# The Economic Impacts of Air Pollution Policies in the EU

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## Abstract

This paper uses the computable general equilibrium model called WorldScan to analyse interactions between European air pollution policies and policies aimed at addressing climate change. WorldScan incorporates the emissions of both greenhouse gases ($CO_2$, $N_2O$ and $CH_4$) and air pollutants ($SO_2$, $NO_x$, $NH_3$ and $PM_{2.5}$). WorldScan has been extended with equations that enable the simulation of end-of-pipe measures that remove pollutants without affecting the emission-producing activity itself. This paper analyzes simulations of air policies in the EU by introducing emission ceilings for air pollutants at the level of member states. The simulations show that mitigation consists of implementing not only emission control technologies, but also efficiency improvements, fuel switching and structural changes. Greenhouse gas emissions thereby decrease, which renders climate change policies less costly. The decrease in the greenhouse gas price may be substantial, depending on the ambition level of the air pollution policy and the context of international climate policies.



*Keywords*: air pollution, climate change, energy, co-benefits, interaction policies

## 1. Introduction

The economic literature has dealt with the interactions between mitigating greenhouse gas (GHG) emissions and reducing air pollution (Burtraw and Toman, 1997; Aunan et al., 2006; Rive, 2010). These studies have in common that they analyze only part of the problem. They lack complex interactions because they do not cover all types of gases that are relevant for air pollution and climate change or because they disregard the pollution of small sources from freight and personal transport. This paper aims to fill this gap in the literature and assess the economic impacts of air and climate policies based on a model with complete coverage of the most relevant air pollutants and GreenHouse Gases (GHG's). The focus in this paper is on recent proposals aiming to mitigate air pollution in Europe and lower their contribution to climate change, taking into account the complex interactions between these policy targets.[3]

In 2005, the European Commission launched the Thematic Strategy on Air Pollution (TSAP) (EC, 2005). The ultimate objective is to attain *"levels of air quality that do not give rise to significant negative impacts on, and risks to human health and the environment"*. The TSAP establishes interim objectives for air quality for the period up to 2020. One of the actions announced is a revision of the National Emission Ceilings (NEC) Directive, which requires Member States to meet emission ceilings for the air pollutants sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), particulate matter (PM), Volatile Organic Compounds (VOC) and ammonia ($NH_3$) by 2010 and later years.[4] The revision of the NEC Directive aims to align the national ceilings with the 2020 TSAP objectives and specifically to introduce a ceiling for particulate matter (PM). The revision was postponed in order to account for the outcome of the negotiations on the EU Climate

[3] In this paper, interactions refer to economic impacts from mitigating emissions. Also, there are interactions between climate change and air pollution in the long run. For example, there are temperature changes from $SO_x$ (-) and $CO_2$(+) and of VOC(-) to $O_3$(+); see IPCC (2007). These are beyond the scope of analysis of this paper.

[4] We disregard VOC in this paper, although it impacts health through ozone formation. Like PM, the exposure to ozone leads to mortality, but instead its' impact is not as large as pollution related to PM. Moreover, it concerns a global air pollutant, which implies that other regions also contribute to Europeans exposure to ozone. Finally, VOC emissions are mainly non-energy related. Thus, there will be less interactions with climate change policies.

Change and Energy Package and because of the economic crisis. Adoption of an up-to-date clean air strategy is envisaged no later than 2013 (EC, 2011).

The EU Climate Change and Energy Package was agreed upon by the European Parliament and Council in December 2008 and became law in June 2009.[5] The EU is also proposing a 30% emission reduction, provided other major emitting countries in the developed and developing worlds commit to do their fair share under a global climate agreement within the United Nations Framework Convention on Climate Change (UNFCCC). Moreover, the EU's Road Map for a Low-Carbon Economy also aims for a more restrictive carbon constraint in the longer term (EC, 2011).

Emissions of air pollutants, such as $SO_2$ and $NO_x$, and GHG are correlated, as both types of emissions are largely caused by the combustion of fossil energy (EEA, 2009). Emissions can be reduced through structural changes in the economy. For example, pricing carbon will generate a fuel switch that lowers the average carbon content of energy use. Further, carbon prices increase energy prices, which in turn may lead to a reallocation of resources towards sectors with a lower energy intensity, and within a sector or household may lead to energy savings that reduce the energy use per unit of output or income earned. The changes in energy demand (including changes in the fuel mix) will be called structural changes in the remainder of this paