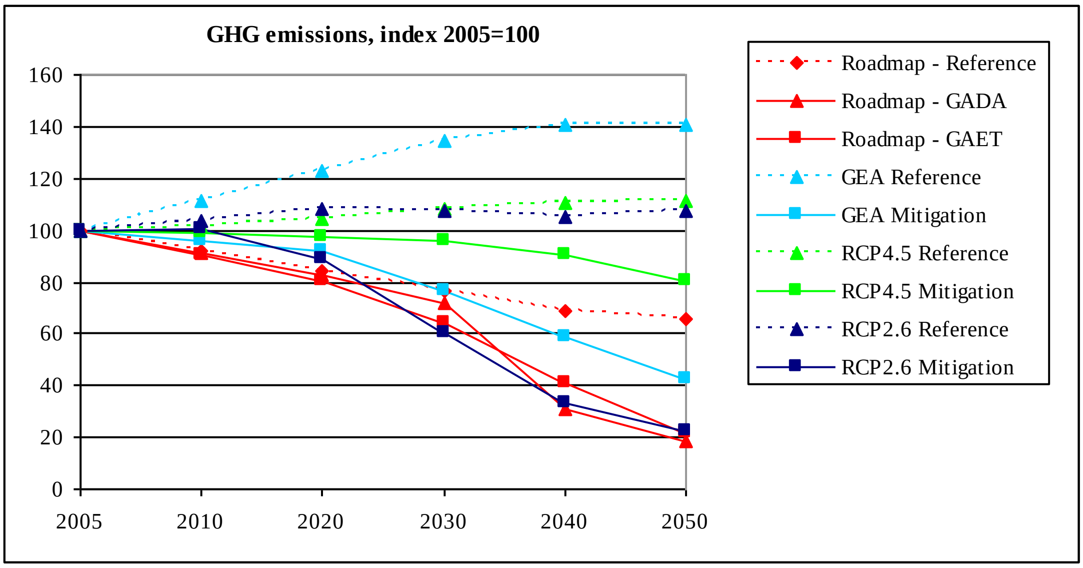

Figure 1 : Greenhouse gas emission trends for Europe for two Commission Roadmap for the EU mitigation scenarios (Global Action Delayed Climate Action = GADA; and Global Action Effective Technology = GAET), the GEA mitigation scenario, RCP4.5 and RCP2.6 mitigation scenarios, as well as the corresponding baseline scenarios. The Commission Roadmap for the EU trends pertain to the EU27, those of RCP4.5, RCP2.6 and GEA to Western plus Central and Eastern Europe (which in case of RCP4.5 and GEA also includes Turkey).

European greenhouse gas emission reduction in the climate mitigation scenarios of the Commission Roadmap for the EU (Global Action Delayed Climate Action = GADA and Global Action Effective Technology = GAET) and RCP2.6 amounts to about 80% in 2050 compared to 2005. GHG emission reductions for Europe in the GEA (-60%) and RCP4.5 (-20%) scenarios are more limited (partly because Turkey in included in these two scenarios). The RCP4.5 mitigation scenario even shows higher emissions than the Commission Roadmap for the EU reference scenario, which assumes amongst others substantial reductions in the ETS-sector. In the Commission Roadmap for the EU delayed climate action scenario, the emission reductions until 2030 are close to the reference, and sharply decline afterwards. For the other mitigation scenarios, the emission reductions exhibit a more smooth behaviour in time. Note that care must be taken for such a regional comparison of scenarios developed with a different geographical scope in mind. For instance (Riahi et al., 2012) show that the reference GEA trajectory is identical in terms of global radiative forcing to the RCP8.5, whereas GHG emissions over Europe can be quite different, as seen on Figure 1.

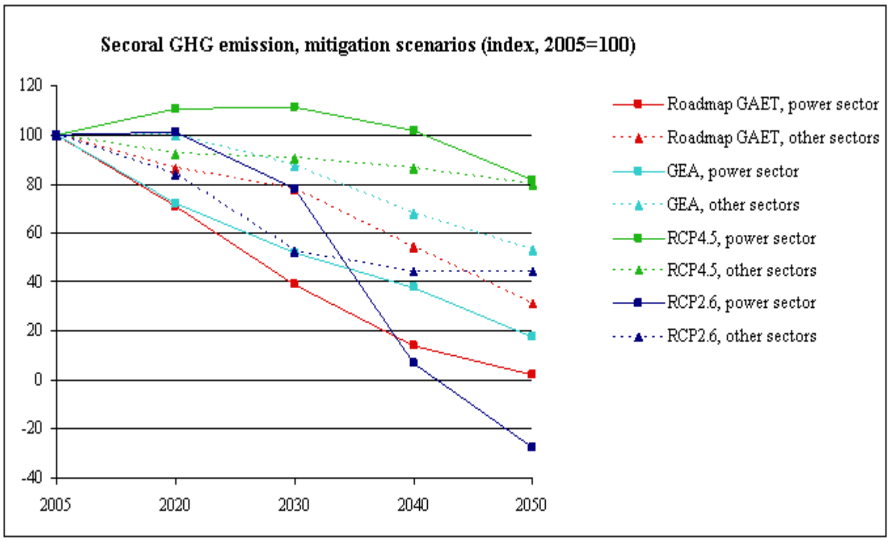

Figure 2 : Greenhouse gas emission trends for Europe (see **Figure 1** for the list of countries) according to mitigation scenarios of the Commission Roadmap for the EU (global action, effective technology scenario), GEA, RCP4.5 and RCP2.6, distinguishing reductions in the power sector from those in the other sectors. Even negative emissions may result in the power sector through large scale application of biomass and CCS.

The emission trends in the power sector and the total of other sectors are compared in Figure 2, for the Commission Roadmap for the EU (global action, effective technology) scenario, the GEA mitigation scenario, the RCP4.5 scenario, and the RCP2.6 scenario. In all these mitigation scenarios (except RCP4.5 in the period before 2050), emissions in the power sector decrease more strongly than those in other sectors. The reason is that a relatively large number of low carbon technologies exist which may replace fossil fuel based electricity production, and at lower costs than mitigation measures in other sectors. The difference between the power sector and the total of other sectors is particularly large in the RCP2.6 scenario. In the RCP2.6-scenario, the power sector even becomes a strong sink through the assumed large-scale application of biomass and CCS technology. Through the combination of biomass and CCS (Bio-Energy with carbon capture and storage), CO2, which is taken up from the atmosphere by the biomass, will be long-term stored in geological reservoirs, such that negative emissions result (no matter which time frame is considered since such reservoirs constitute a permanent sink). In the RCP4.5 scenario, only after 2050 (not shown here) emissions in the power sector do show a stronger reduction compared to other sectors.

2.2.5 Comparison of air pollutant emissions

Figure 3 shows trends of NOx, SO_2, VOC and NH_3 emissions for the GEA, the RCP4.5 and RCP2.6 scenarios for Europe. Both the reference and mitigation scenarios project decreasing air pollutant emissions resulting from air pollution abatement policies (except for NH_3 in the RCP4.5 scenario). These emission reductions are reinforced by climate policies for the mitigation scenarios. Decreases are strongest for SO_2 and smallest for NH_3. Ammonia emissions remain relatively high in all scenarios, and are not affected by climate policies in the RCP2.6 and GEA scenarios, but appear to be affected by climate measures in the RCP4.5 scenario, probably because of different agricultural scenarios.

We noted that absolute emission levels for 2005 of the scenarios described above (GEA, RCP2.6 and RCP4.5) may differ substantially from officially reported emission data - UNFCCC for greenhouse gases[6] and air pollutants reported within the CLRTAP process[7]. For greenhouse gas emissions, such differences are generally smaller than 10%. For air pollutant emissions (using different base year emissions (see below), for which both mitigation and reference emissions are available), differences of up to several tens of percents (sic) between these scenarios and emissions used by EMEP may occur. Differences are particularly large for emissions of VOC, CO and NH_3. NOx and SO_2 emissions tend to agree better. Some RCP-scenarios are therefore harmonised, such that emission outputs from the integrated assessment models used to make the scenarios are adjusted in such a way that emissions in the reference year are equal to a reference data set (with these adjustments extended into the future, in some manner, to assure smooth data sets) (van Vuuren et al., 2011a).

2.2.6 Relation between GHG and air pollutant emission changes

The effect of climate policies on air pollution depends (ceteris paribus) on the mix of climate measures taken. Reducing energy demand and increasing the share of carbon-free electricity lead to a decrease of air pollutant emissions too. However, this is not necessarily the case for substitution of fossil fuels by biomass, nor for the application of CCS. Their effect depends on the specific technology used, and can be different for different air pollutants. For example, application of post-combustion CCS using amine to capture CO_2 also requires the removal of SO_2 from exhaust gases (EEA, 2011). On the other hand, this technology requires substantially more energy, and hence NOx emissions may increase. Hence, depending on the climate measures taken in a specific scenario, effects on air pollutant emissions may differ.

Figure 4 illustrates the relation between the change of GHG emissions and that of air pollutants (both changes relative to baseline developments), for the GEA, RCP4.5 and RCP2.6 mitigation scenarios and for the period until 2050. For the Commission Roadmap for the EU, such a figure cannot (yet) be produced because of lack of published data. The different years can be discerned along the x-axis as different steps of GHG reductions (every 10 years from 2010-2050 for the RCP scenarios, and for the years 2020, 2030 and 2050 for the GEA scenario).

Given that identical assumptions about the evolution of air pollution emission factors are made in the reference and mitigation scenarios of each scenario group, the emission reductions presented in Figure 4 can be considered as co-benefits of climate mitigation policies. Co-benefits for all air pollutants exist, and they are rather linearly related with the GHG emission reduction for the GEA scenario, while they level off slightly for the RCP2.6 scenario (such that a doubling the GHG emission reduction leads to less than a doubling of the air pollutant emission reduction; this is particularly for VOC, and to a lesser extent for NOx and SO_2). For the RCP4.5, both GHG emission reductions and the corresponding air pollutant emission reductions are relatively small.

[6] http://unfccc.int/ghg_data/ghg_data_unfccc/ghg_profiles/items/4625.php
[7] http://www.ceip.at/emission-data-webdab/emissions-as-used-in-emep-models/

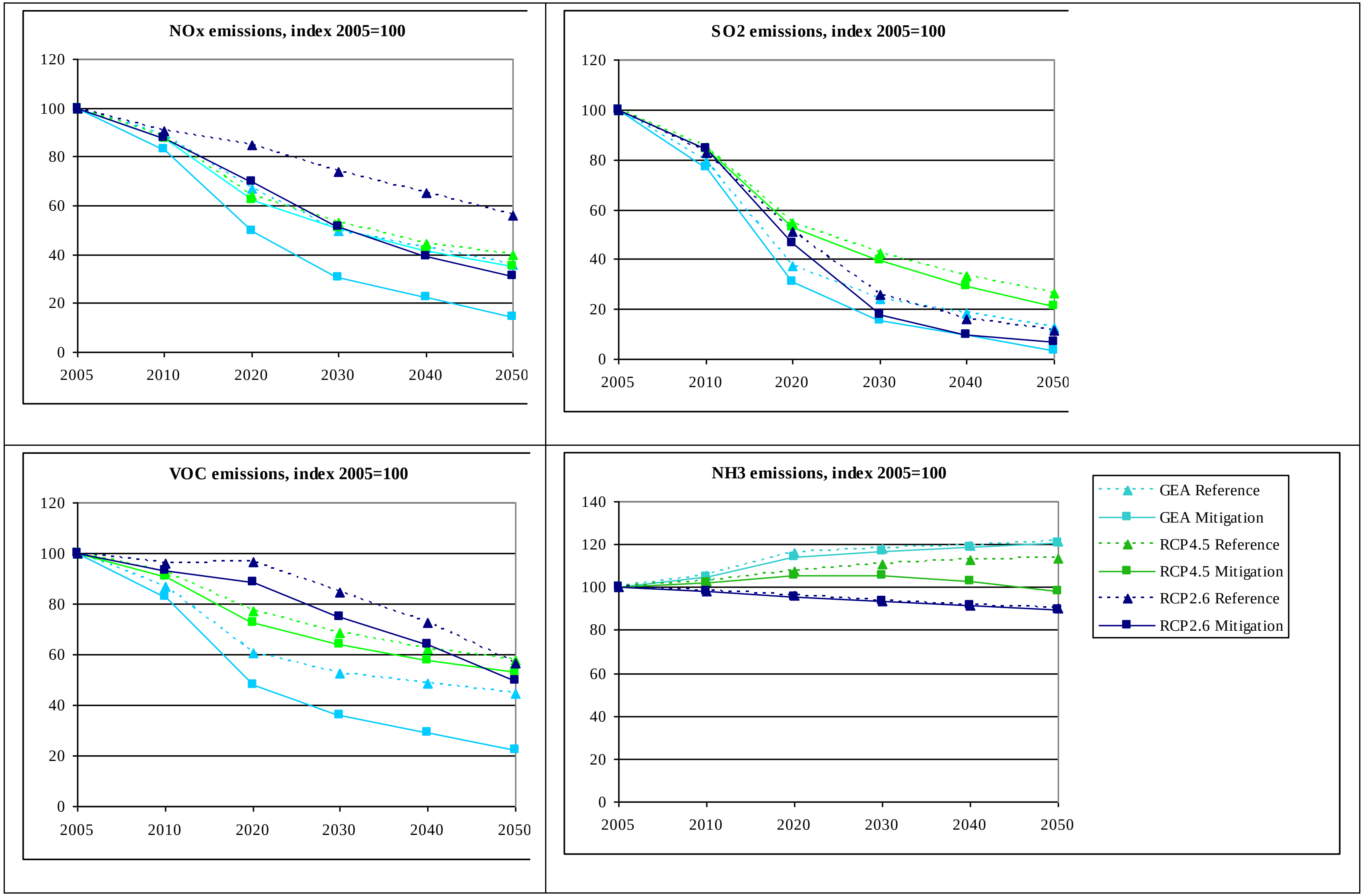

Figure 3 : Emission trends of NOx, SO_2, VOC and NH_3 in Europe relative to the 2005-level (=100 on the y-axis)

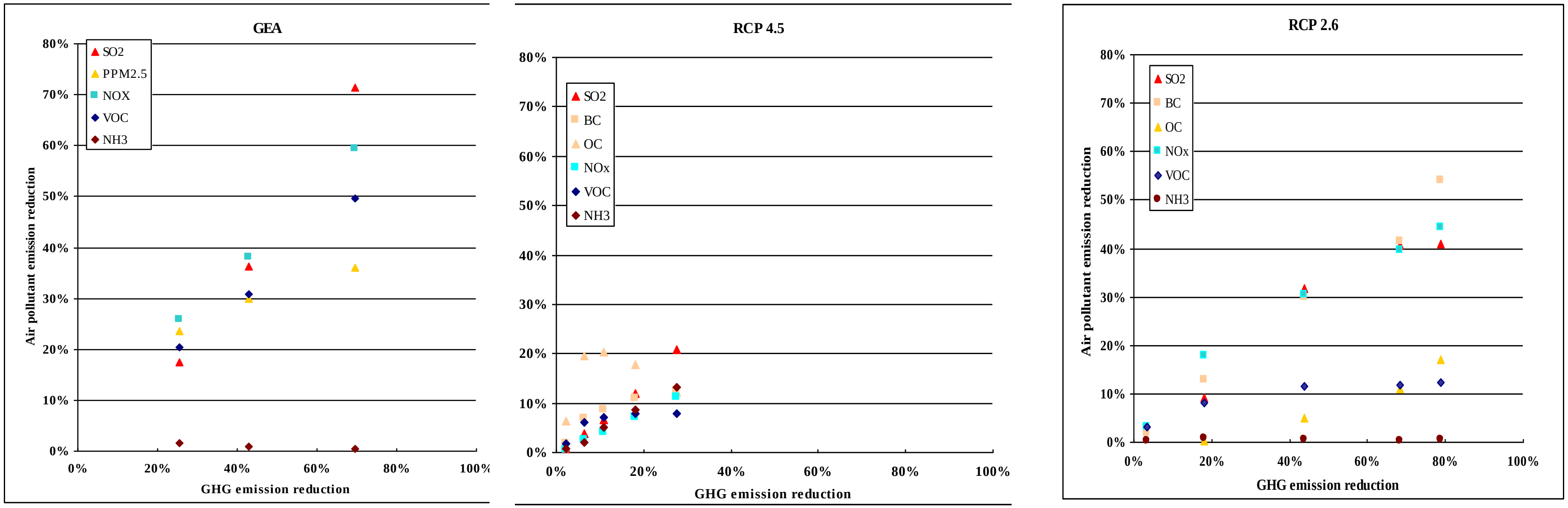

Figure 4 : Emission reduction of air pollutants compared to that of GHGs. Both GHG and air pollutant emission reductions are emission reductions relative to their baseline development. In the reference and mitigation scenarios, the same assumptions on air pollutant emission factors have been made. The selected years for the RCPs are 2010, 2020, 2030, 2040, and 2050, and for GEA 2020, 2030 and 2050 are displayed.

Both for the RCP2.6 and GEA scenarios, emission reductions of NOx and SO_2 resulting from climate mitigation measures are larger than those of VOC. It can be observed that ammonia emissions are hardly affected by climate mitigation policies in the RCP2.6 and GEA scenarios. This might be expected because NOx and SO_2 emissions result to a larger extent from fossil fuel combustion than emissions of VOC and NH_3 (van Vuuren et al., 2008).

It can also be observed that, in case of the GEA scenarios, the co-benefits are in general larger than those in the two RCP scenarios (for a similar GHG reduction). This is mainly due to the fact that for the GEA scenarios policies on energy efficiency are included in addition to a global GHG constraint. This is reflected in significantly lower energy demands in the GEA mitigation scenario, whereas other scenarios (such as the RCPs) may chose a pathway to achieve the same radiative forcing target that offers a lower reduction of air pollutant emissions. Besides differences in climate mitigation measures, different responses may also result from different reference developments (e.g. differences in fossil fuel mix). Similar differences in co-benefits between scenarios were observed by (van Vuuren et al., 2011c) for global GHG and NOx emissions.

In the impact assessment of the Commission Roadmap for the EU, some results of air pollutant emission developments are presented for the reference, global action effective technology scenario and the global action delayed climate action scenario. Impacts of climate policies on emissions of PM2.5, NOx and SO_2, as well as various impacts for health, ecosystems and air pollution control costs are given compared to the reference development. According to the Impact Assessment, the sum of PM2.5, NOx and SO_2 emissions will decrease by 68% and 67% with respect to 2005-levels in 2030 and 2050, respectively in the global action effective technology scenario. This means that the sum of these emissions decreases strongly until 2030, but does not decrease between 2030 and 2050. In the delayed action scenario, air pollutant reductions are smaller in 2030 but larger in 2050 compared to the effective technology scenario. Unfortunately, the Impact Assessment does not present absolute emission developments for PM2.5, NOx and SO2 separately.

In order to summarise the results of the different scenario groups in a comprehensive indicator allowing for comparison across the different scenario groups, we have calculated the ratio of the relative reduction of air pollutant emissions to that of GHG-emission reductions (where both air pollutant and GHG emission reductions are relative to a baseline). We refer to this ratio as the 'co-benefit factor' on emissions. In fact, the co-benefit factor is the slope of the linear fit of the scatter plots shown in Figure 4. For instance, if NOx emissions decrease at the same relative pace as the GHG-emissions (compared to their baseline developments), the co-benefit factor equals unity, while if NOx emissions decline only half as much as those of GHG-emissions, the co-benefit factor equals 0.5. If air pollutant emissions do not change at all while GHG emissions decrease, the co-benefit factor is null. In case of a net trade-off, the co-benefit factor would become negative, which is never the case here.

2030	NOx	SO2	PPM2.5[8]	VOC	SO2+NOx+PPM2.5[9]
Commission Roadmap for the EU, global action, effective tech.	n.a.	n.a.	n.a.	n.a.	0.63
Commission Roadmap for the EU, global action, delayed action	n.a.	n.a.	n.a.	n.a.	0.99
GEA mitigation	0.89	0.85	0.70	0.72	0.86
RCP4.5	0.38	0.61	1.53	0.64	0.53
RCP2.6	0.70	0.73	0.26	0.27	0.56
2050	NOx	SO2	PPM2.5	VOC	SO2+NOx+PPM2.5
Commission Roadmap for the EU, global action, effective tech.	n.a.	n.a.	n.a.	n.a.	0.42
Commission Roadmap for the EU, global action, delayed action	n.a.	n.a.	n.a.	n.a.	0.42
GEA mitigation	0.85	1.02	0.52	0.71	0.85
RCP4.5	0.40	0.76	0.44	0.29	0.51
RCP2.6	0.56	0.52	0.31	0.16	0.47

Table 6 : Co-benefit factors for 2030 and 2050 (ratio of relative reductions of air pollutants and of GHG-emissions)

From Table 6, it can be observed that in 2050 the Commission Roadmap for the EU scenarios exhibits co-benefit factors for the sum of SO_2, NOx and PM2.5 that are smaller than that of the GEA scenario, while they are similar to those of the RCP2.6 and RCP4.5 scenarios. Apparently, in the Commission Roadmap for the EU scenarios the reduction of air pollution in 2050 relative to the baseline scenario is less than half of that of the GHG-emission reduction. In 2030, the co-benefit factors are often higher than in 2050. This illustrates that the overall air pollutant emissions decrease at a lower pace than GHG-emissions in the period after 2030. The Commission Roadmap for the EU delayed action scenario has a high co-benefit factor in 2030, but in absolute terms the emission reduction compared to the reference is limited.

[8] For RCP2.6 and RCP 4.5, primary PM2.5 (PPM2.5) is calculated as the sum of OC and BC.
[9] This is the arithmetic sum of emissions of SO2 (kton SO2), NOx (kton NO2) and PPM2.5 (kton).

3 Focus on the emissions of the transport sector

The "Roadmap for moving to a competitive low carbon economy in 2050" published by the European Commission targets a 80 % reduction of GHG by 2050 from 1990 levels (EC, 2011b). Taking into account its technological and economic potential, the transport sector is expected to reduce its emissions by 54 to 67 %. The transport White Paper (EC, 2011c) defines some challenging goals – including phasing out conventionally fuelled cars from cities by 2050, and a 50 % shift in middle distance passenger and longer distance freight journeys from road to other modes – to achieve a 60 % reduction in CO_2 emissions from 1990 levels and comparable reduction in oil dependency. Air pollution levels are also expected to be considerably reduced as a co-benefit of these targets.

Considering the effort shared between the different economic sectors, the contribution of transport to the overall target is lower compared to the other sectors. The power sector has the biggest potential for reducing emissions (93 to 99 %), followed by the residential (88 to 91 %) and the industrial (83 to 87 %) sectors, whereas the contribution of agriculture is lower (42 to 49 %).

However, emissions of air pollutants from the transport sector have a much higher reduction potential than GHG due to the combined effect of lower fossil fuel consumption and technological improvements imposed by tighter emission standards. As an example, maximum PM emissions from Euro 6 diesel cars (to be introduced by the end of 2014) are reduced by 80 % compared to those of Euro 4 cars (effective since 2005). Although real-world reductions may be somewhat lower than emission standards imply, the environmental benefits – in addition to any reductions achieved due to the decarbonisation of transport – are expected to be significant.

In view of the above and in an attempt to quantify the expected impact of the 2050 roadmap studies on air pollution and consequently to air quality a number of socio-economical scenarios specifically relevant for the transport sector are studied in the following.

A broad range of studies have been conducted at the European as well as at a global level to assess possible pathways towards reaching GHG targets. Various scenarios have been considered to this aim. The main objective of this chapter is to identify and evaluate appropriate transport scenarios to be used in future modelling exercise of the atmospheric effects of air and climate policies.

3.1 Overview and evaluation of transport scenarios

A large number of studies covering a wide range of transport scenarios have been considered with regard to their suitability for the purposes of the present study. Out of these, five studies were eventually selected and have been reviewed and assessed in more detail. The selected sample includes both large-scale projects with a high visibility at the EU level, as well as smaller scale exploratory studies. A common characteristic of all studies is the focus on CO_2 emissions and climate change mitigation, whereas the possible effects on air pollutants have not been sufficiently considered by these studies.

The main characteristics of these studies are included in Chapter 2 (Table 1), in which the type of scenario and target year of the study is discussed, as well as the geographical coverage, resulting emissions and availability of data. The main advantages and disadvantages for each of these studies are described in the following and Table 7 summarises these findings and complements the information already included in Table 1. More information on the scenarios considered in each of these studies, including storylines and assumed policies, is provided in Annex 1: Transport Scenarios

The **Clean Transport Systems (CTS)** study is based on the PRIMES-TREMOVE model and produces detailed transport outlook tables for each MS up to 2050 (E3MLab, pers. comm., 2011). The model complements the overall PRIMES model by providing a more detailed and sophisticated representation of the transport sector. The transport modes covered include road transport, rail, inland navigation (inland waterways and short sea shipping) and aviation (only intra EU air transportation). The PRIMES-TREMOVE transport model uses input data from the overall PRIMES model, such as fuel prices, which therefore assure consistency with the overall PRIMES scenarios.

The main strength of the CTS study in relation to the purposes of the present study is that all scenarios were developed in agreement with the European Commission (e.g. the Reference scenario corresponds to the Reference scenario to 2050 endorsed by DG Ener and DG Clima for the 2050 Commission Roadmap for the EU studies). Hence, all three policy scenarios deliver the required emission reduction in transportation of 60 % in 2050 from 1990 levels and 70 % compared to 2005. Also all the latest EU policies (adopted until April 2010), such as the Biofuels Directive and the Regulation on CO_2 from cars, have been included in the Reference scenario.

On the other hand, the main disadvantage is that no indication of the expected effect of the various scenarios on air pollutants is provided. However, since the TREMOVE model already includes detailed emission factors (EF) for all transport modes – down to technology level – it is principle possible to calculate emissions of air pollutants, e.g. by using a model such as GAINS, as will be done in the following (Section 3.2.2).

In **iTREN-2030 (Integrated transport and energy baseline until 2030)**, the TRANS-TOOLS model is coupled with three other models, ASTRA, POLES and TREMOVE, in order to extend the forecasting and assessment capabilities of TRANS-TOOLS to new policy issues arising from the technology, environment and energy fields. The same transport modes as in the CTS study are covered, i.e. road transport, rail, inland navigation (inland waterways and short sea shipping) and aviation (only domestic and intra EU air transportation).

The Reference scenario (Fiorello et al., 2009; Schade et al., 2010)considers only policies decided at the EU level by mid 2008, whereas other studies include more recent policies, e.g. the CTS study includes policies adopted until April 2010. As a result, some important policies, e.g. the Regulation on CO_2 from passenger cars, have been left out of the assessment. Another important drawback is that projections are only available to 2030, whereas 2050 is the target year for most of the other studies considered for the purposes of the present analysis.

On the other hand, detailed NOx and PM emissions as well as activity data are also estimated along with CO_2 emissions. A further advantage is the availability of all emissions data in the final report of the project.

The **Transport, Energy and CO_2 study** (IEA, 2009) has been based on the Mobility Model (MoMo) developed by the **International Energy Agency (IEA)**. An important aspect of MoMo is that it is a global transport model, covering 22 countries and regions, supporting projections and policy analysis. It contains a good deal of technology-oriented details, including underlying IEA analyses on fuel economy potentials, alternative fuels and cost estimates for most major vehicle and fuel technologies, with cost tracking and aggregation capabilities. Due to its global scope, however, the model has the drawback of considering only some general policies, such as land use planning, encouraging car sharing and non-motorised travel, etc. As a result, current and expected EU policies are not sufficiently taken into account and hence any CO_2 reductions achieved are not in line with EU targets.

MoMo tracks energy use, GHG and pollutant emissions for all transport modes (including international aviation and maritime). The results are then checked against IEA energy use statistics to ensure that the identity is solved correctly for each region. However, the quality of pollutant emission projections is considered as poor, as these are only based on emission standards and ignore real-world emission factors. As real-world emissions may vary considerably from what the emission standards imply this may lead to substantial underestimation of emissions, particularly in urban environments.

In the **TRANSvisions** study (Petersen et al., 2009), targets of 10 % in 2020 and 50 % in 2050, compared to 2005, have been arbitrarily set in order to analyse different transport policy options to obtain reductions of the transport sector's CO_2 emissions. The assumed reductions are somewhat lower compared to EU targets and related policies are set in a rather abstract way without setting any quantitative targets. The effect on air pollutants has also not been considered. Similarly to the IEA study, all transport modes are covered.

The **Policies to decarbonise transport in Europe: 80 by 50** study (Dalkmann et al., 2010) is similar to the TRANSvisions study in the sense that emission targets have been set arbitrarily and the policies to achieve these targets are examined. Although there is clear reference to a number of policies, very little quantitative information is provided (e.g. on the uptake of biofuels or penetration of electric vehicles). Air pollutants seem to have been left out of the scope of the study. All transport modes except shipping are covered by the study.

Based on the above assessment Table 7 below summarises the qualitative characteristics of each of the above studies in addition to the characteristics already included in Table 1, as explained above. A 4-point rating scale ranging from (-) to (++) is used, indicating the relative position of the above studies in terms of the selected characteristics. A negative value (-) is assigned in case a criterion is not fulfilled, whereas a positive value (+ or ++) is assigned in case a criterion is fulfilled. This is further distinguished into (+) and (++) to indicate the relative difference between two different studies. As an example, both the CTS and the iTREN-2030 studies include recent EU policies, however the CTS study includes policies adopted until April 2010, whereas the iTREN-2030 considers only policies decided by mid 2008.

	Peer reviewed	Availability of activity data	Recent policies included	Quality of air pollutant EFs
Clean Transport Systems E3MLab	++	+	++	0
iTREN-2030 (Integrated transport and energy baseline until 2030) (Schade et al., 2010)	+	+	+	+
Transport, Energy and CO_2 (IEA, 2009)	+	+	-	-
TRANSvisions (Transport Scenarios with a 20 and 40 Year Horizon) (Petersen et al., 2009)	+	+	+	-
Policies to decarbonise transport in Europe: 80 by 50 (Dalkmann et al., 2010)	0	-	-	-

Table 7 Qualitative evaluation of the studies on the emission of the transport sector.

3.2 Air pollutant emissions

In view of the above evaluation of available scenarios the CTS study has been selected on the basis of its good qualitative characteristics (Table 1 and Table 7). In addition, the results of this study are generally accepted at the European Commission level. However, as explained above, emissions of air pollutants are not sufficiently covered by the study and hence it was decided to estimate these by using results from the GAINS model as explained in the following.

In this section the reference scenario and the three scenarios developed in the CTS study in agreement with the Commission Roadmap 2050 scenarios are briefly described.

The '**reference' scenario** is based on the Reference scenario for 2050 from DG Ener, DG Clima for the 2050 roadmap studies. The basic assumptions behind the scenario are the 20-20-20 energy and climate policies and the successful implementation of a number of Directives on energy efficiency. Vehicle technology development goes up to EURO 6 (VI) for road transport modes and for non-road transport modes efficiency improvements are taken into account.

The '**dominant electrification' scenario** assumes that major breakthroughs will occur in the road transport section, mainly towards the replacement on internal combustion engines by electrical (mild or full) systems. This is strongly supported by a reduction to the battery cost and the extended travel range as well as policies aiming to this direction (R&D incentives, different taxation for CNG and LPG etc). Hydrogen fuel cells do not play a significant role mainly due to their higher cost. Non-road transport develops similarly to the reference scenario although faster implementation of improved technologies is assumed.

The ‘**dominant biomass’ scenario** assumes that big improvements in the efficiency of vehicle technologies will take place. Moreover the percentage of 2nd generation biofuels will be increased in the total fuel consumption. Reduction to the production cost of 2nd generation biofuels is assumed as well as a more stable biofuel production. Compared to the electrification scenario electric vehicles will follow a less aggressive penetration in the total fleet. Non road transport develops similarly to the reference scenario although faster implementation of improved technologies is assumed.

The ‘**renew’ scenario** combines the above two. The difference is that since the effort to technically improve the transport powertrain will be divided between two different paths the improvements will be mild in both cases (electrification and biofuel). This is against historical evolution of transport systems where single fuel technologies were used. This is mainly due to the high cost of infrastructure required to support the production and distribution of the different fuel types. Non road transport develops similarly to the reference scenario although faster implementation of improved technologies is assumed.

3.2.1 Scenario

The calculated consumption of energy in the transport sector for all 4 scenarios shows a clear trend towards reduction in the overall energy consumption if new technology and policy measures are included in the future agenda. Looking at the reference scenario no reduction in future fuel consumption is expected. The electricity scenario assumes the largest reduction in energy consumption followed by the renew and the biomass scenarios.

Table 8 summarises the changes in the energy consumption (2050 compared to 2005) for the main energy sources for the scenarios considered. A positive number indicates an energy increase. Table 9 shows the projected evolution of the energy consumption (in absolute numbers) from 2005 to 2050 for all scenarios.

[%]	Reference scenario	Electrification scenario	Biomass scenario	Renew scenario
Electricity	39.8	558.0	291.6	406.0
Gaseous Fuels	67.7	463.0	1050.7	630.4
Liquid Fuels	5.4	-61.3	-48.6	-57.6
Total	6.8	-42.5	-26.9	-37.3

Table 8: Difference in EU energy consumption [%] in 2050 compared to 2005 for all scenarios. Source: E3MLab (pers. comm., 2011).

Reference scenario [Mtoe]	2005	2020	2030	2050
Electricity	6.4	7.7	8.6	8.9
Liquified hydrogen	0.0	0.0	0.0	0.0
Gaseous Fuels	5.0	8.9	8.7	8.4
Bio fuels	*0.0*	*0.0*	*0.0*	*0.0*
Fossil fuels	*5.0*	*8.9*	*8.7*	*8.4*
Liquid Fuels	351.0	381.2	374.2	369.9
Bio fuels	*3.1*	*30.3*	*37.0*	*38.3*
Fossil fuels	*347.9*	*350.9*	*337.2*	*331.6*
Total	362.4	397.9	391.5	387.2

Electrification scenario [Mtoe]	2005	2020	2030	2050
Electricity	6.4	9.3	15.2	41.8
Liquified hydrogen	0.0	0.0	0.0	2.3
Gaseous Fuels	5.0	25.3	54.5	28.3
Bio fuels	*0.0*	*0.0*	*0.2*	*3.4*
Fossil fuels	*5.0*	*25.3*	*54.3*	*24.9*
Liquid Fuels	351.0	338.3	273.5	135.9
Bio fuels	*3.1*	*27.2*	*26.0*	*45.9*
Fossil fuels	*347.9*	*311.1*	*247.5*	*90.0*
Total	362.4	372.9	343.2	208.4

Biomass scenario [Mtoe]	2005	2020	2030	2050
Electricity	6.4	9.2	11.8	24.9
Liquified hydrogen	0.0	0.0	0.0	1.8
Gaseous Fuels	5.0	24.4	59.8	57.8
Bio fuels	*0.0*	*0.0*	*1.1*	*18.8*
Fossil fuels	*5.0*	*24.4*	*58.7*	*39.0*
Liquid Fuels	351.0	339.1	282.0	180.5
Bio fuels	*3.1*	*27.4*	*28.8*	*105.2*
Fossil fuels	*347.9*	*311.8*	*253.2*	*75.3*
Total	362.4	372.8	353.6	265.0

Renew scenario [Mtoe]	2005	2020	2030	2050
Electricity	6.4	9.5	15.8	32.1
Liquified hydrogen	0.0	0.0	0.1	9.5
Gaseous Fuels	5.0	25.5	54.0	36.7
Bio fuels	*0.0*	*0.0*	*0.3*	*5.0*
Fossil fuels	*5.0*	*25.5*	*53.7*	*31.7*
Liquid Fuels	351.0	337.2	270.5	148.9
Bio fuels	*3.1*	*27.0*	*26.1*	*65.2*
Fossil fuels	*347.9*	*310.2*	*244.4*	*83.7*
Total	362.4	372.3	340.4	227.2

Table 9: Projected evolution in EU energy consumption [Mtoe] for all scenarios up to 2050. Source: E3MLab (pers. comm., 2011).

3.2.2 Estimation of emission factors

The above changes in energy consumption alone are not sufficient to quantify the expected benefits in terms of reductions in the overall emissions of air pollutants. The CTS study does not provide any information on the emissions of air pollutants. Therefore, in order to assess the impact of the various vehicle categories and technologies in air pollutant emissions, relevant emission factors have to be calculated.

For the purposes of the present study this information was taken from the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model[10]. GAINS has been developed by IIASA as a tool to support the integrated assessment of GHGs and air pollutants in Europe. GAINS uses a number of scenarios for emissions calculations. Among these scenarios, the “PRIMES 2009” scenario has been selected in order to ensure consistency with the CTS study.

Emission and energy consumption data were extracted from GAINS and hence it was possible to calculate emission factors (in grams of pollutant per unit of energy) disaggregated into the various vehicle and fuel types. Table 10 to Table 12 summarise the emission factors calculated for NOx, PM and VOC for the years 2005, 2020 and 2030. For the years between 2030 and 2050 no evolution of emission factors was assumed.

[10] http://gains.iiasa.ac.at/index.php/home-page

2005	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.121			0.350	0.474	
NG				0.121			0.350	0.474	
Ethanol		0.497	1.000	0.447	0.454	0.087	0.175	0.320	0.176
Bio Gasoline in blend		0.497	1.000	0.447	0.454	0.087	0.175	0.320	0.176
Bio Diesel in blend		1.111	1.066	0.824	0.768		0.310	0.354	
Kerosene	0.029								
Diesel		1.111	1.066	0.824	0.768		0.310	0.354	
Gasoline		0.497	1.000	0.447	0.454	0.087	0.175	0.320	0.176

2020	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.121	0.712		0.047	0.139	
NG				0.121	0.712		0.047	0.139	
Ethanol		0.563	0.750	0.453	0.454	0.260	0.029	0.059	0.152
Bio Gasoline in blend		0.563	0.750	0.453	0.454	0.260	0.029	0.059	0.152
Bio Diesel in blend		0.935	0.816	0.233	0.157		0.155	0.159	
Kerosene	0.030								
Diesel		0.935	0.816	0.233	0.157		0.155	0.159	
Gasoline		0.563	0.750	0.453	0.454	0.260	0.029	0.059	0.152

2030	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.100	0.716		0.017	0.071	
NG				0.100	0.716		0.017	0.071	
Ethanol		0.544	0.800	0.455	0.456	0.290	0.022	0.035	0.122
Bio Gasoline in blend		0.544	0.800	0.455	0.456	0.290	0.022	0.035	0.122
Bio Diesel in blend		0.803	0.508	0.088	0.062		0.104	0.098	
Kerosene	0.030								
Diesel		0.803	0.508	0.088	0.062		0.104	0.098	
Gasoline		0.544	0.800	0.455	0.456	0.290	0.022	0.035	0.122

Table 10: Calculated NOx emission factors for the various subsectors and years [kt/PJ]. Source: ETC/ACM calculations using GAINS.

2005	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.003			0.001	0.002	
NG				0.003			0.001	0.002	
Ethanol		0.052		0.026	0.027	0.127	0.001	0.001	0.037
Bio Gasoline in blend		0.052		0.026	0.027	0.127	0.001	0.001	0.037
Bio Diesel in blend		0.076	0.092	0.025	0.020		0.024	0.036	
Kerosene	0.001								
Diesel		0.076	0.092	0.025	0.020		0.024	0.036	
Gasoline		0.052		0.026	0.027	0.127	0.001	0.001	0.037

2020	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.003	0.002		0.000	0.001	
NG				0.003	0.002		0.000	0.001	
Ethanol		0.034	0.025	0.027	0.026	0.033	0.000	0.000	0.013
Bio Gasoline in blend		0.034	0.025	0.027	0.026	0.033	0.000	0.000	0.013
Bio Diesel in blend		0.061	0.062	0.004	0.002		0.004	0.005	
Kerosene	0.001								
Diesel		0.061	0.062	0.004	0.002		0.004	0.005	
Gasoline		0.034	0.025	0.027	0.026	0.033	0.000	0.000	0.013

2030	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.003	0.002		0.000	0.001	
NG				0.003	0.002		0.000	0.001	
Ethanol		0.034	0.040	0.026	0.026	0.020	0.000	0.000	0.005
Bio Gasoline in blend		0.034	0.040	0.026	0.026	0.020	0.000	0.000	0.005
Bio Diesel in blend		0.045	0.030	0.001	0.000		0.001	0.002	
Kerosene	0.001								
Diesel		0.045	0.030	0.001	0.000		0.001	0.002	
Gasoline		0.034	0.040	0.026	0.026	0.020	0.000	0.000	0.005

Table 11: Calculated PM emission factors for the various subsectors and years [kt/PJ]. Source: ETC/ACM calculations using GAINS.

2005	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.545			0.234	0.375	
NG				0.545			0.234	0.375	
Ethanol		1.083	1.000	0.623	0.645	4.452	0.148	0.294	0.930
Bio Gasoline in blend		1.083	1.000	0.623	0.645	4.452	0.148	0.294	0.930
Bio Diesel in blend		0.134	0.155	0.066	0.059		0.028	0.033	
Kerosene	0.010								
Diesel		0.134	0.155	0.066	0.059		0.028	0.033	
Gasoline		1.083	1.000	0.623	0.645	4.452	0.148	0.294	0.930

2020	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.545	0.550		0.032	0.127	
NG				0.545	0.550		0.032	0.127	
Ethanol		0.597	0.750	0.592	0.639	1.227	0.021	0.058	0.333
Bio Gasoline in blend		0.597	0.750	0.592	0.639	1.227	0.021	0.058	0.333
Bio Diesel in blend		0.111	0.125	0.025	0.021		0.019	0.020	
Kerosene	0.010								
Diesel		0.111	0.125	0.025	0.021		0.019	0.020	
Gasoline		0.597	0.750	0.592	0.639	1.227	0.021	0.058	0.333

2030	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.533	0.549		0.012	0.069	
NG				0.533	0.549		0.012	0.069	
Ethanol		0.598	0.800	0.580	0.621	0.897	0.012	0.033	0.173
Bio Gasoline in blend		0.598	0.800	0.580	0.621	0.897	0.012	0.033	0.173
Bio Diesel in blend		0.093	0.097	0.014	0.013		0.018	0.019	
Kerosene	0.010								
Diesel		0.093	0.097	0.014	0.013		0.018	0.019	
Gasoline		0.598	0.800	0.580	0.621	0.897	0.012	0.033	0.173

Table 12: Calculated VOC emission factors for the various subsectors and years [kt/PJ]. Source: ETC/ACM calculations using GAINS.

Table 13 shows the breakdown of the energy consumption of the different fuel types to the different vehicle categories based on GAINS assumptions. The same breakdown in terms of vehicle type for all scenarios was assumed for the whole period. Although the energy consumption for a specific fuel differs in the various scenarios, it was assumed that the percentage allocation into the different vehicle types remains the same for all scenarios. The error induced by this assumption is rather small as the improvements in the energy efficiency of the various technologies are expected to be similar for the various vehicle categories.

From the above tables it is evident that emission factors from road transport are reduced considerably over the 2005-2030 period as a result of advanced technology and stricter emission standards. The only exception is gasoline-fuelled heavy duty vehicles (buses and heavy duty trucks) which however contribute only marginally to the overall energy consumption (only 0.1 % share in 2005 as shown in Table 13).

2005	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.2%			98.2%	1.6%	
NG				0.2%			98.2%	1.6%	
Ethanol		0.2%	0.0%	0.0%	0.1%	2.3%	87.4%	6.2%	3.9%
Bio Gasoline in blend		0.2%	0.0%	0.0%	0.1%	2.3%	87.4%	6.2%	3.9%
Bio Diesel in blend		1.1%	1.7%	3.0%	36.5%		36.1%	21.6%	
Kerosene	100.0%								
Diesel		1.1%	1.7%	3.0%	36.5%		36.1%	21.6%	
Gasoline		0.2%	0.0%	0.0%	0.1%	2.3%	87.4%	6.2%	3.9%

2020	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.1%	0.4%		94.5%	4.9%	
NG				0.1%	0.4%		94.5%	4.9%	
Ethanol		0.3%	0.0%	0.1%	0.1%	1.4%	85.1%	7.4%	5.6%
Bio Gasoline in blend		0.3%	0.0%	0.1%	0.1%	1.4%	85.1%	7.4%	5.6%
Bio Diesel in blend		1.1%	1.4%	2.7%	34.8%		34.3%	25.8%	
Kerosene	100.0%								
Diesel		1.1%	1.4%	2.7%	34.8%		34.3%	25.8%	
Gasoline		0.3%	0.0%	0.1%	0.1%	1.4%	85.1%	7.4%	5.6%

2030	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
LPG				0.1%	0.4%		94.5%	5.0%	
NG				0.1%	0.4%		94.5%	5.0%	
Ethanol		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%
Bio Gasoline in blend		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%
Bio Diesel in blend		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Kerosene	100.0%								
Diesel		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Gasoline		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%

2050	Air	Inland Waterways	Rail	Buses	Heavy-duty vehicles	2 stroke	Passenger cars	Light-duty vehicles	Two-wheelers
Methane from Biogas				0.1%	0.4%		94.5%	5.0%	
Biogas in blend				0.1%	0.4%		94.5%	5.0%	
LPG				0.1%	0.4%		94.5%	5.0%	
NG				0.1%	0.4%		94.5%	5.0%	
Bio Heavy		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Bio Kerosene in blend	100.0%								
Ethanol		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%
Bio Gasoline in blend		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%
B100		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
DME		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Bio Diesel in blend		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Residual fuel oil									
Kerosene	100.0%								
Diesel		1.2%	0.2%	2.7%	34.9%		33.6%	27.4%	
Gasoline		0.3%	0.0%	0.2%	0.1%	1.0%	79.6%	12.5%	6.3%

Table 13: Energy breakdown [%] of the main fuel types to the different vehicle types. Source: ETC/ACM calculations using GAINS.

3.2.3 Results

Total emissions decrease consistently for all scenarios. In the reference scenario, although the total energy consumption increases slightly in 2050 compared to 2005 levels, total emissions decrease due to the technological advances and the switch to cleaner energy sources (e.g. electricity partially replaces fossil fuels). Table 14 and Table 15 summarise the air pollutant emissions and energy consumption respectively for all scenarios up to 2050. The percentage reductions between 2005 and 2050 are also included in the tables. It is evident that the dominant electrification scenario achieves the highest reductions in both energy consumption and emission of NOx, PM and VOC. This is mainly due to the large use of electricity in road transport modes and in particular passenger cars. The renew scenario produces somewhat better results than the biomass scenario, which are more prominent for the energy consumption. The dominant biomass scenario still largely depends on the use of internal combustion engines (ICE) and hence the lowest reductions in energy consumption and pollutant emissions compared to the electricity and renew scenario.

It should be noted that air pollutant emissions from electricity production where not taken into account in the calculations. However, the additional emissions incurred are estimated to be rather small in 2050, considering that the power generation sector shifts away from fossil fuels mainly towards renewable energy sources and nuclear in the decarbonisation scenario of the CTS study. The decarbonisation scenario is used to quantify the contribution required from the transport sector in the overall decarbonisation effort. The three policy scenarios (dominant electrification, dominant biomass and renew) developed take place in the context of overall decarbonisation of the economy in the EU, global climate action worldwide, as well as effective technology development and deployment. As a result, CO2 emissions from the power generation sector are reduced by 96% in 2050 compared to 2005 levels.

Total NOx [kt]	2005	2020	2030	2050	2005-2050
Reference scenario	5,079.3	1,852.5	1,069.7	1,049.0	-79.3%
Electrification scenario	5,079.3	1,624.2	780.6	348.7	-93.1%
Biomass scenario	5,079.3	1,626.6	796.2	503.3	-90.1%
Renew scenario	5,079.3	1,619.9	769.5	403.8	-92.0%
Total PM [kt]	**2005**	**2020**	**2030**	**2050**	**2005-2050**
Reference scenario	234.5	52.7	20.0	19.6	-91.6%
Electrification scenario	234.5	45.4	14.4	6.1	-97.4%
Biomass scenario	234.5	45.5	14.9	9.1	-96.1%
Renew scenario	234.5	45.2	14.2	7.0	-97.0%
Total VOC [kt]	**2005**	**2020**	**2030**	**2050**	**2005-2050**
Reference scenario	1,797.1	513.6	342.5	335.2	-81.3%
Electrification scenario	1,797.1	483.3	275.1	106.4	-94.1%
Biomass scenario	1,797.1	483.3	289.1	184.0	-89.8%
Renew scenario	1,797.1	481.7	270.9	127.3	-92.9%

Table 14: Total emissions of NOx, PM and VOC for all 4 scenarios [kt]. Source: ETC/ACM calculations using GAINS.

Total Energy [Mtoe]	2005	2020	2030	2050	2005-2050
Reference scenario	362.4	397.9	391.5	387.2	6.8%
Electrification scenario	362.4	372.9	343.2	208.4	-42.5%
Biomass scenario	362.4	372.8	353.6	265.0	-26.9%
Renew scenario	362.4	372.3	340.4	227.2	-37.3%

Table 15: Energy consumption for all 4 scenarios [Mtoe]. Source: ETC/ACM calculations using GAINS.

3.3 Discussion

Total air pollutant emissions decrease considerably for all scenarios. Compared to the reference scenario, the other three scenarios deliver higher emissions reductions, on the order of 90 to 97 %. This is illustrated in Figure 5, which shows the relation between GHG and air pollutant emission reductions against their baseline developments.

Slight differences in the overall reductions of air pollutant emissions can be observed among the various scenarios, showing that most of the improvement is brought about by the trend in energy demand. The dominant electrification scenario delivers the highest reductions, followed by the renew scenario, whereas the dominant biomass scenario achieves somewhat lower reductions.

Although the introduction of biofuels increases the share of renewables in transport, it has also side effects. Compared to fossil fuels, biofuels increase NOx and aldehyde emissions, whereas they decrease PM emissions. This side effect, however, is not visible in the above results when comparing the dominant biomass and the reference scenario. This is due to the fact that in the biomass scenario there is a substantial decrease of about 27 % in the total energy consumption, whereas the energy consumption increases by almost 7 % in the reference scenario. In addition to this, electricity use is about three times higher than in the reference scenario. It should be noted however, that these results do not take into account the emissions from other sectors, namely from power generation and agriculture. Although it is assumed that in the scenarios the entire energy system will aim at decarbonisation, some significant emissions should be expected in 2020 and 2030 depending on the fuel mix used for power generation.

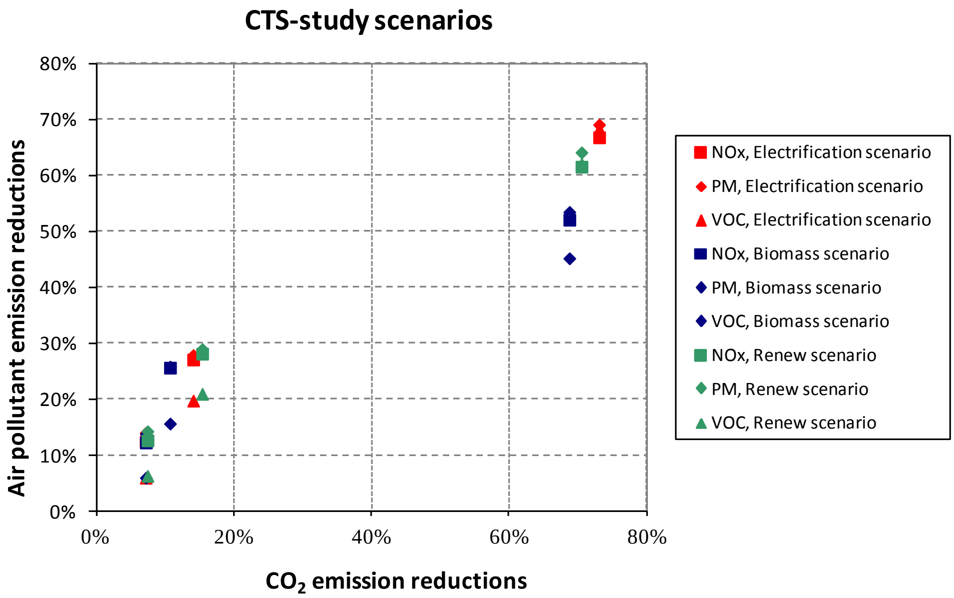

Figure 5: Air quality/climate cobenefits: reductions in NOx, PM and VOC emissions against reduction of CO_2 emissions for the CTS scenarios

4 Air Quality Projections for 2030

Investigating emission projections does not suffice to assess future air pollution. Air pollutant concentrations are extremely sensitive to primary emissions but their processing in the atmosphere must also be accounted for. This is achieved by implementing Chemistry Transport Models (CTM) that represent non-linear chemical reactions, as well as transport and deposition processes. As such, chemistry transport modelling constitutes an essential part of the quantification of anticipated benefits under prospective emission reductions.

The strategies to analyse the impact of future air pollution emission scenarios can be divided in three categories:

- Quantitative comparison of the primary emissions. We saw above (in Chapter 2) that such analysis can provide a wealth of information about the different trajectories, although it neglects atmospheric transport and transformation processes. Such approaches are often implemented by the scientific groups involved in the development and evaluation of emission scenarios themselves (Granier et al., 2011; Rafaj et al., 2010; Riahi et al., 2011; van Vuuren et al., 2011a).

- Atmospheric response modelling. Various techniques have been developed to probe the emission-pollutant relationship and build response surfaces without having to implement a full CTM. The GAINS model makes use of sensitivity of source-receptor relationships in its optimisation process (Amann et al., 2011; Schöpp et al., 1998). It has been used to investigate future projection, e.g. in the CAFE programme of the European Commission (EC, 2005) or in support of the CityDelta (Cuvelier et al., 2007) and EuroDelta (Thunis et al., 2008) exercises.

- Full Chemistry Transport Modelling. Here a complete model of the atmosphere (that can even include the impact of global climate change) is implemented and fed with the projected primary emission changes. This approach is much more demanding in terms of computational resources so that there is no example to date of a full simulation system at the regional scale that accounts for all the processes involved (anthropogenic emission projection, global and regional climate, as well as global atmospheric chemistry at the boundaries). There are however several studies that cover one or more of the components of such a modelling chain: global atmospheric chemistry under various anthropogenic scenarios (Stevenson et al., 2006; van Aardenne et al., 2010), regional air quality under various anthropogenic scenarios (Thunis et al., 2007; van Loon et al., 2007), regional air quality accounting for climate change (Katragkou et al., 2011; Meleux et al., 2007), regional air quality projection accounting for the global chemical forcing at the boundaries (Katragkou et al., 2010; Szopa et al., 2006).

The analysis discussed in the present chapter falls in this last category. Atmospheric response models have been used successfully in the past for medium term projections, but their implementation for long term perspectives raises unprecedented issues. By the mid-21st century, climate conditions and the hemispheric burden of pollution (through long range transport) will reach such levels that the range of conditions used to calibrate the atmospheric response model could be exceeded. In order to support EEA in its evaluation of air quality and climate interaction, it thus was decided to implement a CTM, considering that it would provide an interesting benchmark to compare with atmospheric response models in the specific context of long term projections.

The present work constitutes a first step towards the overarching goal of building a full modelling chain of future air quality. The results presented here only account for anthropogenic emission changes. Chemical boundary conditions and regional climate forcing are those of the current (early 21st century) situation. Climate change will have a significant impact on air quality. Besides the impact of the temperature on chemical reaction rates, one shall mention the expected increase in biogenic emissions, and also the increase of OH free radicals associated to enhanced water vapour (Hedegaard et al., 2008). Precipitation and wind patterns will also have an impact on the dispersion processes (Menut et al., 2012), so that all pollutants are concerned. Several studies have documented the impact of climate on air quality. As far as regional air quality projections are concerned we can mention (Meleux et al., 2007) and (Andersson and Engardt, 2010) who focused on the 2070-2100 period, (Langner et al., 2012) who investigated the 2040-2050 decade while (Katragkou et al., 2011) compared the 2040’s and 2090’s decades. The 2030 period has not been documented in the literature with regional air quality models accounting exclusively for the impact of climate. This is because, for this time frame, expected climate-induced changes are small compared to the magnitude of emission changes. The model uncertainties for these projections are still high but the recent studies report differences of the order of 1ppv for ozone the 2040-2050 decade compared to present (2000-2010) conditions (Katragkou et al., 2011; Langner et al., 2012). These considerations led us to neglect the impact of climate for the simulations presented in this report. However, there are ongoing initiatives to improve existing models so that they take into account regional climate change as well as anticipated evolution of the global chemical boundaries.

The recent release of revised projections of anthropogenic emissions of pollutants constituted another motivation of the present initiative. The primary objective was to assess the EU “Roadmap for moving to a competitive low carbon economy in 2050” (EC, 2011b). Unfortunately, the level of detail in the Commission Roadmap for the EU delivered in 2011 was not satisfactory for implementation in a CTM. If the IPCC Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011a) are technically suitable for AQ computations, they are primarily designed for global climate studies, and their implementation for local or regional air quality should be handled with care.

The year 2011 saw also the release of the Global Energy Assessment projections that are consistent with the RCPs, yet developed with a stronger focus on the socio-economic perspective. This dataset includes several climate policy trajectories, so that, similarly to the RCPs, the cobenefits of climate policy in terms of air pollution can be investigated. A more detailed presentation of existing scenarios can be found in Chapter 2. In particular we show that the estimation of the cobenefits of climate policies for air pollution matters is larger in the GEA than in the RCP, where a lower priority was set on the description of current air quality legislation.

In addition to providing a revised evaluation with updated projections, the modelling setup of the present work makes use of the latest development in regional chemistry transport modelling. We will be able to discuss projections using a statistically significant number of years since 10 full years where modelled for each scenario, giving support in the results compared to previous studies where single years, or even single seasons were investigated. In addition, our projections account for aerosol transformation, so that we can discuss projections of PM10 levels as well as their impact on the radiative forcing at the regional scale.

The simulations presented here were conducted by INERIS with the CHIMERE model using the GEA projections delivered by IIASA in the context of the CityZen research project of the Seventh Framework Programme of the European Commission.

4.1 Modelling setup

The CHIMERE model (www.lmd.polytechnique.fr/chimere) is developed, maintained and distributed by the Institut Pierre Simon Laplace (CNRS) and INERIS (Bessagnet et al., 2008). It is used for daily operational air quality forecasting in France (Honoré et al., 2008) and beyond (e.g. through the MACC[11] project of the European Global Monitoring for Environment and Security Programme, GMES).

A recent study by (Colette et al., 2011) also illustrated the skill of the model when used over long time periods. With the exception of emission inventories, the setup of the simulations presented here is the same as in (Colette et al., 2011). The horizontal resolution is about 50km; the forcing meteorological fields are those of the past decade: 1998-2007 obtained from the ERA-interim reanalysis downscaled dynamically with the WRF model (Skamarock et al., 2008); and the chemical boundary conditions are derived from monthly average of the global CTM LMDz-INCA (Hauglustaine et al., 2004).

4.2 Implementation of the GEA scenarios

The International Institute for Applied Systems Analysis (IIASA, Austria) produced prospective scenarios in the framework of the Global Energy Assessment. These scenarios were designed to help decision makers address the challenges of providing energy services for a sustainable development. An overview of these scenarios is given in Chapter 2 and in (Rafaj et al., 2010).

It should be noted that whereas the GEA emissions projections are well suited for CTM computation, they had to be pre-processed according to the following procedure:

- Total NOx (=NO+NO_2) emissions are provided in the scenarios. But IIASA also delivered projections developed in the framework of the CAFE programme (EC, 2005) for the evolution between NO and NO_2 by activity sector and by country for Europe by 2020 since this information was not available for longer time frames.

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[11] www.gmes-atmosphere.eu/

- Primary particulate matter is expressed as BC and OC in the scenarios. It should be noted that there is no data for other constituents (heavy metals) or for the coarse fraction (above 2.5µm in diameter) in the emissions.

- Biomass burning emissions are neglected considering that these projections regard exclusively anthropogenic sources.

- Gaseous biogenic emissions are not part of the emission dataset; they are accounted as a function of the meteorology. In the present case they are thus representative of the conditions of the early 21st century.

- Due to the lack of information regarding their vertical distribution, aircraft emissions were neglected (for all flight sections: taxi, takeoff/landing and cruise).

Only two out of the four GEA scenarios were investigated for the year 2030 in addition to the (2005) control:

- Reference:
    - Full implementation of all current and planned air pollution legislation worldwide.
    - No specific policies on climate change and energy access. In that sense it is designed to be similar to the RCP8.5 trajectory in terms of climate response (see Chapter 2).
- Mitigation:
    - Full implementation of all current and planned air pollution legislation worldwide
    - Stringent climate policy. This scenario complies approximately to the 2 degrees global temperature increase by 2100. In that sense it is comparable to the RCP2.6 trajectory (see Chapter 2).

4.3 Results: Air Pollution

The above scenarios were implemented in the CHIMERE modelling chain over the whole Europe at 50km resolution for a 10-yr long simulation in order to fully capture interannual variability and gain statistical significance.

4.3.1 Nitrogen Dioxide

The modelled surface NO_2 concentrations (averaged over the 10 years of simulation period) are displayed on Figure 6. The "present day" reference simulation with the GEA emission for 2005 given on the top left panel displays the usual patterns with hotspots of pollution in the Po-Valley (Italy) and South-Eastern France, South-Eastern UK, and the Benelux-Germany area.

For comparison purposes, the analogous field obtained with EMEP reference emissions over the same meteorological years is also displayed on this figure (bottom left). The above mentioned hotspots in the GEA emissions match well those currently reported in this official inventory. However there are also some significant differences, over the main ship tracks but also over the Benelux area and in Spain. Lastly the hotspot in Helsinki does not appear in the EMEP inventory. The differences between the GEA dataset and the EMEP inventory were mentioned in Section 2.2.5. The GEA projections were harmonised to 2005 emission data but this harmonisation was performed on a global scale and an agreement at the European scale was not expected since there are notable documented differences between existing regional and global inventories (Granier et al., 2011) .

On the same figure, we display the average concentration according to the Reference and Mitigation scenarios in 2030. It appears that NO_2 levels are curbed very efficiently, to such extent that the main hotspots barely stand out of the background. In Western Europe, only the Po-Valley and the Marseille plume can still be distinguished. In Eastern Europe, and Northern Africa NO_2 concentrations remain higher than the background but no-where as close as the present day hotspots. The decrease of NO_2 is larger for the Mitigation trajectory. The colour shading of Figure 6 somewhat minimises the difference between the Mitigation and Reference changes and a quantitative analysis of the delta of NO2 concentrations shows that it is more important than it seems.

A quantitative analysis of the cobenefits is provided on Table 16. The quantity of each modelled substance is cumulated over the whole domain and we provide the relative change of this aggregate between the Mitigation and Reference scenario for 2030. This number is computed from the raw concentrations, and after applying a weighting corresponding to the population density to highlight changes over high exposure areas. We also display in the table the same figures derived from the emissions, but these cannot be directly matched to those of Chapter 2 (Figure 4) because the aggregation domains differ. For nitrogen oxides, the relative change is identical when aggregated over the whole domain. This is because the vast majority of NOx in the atmosphere is emitted as a primary constituent, and the contribution from boundary conditions is minor given its short lifetime. When aggregated after applying the population weighting, the cobenefit is slightly higher in CHIMERE as a result of transport and mixing. This is because in the GEA projections, NOx emissions are curbed very efficiently in urban areas compared to rural areas by 2030. Nevertheless, for nitrogen oxides, we conclude that the cobenefits of the climate policy are very significant (50%) and very similar in the primary emissions and in the modelled concentrations.

4.3.2 Ozone

The average ozone fields for the summer months (April 1st to September 30th) are provided in Figure 7 in an analogous way as for NO_2 above. The background and North-South gradient is consistent between GEA emissions in 2005 and EMEP emissions over the 1998-2007 decade. Over populated areas, O_3 fields are quite different: in the hotspots, the titration effect of NOx (in very high NOx emissions areas, the net effect of the night time consumption of ozone by nitrogen oxides can exceed the daytime formation, resulting in a local minima) obtained with EMEP emissions vanishes and background levels are much higher with GEA emissions. While the first pattern can be explain by the less contrasted geographical distribution in GEA emission seen for NO_2 above, the second has to do with changing chemical regimes. When aggregated over France, UK and Germany NOx emissions are 17% larger in GEA (for 2005) compared to EMEP (for 2006), but for non-methane volatile organic compounds, this difference reaches 35%. So that the VOC to NOx ratio is 67% and 77% for the EMEP and GEA emissions, respectively. The magnitude of this discrepancy can explain a switch in the chemical regimes between both sources of data, so that the hotspot of pollution around the greater

Benelux area would not be NOx-saturated in the GEA dataset for 2005. Considering the important non-linearity of ozone chemistry, this finding constitutes and important limitation of the conclusions drawn from the present work.

The O_3 concentrations by 2030 are provided on the other panels of Figure 7 for the Reference and Mitigation scenarios. A widespread decrease of O3 is found. The geographical pattern is very similar for both scenarios, only the magnitude of the change is larger for Mitigation. Over the South-Eastern UK, an increase is found, as well as in Helsinki. These areas are thus probably the only place where the chemical regime remains NOx saturated, so that a decrease in the emission of NOx, leads to an increase of O_3 (because, again, of the so-called NOx titration process).

Since ozone is exclusively produced in the atmosphere, cobenefits cannot be quantified from the raw emissions. According to modelled concentrations in the CHIMERE CTM, the relative difference between the Mitigation and Reference scenarios is very large (Table 16). The total (cumulated) surface O3 is 124% lower for the Mitigation scenario. When weighted by the population, the relative change is even of negative sign.

This negative sign of the co-benefit does not reflect a trade-off. It would be the case if the Reference scenario exhibited a decrease of pollution. But here the cumulated weighted O3 actually increases in the Reference trajectory (compared to the baseline using GEA emissions for 2005) since most average ozone increases occur over densely populated, NOx saturated, areas. Therefore we conclude that in all cases, the climate policy leads to cobenefits in terms of air pollution. This cobenefit being large enough to compensate the negative effects of the lack of climate policies.

4.3.3 Particulate Matter

The projected PM10 concentrations are given on Figure 8. Again, the comparison of present day fields (obtained with GEA/2005 and EMEP/1998-2007 emissions on the left-most two panels) shows that the emissions hotspots stand out of the background with a higher spatial variability using EMEP emissions while the GEA emission lead to more evenly distributed PM10 concentrations. It should be recalled that only the fine fraction of PM is provided in the GEA dataset, which is partly the reason why natural sources (desert dust and sea salt – that are included in the simulation but kept constant in 2030 compared to 2005) constitute a significant source on these PM10 maps.

The projections for 2030 with the Mitigation scenario suggest a very efficient decline of PM10 concentrations throughout Europe with values over populated areas only a couple of $\mu g/m^3$ above levels usually observed over pristine regions. The various compounds constituting PM10 contribute differently to this total change (Figure 9). The decrease of sulphate is very widespread with a relative maximum over Eastern Europe. Organic and black carbon changes are more concentrated around pollution hotspots. These patterns will have important consequences for the radiative forcing estimates discussed below.

For particulate matter, the cobenefits of the climate policy can be compared to the modelled estimates (Table 16). However, the emissions of PM only concern the primary fraction, while the model accounts for secondary particle formation. That is why the cobenefit is larger according to the concentrations calculated by the CTM (29.6% instead of 21.7% for the primary emissions): because it also reflects the reduction of emissions of gaseous precursors of particles. It is interesting to note that cobenefits in the emissions are higher when weighted according to the population in the emissions, showing that densely populated areas bear most of the cost of emission reduction in the GEA inventory (see Chapter 2.2.2). On the contrary, the population-weighted cobenefit is lower in the CTM compared to the raw cumulated estimate. This is because a large part of the secondary particle formation occurs over rural areas (ammonium nitrate resulting from the spreading of agricultural fertilizers). To sum up an analysis based on the non-weighted emissions leads to an underestimation of the cobenefits compared to the CTM, but when it comes to exposure proxies, using the emissions could actually produce an overestimation of the cobenefits.

	Cobenefit in the emissions (raw)	Cobenefit in the emissions (weighted)	Cobenefit in the CTM (raw)	Cobenefit in the CTM (weighted)
NOx	49.7	27.6		
NO_2			49.3	32.5
O_3			124.0	-251.5
PPM2.5	21.7	34.6		
PM10			29.6	27.1

Table 16 : Climate / air quality cobenefits (%). Relative improvement brought about by the climate policy compared to the scenario accounting only for the air-quality legislation. The relative change is computed either from primary emissions (for NOx and PPM2.5) or from the modelled concentrations in the CTM (NO_2, O_3, and PM10). The proxy is either aggregated over the whole domain from raw emissions/concentrations, or after being weighted by the population density.

4.4 Results: Radiative forcing

4.4.1 Introduction

The radiative forcing induced by aerosols constitutes an important part of the uncertainty in climate studies. The competing benefits of climate and air pollution policies are a topic being often debated considering that, depending on their chemical composition, aerosols in general have contributed to limit global warming over the recent past.

Most modelling tools being used to tackle these issues are global models that make use of simplified schemes for the formation of aerosols and are operated at a spatial resolution unsuitable for addressing air quality issues. Some new generation CTMs account for air quality and climate processes in a coupled way, but to date these models have not been implemented for long term studies. Therefore it was decided to implement a comprehensive post-processing suite of models to estimate the radiative forcing of aerosols fields modelled with the CHIMERE CTM. This means that the climatic perturbation induced by aerosols could be investigated using state of the art high-resolution air quality models.

We present here the results obtained with the GEA scenarios described above. The fact that we use emission data specifically developed for climate/air pollution policy co-benefits analysis is another beneficial aspect of the present work whereas existing studies were conducted with scenarios designed for climate studies only.

4.4.2 Methodology

The chemistry-transport model CHIMERE (associated with an aerosol optical module) and the radiative transfer code GAME (Global Atmospheric ModEl) have been used to estimate the impact of aerosol solar extinction on the radiative fluxes, a short overview of the methodology is given here but more details can be found in (Péré et al., 2012).

The calculation of optical properties of particles is a pre-requisite for the evaluation of their radiative impact. That is why we developed a numerical scheme dedicated to derive optical properties from the concentration of aerosols, their distribution in size and their chemical composition modelled by CHIMERE (Pere et al., 2009; Pere et al., 2010). The parameters simulated with this optical module are the Aerosol Optical Thickness (AOT), the Single Scattering Albedo (SSA) and the asymmetry parameter (g).

In a second step, the clear-sky aerosol direct radiative forcing is computed using the radiative transfer code GAME (Dubuisson et al., 1996).

4.4.3 Results

By using a full radiative model taking into account the chemical composition of the aerosols (carbonaceous fraction – BC/OC - as well as other organic and inorganic constituent) we can illustrate the impact of different strategies of reduction for scattering sulphate and absorbing soot particles. In Figure 10, we display changes in total AOT (Aerosol Optical Thickness) and ΔFBOA (direct radiative forcing at the bottom of the atmosphere, i.e. radiative forcing at the surface). The patterns of reduction are not correlated as a result of the non-linear effects of the aerosol extinction processes on solar radiative fluxes depending on the radiative properties of the particles.

The decrease in emissions of primary aerosol and precursors of secondary aerosols is shown to reduce the AOT more efficiently in winter when domestic heating emissions reductions are larger whereas scattering sulphate (originating from industrial emissions) is reduced all year long. During winter, the largest decrease of AOT occurs over the Benelux region and north-eastern Germany (0.05-0.06 ≈ 50-60 %) while in summer, changes in AOT are maximum over southern Poland and Western Ukraine (0.035-0.045 ≈ 35-45 %).

The AOT decrease between 2005 and 2030 leads to a reduction of the surface aerosol direct radiative forcing with a maximum change in summer during the longest period of solar radiation. Over the main anthropogenic emission regions, ΔFBOA is shown to be reduced up to 1.0-1.2 W/m2 (30-40 %) in winter and up to 1.8-2.0 W/m2 (35-45 %) in summer.

By 2030, reductions in aerosol emissions will lead to a decrease of the aerosol cooling effect at the surface and at the top of the atmosphere (Table 17). A relative warming can thus be expected as a result of lower aerosol pollution. The reduction of the radiative forcing mentioned above refers to a reduction of the forcing as a result of the decrease of the particle load (because the interaction of particles with the radiative flux is reduced), even if the radiative flux actually increases and yields a relative warming.

The magnitude of the change is much larger at the surface (0.42 and 0.57 W/m2 for the Reference and Mitigation scenarios, respectively) than at the top of the atmosphere (0.21 and 0.27 W/m2 for the Reference and Mitigation scenarios, respectively). Unlike global models, our approach emphasizes processes occurring near the surface, hence the focus on ΔFBOA. The fact that we find a larger signal at the surface is a confirmation of the relevance of our approach.

The cobenefit brought about by the climate policy in terms of total atmospheric radiative forcing is about 43%. For the Mitigation scenario the change of total atmospheric radiative forcing is of 30% in 2030 compared to 2005, i.e. 43% higher than the relative change for the Reference scenario (21%). Unfortunately, the comparison to global estimates (as those delivered by IPCC) is hampered by the fact that we are focusing on mid-latitude instead of global averages, and the latitudinal variation is an extremely sensitive parameter.

	ΔF_{BOA} (W/m^2)	ΔF_{TOA} (W/m^2)	ΔF_{ATM} (W/m^2)
Control (2005)	-3.26	-1.52	+ 1.74
2030 Mitigation	-2.69	-1.25	+ 1.44
2030 Reference	-2.84	-1.31	+ 1.53

Table 17 : Domain-averaged aerosol direct radiative forcing at the surface (ΔFBOA), at the top of the atmosphere (ΔFTOA) and within the atmospheric layer (ΔFATM), for the reference case (for 2005) and for the two air pollution mitigation scenarios (for 2030).

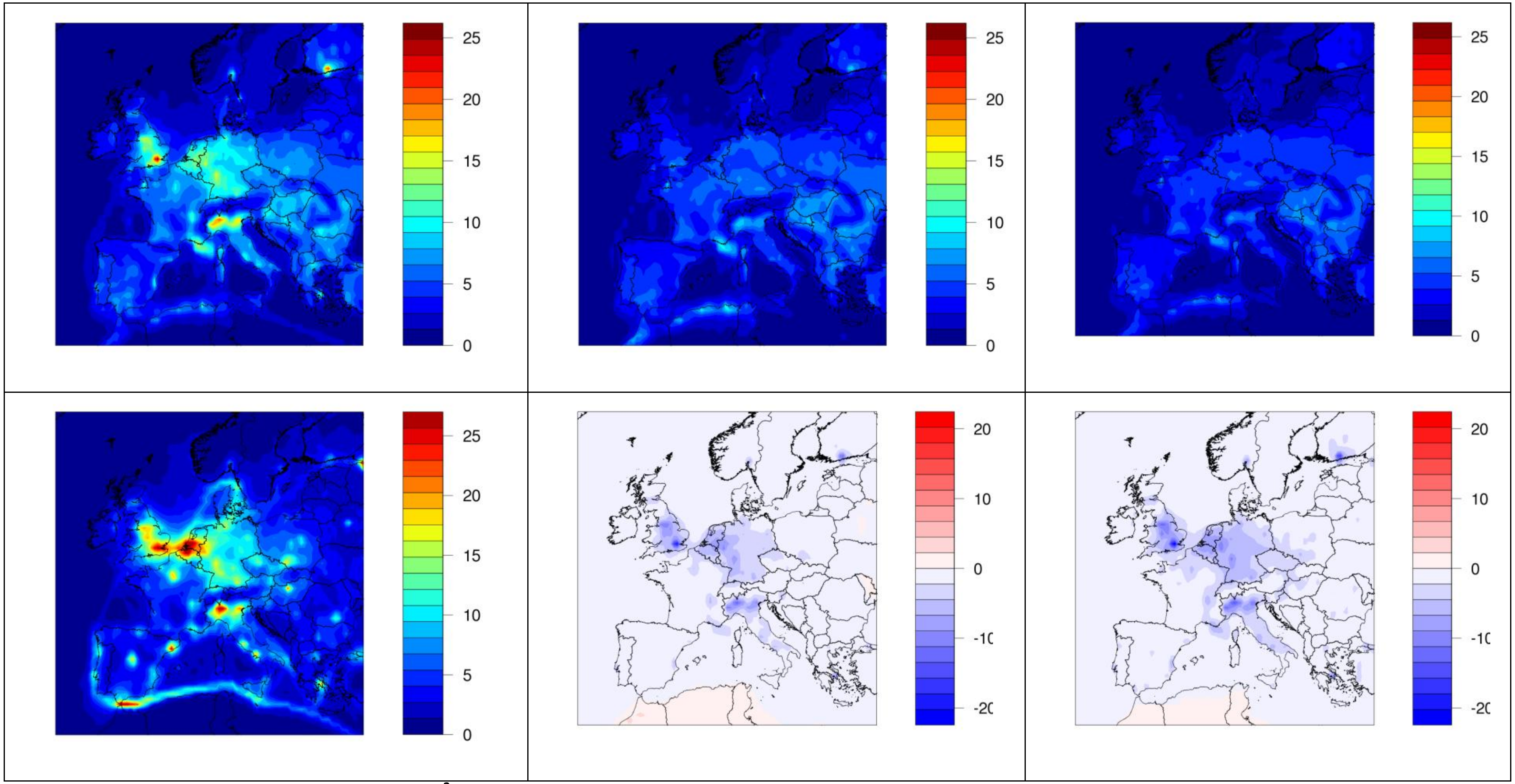

Figure 6 : Surface concentrations of NO_2 (µg/m^3) modelled with CHIMERE. The first column shows the concentrations for the early 21st century: the reference year in GEA emissions (2005: top left) and the 1997-2008 decade in EMEP emissions (bottom left). The remaining columns provide 2030 fields according to the Reference (centre) and Mitigation (right) scenarios. The bottom row gives the difference compared with the reference for Reference (centre) and Mitigation (right). All fields are averaged over 10 years of simulation (1998-2007 meteorology).

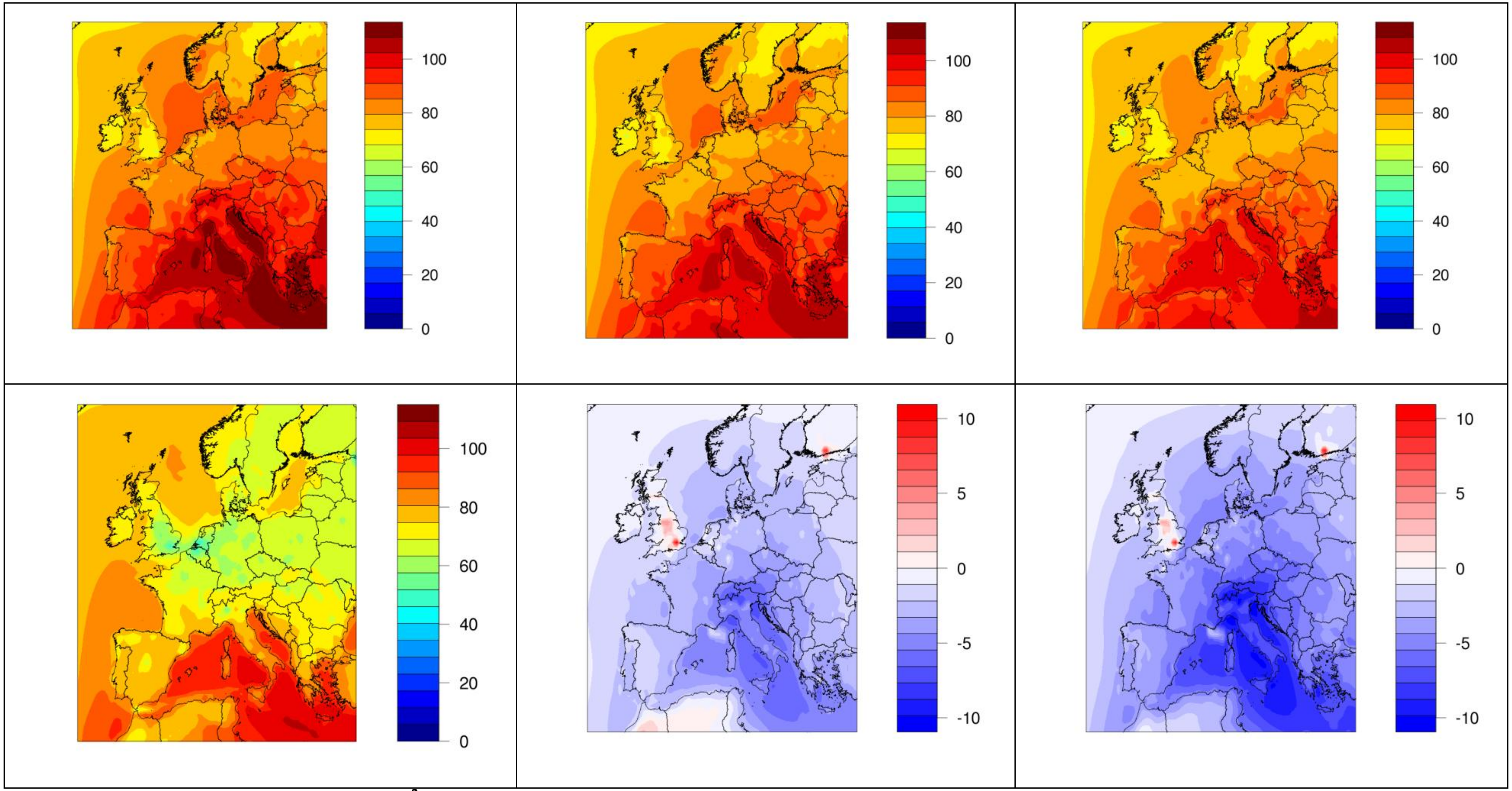

Figure 7 : Surface concentrations of O_3 (µg/m^3) modelled with CHIMERE averaged over the summer months (April-September). The first column show the concentrations for the early 21st century: the reference year in GEA emissions (2005: top left) and the 1997-2008 decade in EMEP emissions (bottom left). The remaining columns provide 2030 fields according to the Reference (centre) and Mitigation (right) scenarios. The bottom row gives the difference compared with the reference for Reference (centre) and Mitigation (right). All fields are averaged over 10 years of simulation (1998-2007 meteorology).

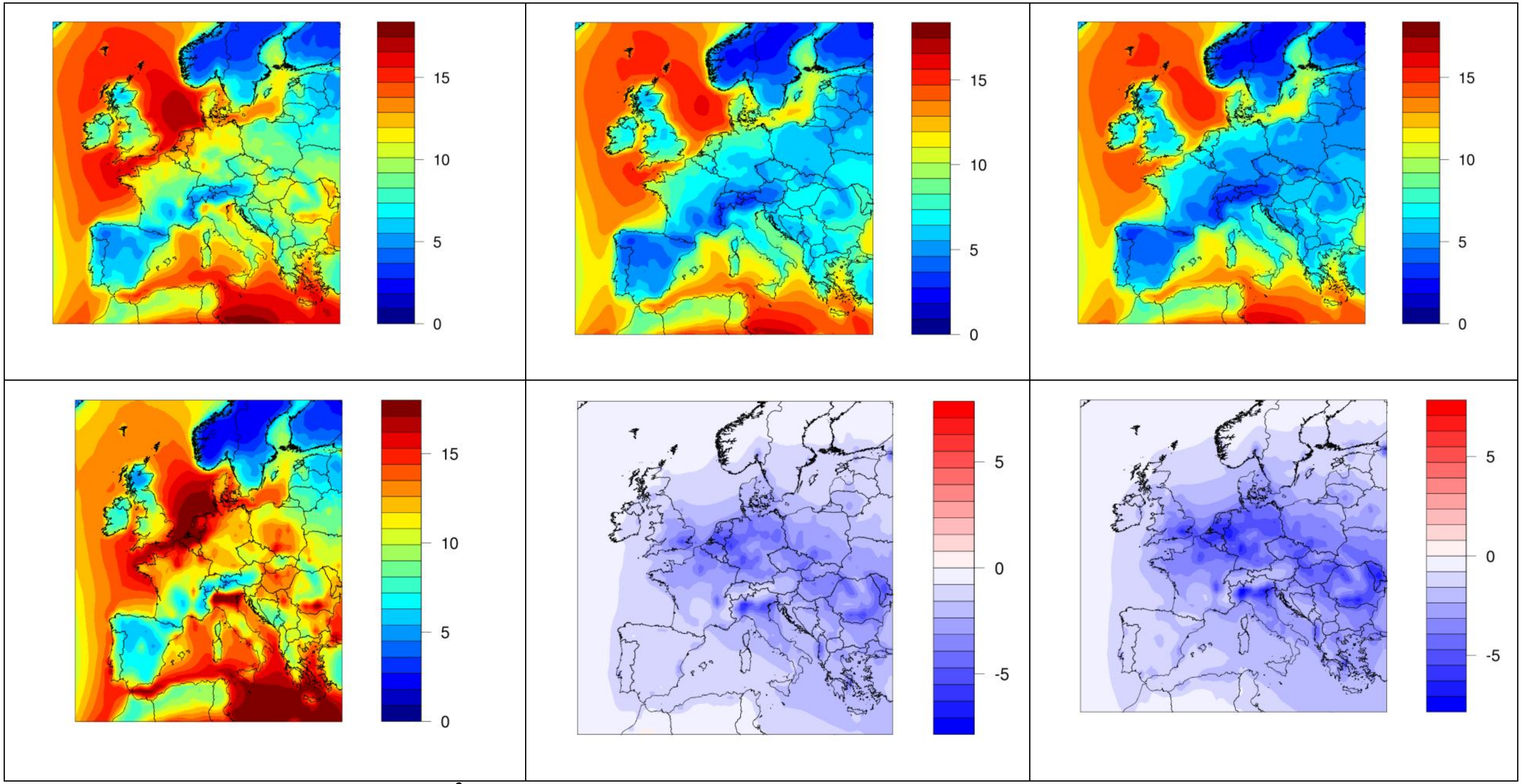

Figure 8 : Surface concentrations of PM10 (µg/m^3) modelled with CHIMERE. The first column show the concentrations for the early 21st century: the reference year in GEA emissions (2005: top left) and the 1997-2008 decade in EMEP emissions (bottom left). The remaining columns provide 2030 fields according to the Reference (centre) and Mitigation (right) scenarios. The bottom row gives the difference compared with the reference for Reference (centre) and Mitigation (right). All fields are averaged over 10 years of simulation (1998-2007 meteorology).

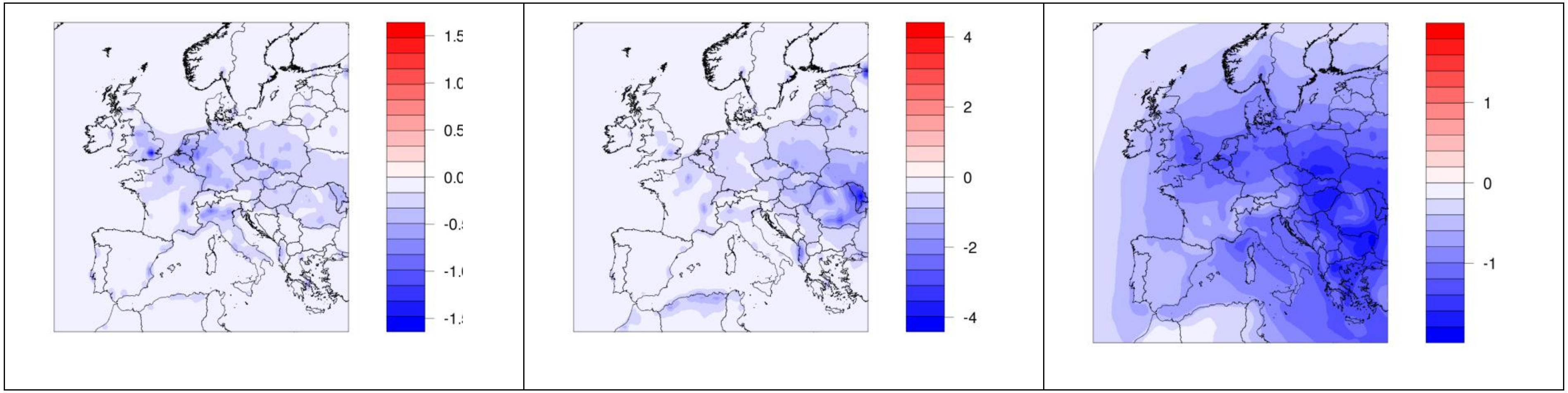

Figure 9 : Difference in surface concentration of particulate constituents between the Mitigation scenario for 2030 minus the 2005 reference. From left to right: organic carbon, black carbon, sulphates (µg/m^3).

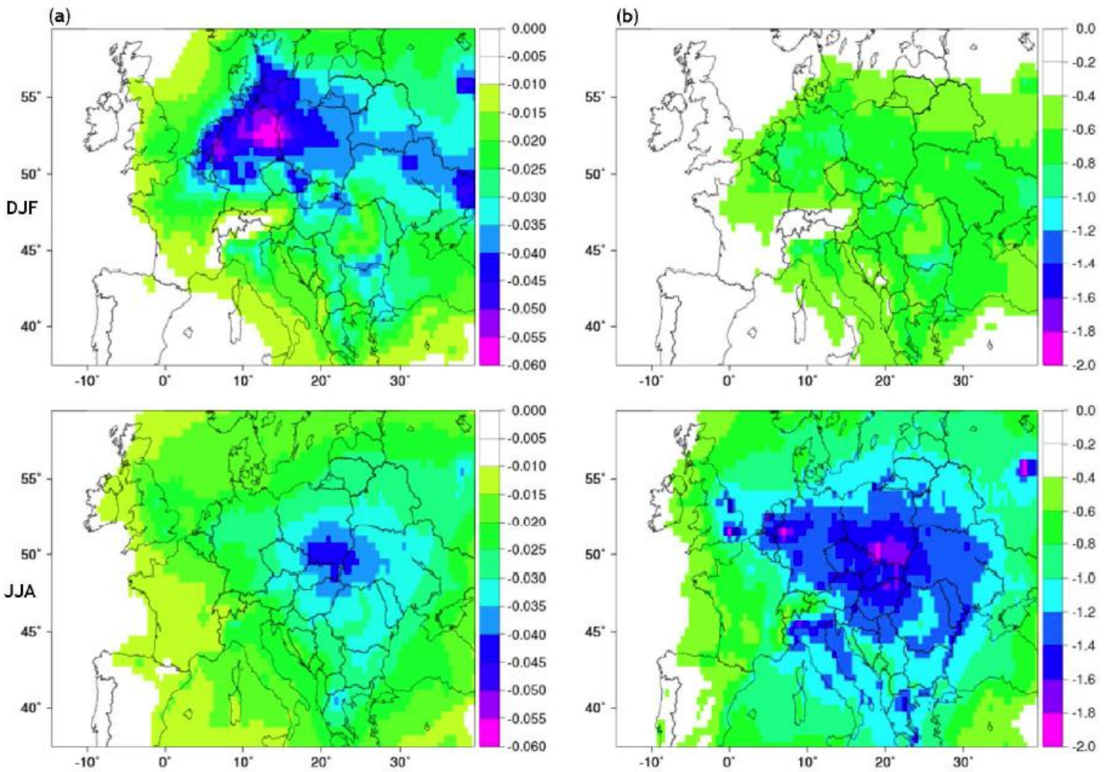

Figure 10 : Changes in aerosol optical thickness (AOT, a) and radiative forcing at the surface (ΔFBOA, b) as the difference between the Mitigation scenario simulation and the reference (2005) simulation, for winter (December, January, February) and summer (June, July, August).

5 Synthesis, Discussion and Perspectives

5.1 Rationale and motivations for the study

The European Commission released in 2011 the 'Roadmap for the EU for moving to a low carbon economy in 2050' (EC, 2011) aiming at reducing domestic greenhouse gas emissions by 80% in 2050 (compared to 1990). Assuming that the rest of the world would target an overall reduction of GHG emissions by 50% in 2050, this goal would contribute to limit global temperature rise to 2 degrees Celsius. The issue of expected collateral effects of this Commission Roadmap for the EU for atmospheric pollution is of particular relevance in the context of Air Quality and Climate Change interlinkages. Climate – through landuse change and meteorology – influences the chemical processes in the atmosphere. Also anthropogenic traces species have an impact on the climate (radiative forcing of aerosols and ozone, indirect effect of aerosols on cloud formation processes). But here the main focus regards the assessment of the improvements that can be expected in terms of surface air quality of the changes brought about by the climate policy, i.e. the cobenefits.

The European Environmental Agency commissioned the European Topic Centre on Air Quality and Climate Mitigation to quantify these cobenefits. This assessment is twofold. First a comparison of the total mass of pollutant emitted under reference and mitigation scenarios allows understanding the underlying hypothesis for each pathway and gives an opportunity to discuss relevant features of the projections. This discussion is complemented by a focus given to the emission reduction that can be anticipated in the transport activity sector for which future greenhouse gases reduction are relatively low compared to other sectors, and the impacts in terms of air pollution are high. Second, we expand the investigation of emission projections and we propose an analysis of the expected outcome in terms of atmospheric concentrations. Two approaches can be implemented to propose an integrated assessment of future air quality projections (1) Atmospheric Response Models mimic the transport and transformation processes in the atmosphere by applying series of transfer functions, and (2) Chemistry Transport Models (CTM) explicitly model in three dimensions all major chemical and physical processes occurring in the atmosphere. Atmospheric Response Models have been used successfully in the past but their implementation for projections at longer time scales raises unprecedented issues. The underlying hypotheses required for their development are valid for present day conditions but their validity outside of the range of calibration is uncertain. Unlike responses models, CTMs are not calibrated. This feature is an essential asset when it comes to projections assessment as they can be applied out of the range of calibration (for example in a changing climate context).

5.2 Methodology

The present report starts with a description of the Commission Roadmap for the EU and other existing emission projection datasets by comparing the underlying policy and socio-economic assumptions and evaluating to which extent EU policies and EU policy emission trends are well represented. A quantitative comparison is also proposed for GHG, and the cobenefits are computed as the ratio of air pollutant reduction for a given unit of reduction of GHG (comparing the climate mitigation against the reference scenario). A chapter is also devoted to the specific issue related to the emissions induced by road traffic. This analysis allows a better understanding of the Commission

Roadmap for the EU. But it constitutes also an important cornerstone for the evaluation of the expected impacts on European air quality. The Commission Roadmap for the EU was unfortunately not available in a format suitable for AQ modelling over the course of this activity. Hence the emission data to be used in the CTM had to be substituted. A more quantitative understanding of total emission in the Commission Roadmap for the EU and in the substituted scenarios was thus crucial for the subsequent analysis.

5.3 Results

The scenarios published since 2007 (i.e. post IPCC AR4) that were included in the present work include (in addition to the Commission Roadmap for the EU): all four IPCC RCPs (Representative Concentration Pathways): RCP2.6, 4.5, 6.0 and 8.5, as well as the GEA (Global Energy Assessment) reference and mitigation trajectories. These projections differ in their scope, design and methodology.

In principle the closest to the Commission Roadmap for the EU is RCP2.6 in the sense that it aims at limiting climate change to a 2 degree global warming. And the GHG reduction is indeed almost 80% for Europe by 2050 for the RCP2.6 (i.e. the target of the Commission Roadmap for the EU) whereas it is 20% for the RCP4.5 and an increase is given in the other pathways.

The other assumptions are similar: the global population is assumed to increase to 9 billion inhabitants by 2050 in both cases and the EU27 population stays at about 500 million, while the GDP of the EU27 is 1.5% per year on average over 2005-2050 for the Commission Roadmap for the EU and 1.7% for the RCP2.6.

The main difference between the RCPs used in this study and the Commission Roadmap for the EU is that in the RCPs air pollution policies are not explicitly taken into account. Emission standards (over the whole period) are assumed to increase together with the income according to the environmental Kuznets curve theory.

This limitation constituted an important motivation to include the GEA pathways in the present report, since – in this dataset – a stronger focus was devoted to the representation of air pollution policies based on information from the GAINS model. In this respect the Commission Roadmap for the EU and the GEA projections are very similar until 2030: no Kuznets coefficients are used and actual projected emission factors corresponding to the current air quality (AQ) legislation are used for the period up to 2030. After 2030 the emission factors are constant and all emission reductions are attributed to changes in the energy mix and energy demand in the Roadmap, while for the GEA scenarios assumptions are made on continuing improvements in emission factors based on levels of economic growth. The only difference between the way AQ legislation is handled in the Commission Roadmap for the EU and GEA projections up until 2030 concerns the underlying model for energy use that is more aggregated for GEA projections so that aggregated GAINS emission factors had to be derived and applied to the MESSAGE energy flows for GEA, while for the Roadmap the underlying PRIMES scenario was implemented in GAINS. After 2030, an additional difference is introduced: any air pollutant emission reduction in the Commission Roadmap for the EU is due to changes in total energy use or changes in the energy mix, while in GEA they are additionally due to assumed improvements in emission reduction technologies.

The comparison between Europe-wide GHG emissions in the various scenarios included in the present report brought to light significant differences that illustrate well the various possible pathways to reach the same target in terms of climate forcing. While both the Commission Roadmap for the EU and the GEA mitigation pathway are designed to reproduce a climate policy leading to a global warming below 2 degrees, we found that the GHG emission reduction within EU27 amounts to 60% by 2050 for GEA while it is 80% for the Commission Roadmap for the EU. The baseline pathway is also very different in both cases, the GEA reference assumes GHG emissions will increase by 40% between 2005 and 2050, while in the Commission Roadmap for the EU these emissions are assumed to decrease by 35%. It is important to keep in mind that the consistency between these scenarios is always addressed in terms of the global climate response. Therefore, discrepancies in terms of regional estimates and for selected subsets of species were not unexpected. In addition, the GEA pathways were purposefully designed to explore the benefits of a wide range of interventions including efficiency measures. That is why the baseline reflects high energy demands and increased fossil fuel consumption, in order to leave room for energy efficiency emphasis in the mitigation pathway. These differences in the rationale for each scenario have a significant impact on the quantification of climate / air quality cobenefits.

A closer look at GHG emissions of the power sector shows that the downward trend is more pronounced than for the total emissions because more low carbon technologies exist, and at lower costs than mitigation measures for the other sectors. For the RCP2.6 pathway, the power sector even becomes a net sink of GHG due to the use of carbon capture and storage technologies.

The investigation of the ratio of the reduction of air pollutant emission divided by the reduction of GHG emissions (analysis of the mitigation scenario relative to the baseline scenario) allows analysing the cobenefits for an air quality perspective brought about by the climate policy. To achieve this, we gathered the reference emission trajectories corresponding to each scenario, while only the mitigation version is commonly used. We find that all scenarios exhibit significant cobenefits. In the GEA dataset, these cobenefits evolve linearly in time, in the RCP2.6 they level-off slightly.

The level of detail available for the Commission Roadmap for the EU is not sufficient to perform a quantitative comparison of the cobenefits for all the species. However, the aggregated reduction of SO_2, NOx, and PPM2.5 claims that anticipated cobenefits by 2050 are largest in the GEA scenario, while they are smaller in the RCP and Commission Roadmap for the EU scenario.

A closer insight into the emissions attributed to road transport is also given, one of the sectors in the Commission Roadmap for the EU 2050 that shows a less strong reduction compared to for example the power sector. A review of existing studies (Clean Transport Systems; iTREN-2030; Transport Energy and CO_2 study of the International Energy Agency; Transvisions; and Policies to decarbonise transport in Europe: 80 by 50) shows that the focus is always on CO_2 emissions and climate change mitigation, and the possible effects on air pollutants has not been sufficiently considered.

Nevertheless the Clean Transport Systems study provides an adequate level of detail in the energy trajectories, so that we could produce quantitative information regarding the air pollutant emissions of the transport system using the GAINS model. In addition the targets of this initiative are compatible with the Commission Roadmap for the EU for 2050. The quantitative emissions of PM2.5, NOx, and NMVOC are provided for 4 scenarios: a baseline, a dominant electrification and a dominant biomass scenario as well as a scenario that combines the former two. Significant co-benefits are achieved by all scenarios, despite some side-effects. Although the power generation and the agriculture sector would be substantially affected by the assumed scenarios, emissions from these sectors have not been quantified.

An important step towards the integrated assessment of air quality projections with a full atmospheric chemistry transport model was achieved by implementing the GEA projections in the CHIMERE model. Ten year long simulations over the whole of Europe were performed in order to reach a statistically robust insight into the projected trends. The scenarios investigated differed in their representation of the climate policy but had the same underlying air quality legislation in order to discuss climate and air quality co-benefits.

A comparison of the control simulation (present day GEA emissions) and an identical simulation using the reference EMEP emission data illustrates the uncertainties associated with the use of global projections of air pollutant emissions. For the current situation, the major hotspots are well captured with the GEA emissions, but the geographical variability is underestimated, and differences in the chemical regimes (related to the VOC/NOx ratio) are likely, although further analysis would be required to confirm this statement.

Surface NO_2 concentrations decrease significantly by 2030 in Europe, so that in the most optimistic scenario the current hotspots of pollution barely stand out of the background. In turn, ozone also decreases over most of Europe, although some increases are observed over NOx saturated areas as a result of the decreased titration effect. In very high emission areas, NOx can be a net sink of ozone when the night time titration exceeds in magnitude the daytime formation. This effect has a strong impact on average daily ozone, whereas it does not reflect peak values that were not investigated in the present report. As far as particulate matter is concerned, the decrease is such that by 2030 natural sources (mineral dust re-suspension and sea salt) will dominate the PM10 budget in Europe.

These findings confirm the outline derived from the analysis of raw emissions data. On a more quantitative basis, we compared the cobenefits derived from the raw analysis of the emissions and the aggregated changes obtained in the CHIMERE simulations. As far as nitrogen oxides are concerned a perfect match is obtained on average over the domain. NOx is mainly found in the atmosphere as a primary constituent, and its short lifetime limits the influence of boundary conditions. As a result we find that both approaches estimate that a 50% cobenefit on NOx levels can be expected from the current climate policy by 2030 on average over the whole of Europe. Of course, ozone co-benefits cannot be derived from the primary emissions since it is exclusively produced in the atmosphere. Thanks to the CTM we found that the cobenefit is very large, average O_3 decrease is about 125% larger for the scenarios accounting for the climate policy. Last, for particulate matter, we find that the cobenefits would have been underestimated by 10% by using only the emissions, since the decrease of emissions of gaseous precursors of secondary particles would not have been accounted for. With the CTM, we find a 30% larger decrease of PM10 with the scenario accounting for the climate policy compared to the baseline.

Last, we propose a quantification of the radiative forcing perturbation in these scenarios. Particulate matter has a detrimental effect on human health but it also changes the radiative budget of the atmosphere with a net cooling effect. Most existing studies addressing this topic are based on climate scenarios using global scale models while we offer a first quantification using scenarios more specifically designed for air pollution issues and using an operational air quality model at a higher resolution.

We find that by 2030, the cooling effect of aerosol is reduced as a result of the reductions in aerosol emissions. This impact is twice as large at the surface compared to the top of the atmosphere, which strongly supports our methodology that focuses on near-surface air quality. The competitive effect of warming (soot) or cooling (sulphate) particles in the atmosphere is not uniform over Europe and we could illustrate this process by comparing aerosol optical depth and atmospheric forcing maps.

Since the aerosols concentration decreases sharply, their radiative forcing (that depicts the magnitude of the perturbation brought about by the aerosols) is also reduced, even though the result in terms of temperature perturbation is a relative warming compared to the present situation. We find that the relative decrease of radiative forcing by 2030 is 30% for the GEA mitigation scenario, while it is only 21% for the reference. The cobenefit brought about by the climate policy in terms of radiative forcing is thus 43%.

5.4 Discussion

This report aimed at setting the scene for a comprehensive assessment of air quality projections based on a full atmospheric modelling system. The material presented here shows that the required tools and input data exist, but that there are limitations in data availability, especially in relation to the scenario datasets. An important integration work also remains to be completed to build a full modelling system that captures all the relevant physical processes. This discussion chapter underlines a few priorities for future studies.

Emission projections developed in the framework of IPCC (RCP) or GEA initiatives are suitable for use in air quality models. However their consistency with present-day situation is not guaranteed (see the comparison between present-day GEA emissions and the reference EMEP inventory discussed in Section 4.3). Atmospheric chemistry being a highly non-linear process, this feature raises serious concerns since a full assessment cannot be limited to relative changes. A better consistency of reference (present day) scenarios with existing regional inventories should be sought.

The level of detail available for air quality information in the Commission Roadmap for the EU for moving to a low carbon economy in 2050 is not yet satisfactory for its implementation in an air quality models. It is not possible either to perform an in depth comparison with existing inventories that would ultimately lead to a substitution of the Commission Roadmap for the EU by a “compatible” trajectory. It is expected that this situation will be improved in the revised version to be delivered in 2012.

Chemistry transport models originally developed to forecast isolated air pollution episodes are now capable to address decadal and continental scale. However, their implementation in an integrated risk assessment framework requires further refinement. Namely: exposure metrics should be derived in addition to average changes (in order to target detrimental air pollution and not only average background changes that shall be harmless for human health). The impact of external factors such as climate change and the evolution of background chemical concentrations at the global scale should also be taken into account. Last, such an assessment would benefit from an ensemble approach and should not rely on the implementation of a single CTM.

Nevertheless, given the non-linearities between emission reductions and air quality concentrations (particularly for ozone and NO_2), we recommend that air quality impacts are to be investigated with a full atmospheric modelling system. When relying exclusively on raw primary emissions, the non-linearities of the atmospheric system are neglected hence the analysis of the cobenefits can be misleading.

We did not perform any comparison of the CTM analysis with an atmospheric response model. Once the detailed Commission Roadmap for the EU is delivered, it will be possible to make this comparison since GAINS results are already available for selected scenarios.

6 Acknowledgements

We would like to thank Allison Thomas and Detlef van Vuuren for their permission to present the reference and mitigation RCP4.5 and RCP2.6 scenarios. Keywan Riahi is also acknowledged for making available the GEA data. We are also grateful to Shilpa Rao, Zbigniew Klimont, and Markus Amann (IIASA) for providing assistance regarding the GEA dataset and the GAINS model. The CTS data were provided by the E^3MLab.

7 Annex 1: Transport Scenarios

7.1 Clean Transport Systems

General
The scenarios have been quantified using the PRIMES-TREMOVE Transport model, developed at E^3Mlab of the National Technical University of Athens.
The PRIMES-TREMOVE Transport model allows treating the policy measures and actions as drivers of transformations and changes as appropriate within the logic of each scenario and produces detailed transport outlook tables for each MS and for each year (5-year steps) up to 2050. The model complements the overall PRIMES model by providing a more detailed and sophisticated representation of the transport sector. The PRIMES-TREMOVE transport model uses input data from the overall PRIMES model, such as fuel prices, which therefore assure consistency with the overall PRIMES scenarios.

Target year of study
Up to 2050 in 5-year steps

Scenario characteristics, distinguishing backcasting and forecasting scenarios and amount of scenarios considered
PRIMES-TREMOVE like the rest of the PRIMES model is a forecasting model which quantifies scenarios for future years in specific contexts based among others on macro-economic, technical, structural and policy assumptions.
In agreement with the Commission the following three scenarios were developed and subsequently analysed:

- Dominant electrification scenario;
- Dominant biomass scenario;
- “Renew” scenario, a combination of elements of the previous two scenarios.

The different contexts are determined by assumptions regarding:

- Development of vehicle technology;
- Range of vehicle;
- Density of refuelling ;
- Policy context.

The scenarios analysed seek to achieve maximum possible oil independence, in the context of decarbonisation of the economy, in which the transport sector should participate by reducing around 60 % emissions compared to 1990.
The Reference scenario for this project corresponds to the Reference scenario to 2050 endorsed by DG Ener and DG Clima for the 2050 Commission Roadmap for the EU studies.
The dominant electrification scenario is characterised by a shift towards low carbon intense gaseous fuels in the medium term and strong electrification in the long-term.
The renew scenario is characterised by the availability and use of a variety of different fuels and sees no domination of a specific fuel.
The dominant biomass scenario is characterised by a high share of bio-fuels in both road and non-road transport.

Assumed policies for both Air Pollution and Climate Change

The Reference scenario assumed implementation of the 20-20-20 energy and climate policies and also the implementation of a series of Directives on energy efficiency. It is assumed that all EU policies adopted until April 2010 will be successfully implemented but no new policies will be put in place. For the period beyond 2020, the projection includes effects from the policies adopted up to April 2010, as for example the ETS (which involves a linear reduction of allowances beyond 2020) and the efficiency directives.

Policies implemented in the transport sector, within the Reference scenario:

- Regulation on CO_2 from cars 2009/443/EC
- Regulation EURO 5 and 6 2007/715/EC
- Fuel Quality Directive 2009/30/EC
- Biofuels directive 2003/30/EC
- Implementation of MARPOL Convention ANNEX VI - 2008 amendments - revised Annex VI
- Labelling regulation for tyres 2009/1222/EC
- Regulation Euro VI for heavy duty vehicles 2009/595/EC
- RES directive 2009/28/EC
- EU ETS directive 2003/87/EC as amended by Directive 2008/101/EC and Directive 2009/29/EC

For the dominant electrification scenario:

- Information campaigns and labelling, as well as legislation to ensure the existence of maintenance services
- Recharging infrastructure for electric vehicles and the electric plugs for the vehicles will be standardised
- All drivers to be eco-driving trained, leading to additional efficiencies for the different transport modes
- Taxation basis changes to an energy and CO_2 based taxation
- Minima for petrol and diesel will be applied for all countries that have lower taxation rates
- CNG and LPG will no longer be completely exempted from taxation, but the energy tax will not be applied to its full extent; taxation on biofuels will also gradually be introduced
- Aviation and road heavy duty vehicles become part of the ETS
- ETS carbon price and the carbon value for the non-ETS sectors are assumed to be equal
- Extension of Regulation 2009/443/EC to 2050 with more stringent CO_2 limits and efficiency improvement targets for other transport modes

For the dominant biomass scenario:

- Policy assumptions on fuel taxation and eco-driving will remain the same as in the dominant electrification scenario
- CO_2 standards for vehicles are less stringent than in the dominant electrification scenario
- Efficiency improvement targets for other transport modes

For the “renew” scenario:

- Eco-driving and labelling continue as before
- Information campaigns and service development for the maintenance of vehicles will also develop
- Taxation of fuels and further financial measures as in the previous scenarios
- The CO_2 standards are assumed to be more moderate than the dominant electrification scenario, but more stringent than the dominant biomass scenario

Indication how flexible mechanisms of the Kyoto-Protocol are dealt with
No

Geographical scale
EU27 (only aggregated data presented in the report)

Level of detail
Transport, CO_2 emissions

Availability of quantitative data on activity data and emissions
By construction all three policy scenarios deliver the required emission reduction in transportation of 60 % in 2050 from 1990 levels and 70 % compared to 2005.
Some emission and activity data are included in the report (e.g. Figure 53, p.83; Table 5, p.34).

If the scenario describes a part of the total system: a judgement how the scenario could be integrated with other scenarios
Reductions of emissions in 2050 compared to 2005 are provided for the following sectors (for reference scenario):

- Power generation
- Energy branch
- Industry
- Residential
- Tertiary
- Transport

Other useful info
Reduction potentials of different fuels (Table 1, p.22)

7.2 *iTREN-2030 (Integrated transport and energy baseline until 2030)*

General
The basic objective of iTREN-2030 is to extend the forecasting and assessment capabilities of the TRANS-TOOLS transport model to the new policy issues arising from the technology, environment and energy fields. This is achieved in iTREN-2030 by coupling the TRANS-TOOLS model with three other models, ASTRA, POLES and TREMOVE that cover these new policy issues.

Target year of study
Up to 2030

Scenario characteristics, distinguishing backcasting and forecasting scenarios and amount of scenarios considered
The basic concept of the Reference Scenario is Frozen Policy 2008, i.e. the scenario considers only policies that were decided by the EU Council and/or EU parliament by mid 2008.
The Integrated Scenario will consider the changing framework conditions until 2030, in particular the policy pressure that comes from climate policy and the increasing scarcity of fossil fuels, as well as the impact of the financial and economic crisis.
The integrated scenario includes (i) the economic and financial crisis of 2008/2009 as well as the economic recovery programmes implemented by the EU and the Member States and (ii) ambitious climate, energy and transport policies that are to be implemented between 2009 and 2025. Such policies include pricing, regulation, technology support and diffusion measures, as well as information measures and behavioural adaptations.

Assumed policies for both Air Pollution and Climate Change
Policy measures considered in the Reference scenario:

- Distance-based motorway charges for HGVs
- CO_2 emission targets agreed by Kyoto Protocol and implemented in national allocation plans (NAP I + II)
- Existing national regulations e.g. phasing-out of nuclear energy for some countries and quotas for renewables incl. biofuels
- Share of renewable energy in the electricity production
- Energy efficiency improvements, reduction of final energy consumption e.g. in buildings
- Voluntary CO_2 reduction target for cars
- LPG / CNG / E85 adaptation and infrastructure
- Euro-V for HGVs / Euro-5 for cars
- Emission standards for diesel trains (UIC Stage IIIA)
- ICAO Chapters 3 (emissions) and 4 (noise)

Policy measures considered in the Integrated scenario:

- Road user charge cars and trucks
- City tolls
- Fuel tax harmonisation
- Air and road transport into EU-ETS
- Railway liberalisation
- CO_2 limits for cars and LDVs
- Use of low resistance tyres for HDVs
- GHG reduction target for the EU for 2020

- 20 % renewable energy by 2020
- Increase of energy efficiency by 1 % annually
- Support for carbon capture and sequestration (CCS)

Indication how flexible mechanisms of the Kyoto-Protocol are dealt with
No

Geographical scale
EU27 MS + CH, NO; transport demand on NUTS2 level, emissions on three region types (metropolitan, urban, non-urban)

Level of detail
Transport, CO_2, NOx, PM_{10} emissions

Availability of quantitative data on activity data and emissions
Emission and activity data by MS are included in the report (Annex 1 and 2).

If the scenario describes a part of the total system: a judgement how the scenario could be integrated with other scenarios
Energy demand by consumer sector is provided (Figure 5, p.15).
Emissions from the energy sector (power sector, transport, industry, residential, other conversion) are also provided (e.g. Figure 5-11, p.105).

Other useful info

7.3 International Energy Agency – Transport, Energy and CO_2

General

IEA has developed the Mobility Model (MoMo), a global transport model that supports projections and policy analysis. MoMo contains historical data and projections to 2050 and includes all transport modes and most vehicle types. MoMo covers 22 countries and regions. It contains a good deal of technology-oriented detail, including underlying IEA analyses on fuel economy potentials, alternative fuels and cost estimates for most major vehicle and fuel technologies, with cost tracking and aggregation capabilities. It therefore allows bottom-up "what-if" modelling, especially for passenger LDVs. The model uses vehicle stock, average travel, and fuel consumption factors to calculate energy use. The results are then checked against IEA energy use statistics to ensure that the identity is solved correctly for each region. MoMo produces projections of vehicle sales, stocks and travel; it also tracks energy use, GHG and pollutant emissions for all modes.

Target year of study

Up to 2050

Scenario characteristics, distinguishing backcasting and forecasting scenarios and amount of scenarios considered

Scenarios considered in the study include:

- **Baseline:** Follows the IEA World Energy Outlook 2008 Reference Case to 2030 and then extends to 2050. It reflects current and expected future trends in the absence of new policies.
- **High Baseline:** Considers the possibility of higher than in the Baseline scenario growth rates in car ownership, aviation and freight travel over the period to 2050.
- **BLUE Map:** It achieves CO_2 emissions by 2050 that are 30 % below 2005 levels. It does this via strong improvements in vehicle efficiency and introduction of advance technologies and fuels such as plug-in hybrids (PHEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). It does not envisage significant changes in travel patterns.
- **BLUE EV success:** Similar to BLUE Map and achieving a similar CO_2 reduction, but with EVs and PHEVs achieving greater cost reductions and better performance to the point where they dominate light-duty vehicle (LDVs) sales by 2050, to the exclusion of FCVs.
- **BLUE Shifts:** Focuses on the potential of modal shift to cut energy use and CO_2 emissions. Air and LDV travel grow by 25 % less that in the Baseline to 2050, and trucking by 50 % less. The travel is shifted to more efficient modes and (for passenger travel) to some extent eliminated via better land-use planning, greater use of information technology, and other measures that reduce the need for motorised travel. Compared to the Baseline in 2050, BLUE Shifts results in a 20 % reduction in energy use and CO_2.
- **BLUE Map/Shifts:** It combines the BLUE Map and BLUE Shifts scenarios, gaining CO_2 reductions from efficiency improvements, new vehicle and fuel technologies, and modal shift. It results in a 40 % reduction in CO_2 below 2005 levels by 2050.

Assumed policies for both Air Pollution and Climate Change

25 different vehicle efficiency measures are considered, including mandatory fuel economy standards for LDVs and trucks, standards for tyres, and the use of other measures to promote fuel economy such as incentives to encourage drivers to drive more economically.

A number of regulatory standards, voluntary targets, financial incentives and improved consumer information have been considered as measures to improve technical fuel efficiency. On-road fuel efficiency measures include (i) improvements in the efficiency of vehicle components, such as air conditioning and lighting, (ii) improvements in the fuel efficiency of after-market equipment, (iii) eco-driving and intelligent transport systems, (iv) improved vehicle maintenance and (v) reductions in traffic congestion.

To reduce demand for LDVs for urban travel, the following policies were considered: (i) land use planning to increase density and mixed-use development, (ii) promoting teleworking and other information-based substitutes for travel, (iii) parking supply and pricing, (iv) encouraging car sharing, (v) road pricing, (vi) improving bus transit systems, (vii) encouraging non-motorised travel such as cycling and walking, (viii) encourage reductions in air travel and LDV use for long-distance travel and use of rail and bus options.

For freight transport, several policies were considered for improving vehicle utilisation, shifting freight from road to rail, increasing truck efficiency, reducing energy intensity of rail freight operations.

For maritime, various international, regional and national measure have been considered.

Indication how flexible mechanisms of the Kyoto-Protocol are dealt with

A list of bus rapid transit systems linked with CDM schemes and their characteristics and CO_2 impact estimates are provided (Tables 5.15-5.18; pp.258-260).

Geographical scale

22 countries and regions: OECD North America (Canada, Mexico, United States), OECD Europe (France, Germany, Italy, United kingdom, Other OECD Europe), OECD Pacific (Australia and New Zealand, Japan, Korea), Former Soviet Union, Eastern Europe, China, Other Asia, India, Middle East, Latin America, Africa.

Level of detail

Transport, GHG and pollutant emissions

Availability of quantitative data on activity data and emissions

Some emission and activity data by country/region are included in the report.

If the scenario describes a part of the total system: a judgement how the scenario could be integrated with other scenarios

No information

Other useful info

7.4 TRANSvisions

General

An important aspect of the study has been to analyse different transport policy options to obtain reductions of the transport sector's CO_2 emissions by arbitrarily set targets of 10 % in 2020 and 50 % in 2050, compared to 2005. The main tool to accomplish this analysis has been the use of "Meta-Models", developed by the project for this particular purpose. The Meta-Models have been calibrated against TRANS-TOOLS results for 2005 and 2030.

Target year of study

Up to 2050

Scenario characteristics, distinguishing backcasting and forecasting scenarios and amount of scenarios considered

A number of different exploratory scenarios for 2050 have been formulated based on the identified external, internal and policy drivers related to transport. The scenarios are formulated as different paths towards a post-carbon society. These scenarios have been named: "Moving alone" or Induced mobility (Individualistic transport, technology, supply management and market spontaneous self-organisation); "Moving together" or Decoupled mobility (pricing and modal shift, land planning, emphasis on cohesion); "Moving less" or Reduced mobility (behavioural policies and regulation, lifestyle changes, priority to local production); and "Stop moving" or Constrained mobility (society initially puts a strong emphasis upon technology, but when breakthroughs do not take place it falls back on regulation and banning activities).

The quantitative scenarios constructed are the following:

- A Global Reference Scenario (Main existing Commission Baselines);
- Two policy scenarios describing different ways to fulfil the some arbitrarily set Climate Change targets for transport for 2020 and 2050, that is a reduction of CO_2 emissions from transport of 10 % and 50 % respectively (back-casting);
- Two other policy scenarios aimed at investigating how transport demand is affected by different types of transport policies;
- The quantitative versions of the four exploratory scenarios outlining the scope of transport development.

The two backcast scenarios (Sustainable Mobility and Efficient Mobility) are based on two of the exploratory scenarios (Decoupled Mobility and Induced Mobility), with adjustments to comply with CO_2 targets (-10 % by 2020, and -50 % by 2050).

Assumed policies for both Air Pollution and Climate Change

Five different groups of policy instrument were defined. These groups include:

- Infrastructure (development of new infrastructure in order to improve cohesion, accessibility and reduce congestion)
- Technology (development of new or improved technology in the transport field)
- Economic (pricing for infrastructure use, fuel and vehicle taxes)
- Regulatory (development of legislation and regulations monitoring traffic, vehicle performance, working hours, and land use and planning regulations)
- Participatory (instruments concerned with citizen involvement).

Indication how flexible mechanisms of the Kyoto-Protocol are dealt with

No

Geographical scale
EU27 (only aggregated data presented in the report)

Level of detail
Transport, CO_2 emissions

Availability of quantitative data on activity data and emissions
Some emission and activity data by MS are included in the report (Annex 7).

If the scenario describes a part of the total system: a judgement how the scenario could be integrated with other scenarios
No information

Other useful info
Overview of assumptions in the TRANSvisions' TRANS-TOOLS scenarios (Table 4.1; p.77) and policy assumptions in the exploratory scenarios (Annex 6)

7.5 Policies to decarbonise transport in Europe: 80 by 50

General

The paper outlines pathways for the European transport sector to contribute to EU's efforts to meet its stated GHG reduction targets over a much greater timescale and focuses on a reduction in emissions by 80 % in the year 2050 compared to 2000 levels.

Target year of study

Up to 2050

Scenario characteristics, distinguishing backcasting and forecasting scenarios and amount of scenarios considered

Paper is mainly based on the findings of a former backcasting study titled "Transport System in a Low Carbon Society: Regional Study of Europe". The backcasting study uses data supplied by the International Energy Agency (IEA) from its Mobility Model Database.

To enable such large reductions in transport GHGs, two alternative images of the future were developed:

- Image A (DENCITY) assumes a drastic change in land use planning and the facilitation of high density developments supported by high levels of public transport
- Image B (SUBCITY) assumes a more natural extension of the situation today, with the vast majority of people living within large towns or small cities which are still heavily dependent upon their own private transport

Assumed policies for both Air Pollution and Climate Change

Policies to decarbonise transport are based on the approach termed "Avoid-Shift-Improve":

- Reform of fuel tax and fuel subsidies
- Parking charges
- Road pricing (inter-city)
- Congestion charging (Inner city)
- HGV tolls
- Park and ride
- Support for non-motorised modes (cycling and walking safety campaigns)
- Support for public transport (convenient and affordable public transport)
- Transit oriented development (TOD)
- Car clubs/ car share schemes
- Alternative fuels (e.g. biofuels)
- Improvement of conventional engine efficiency
- Electric/Hybrid vehicles
- Eco driving
- High speed rail

Indication how flexible mechanisms of the Kyoto-Protocol are dealt with

No

Geographical scale

EU27 (only aggregated data presented in the report)

Level of detail

Transport, CO_2 emissions

Availability of quantitative data on activity data and emissions
Limited emission and activity data are included in the report (Figures 6-9, pp.10-13).

If the scenario describes a part of the total system: a judgement how the scenario could be integrated with other scenarios
No information

Other useful info

8 List of Tables

9 List of Figures

10 References

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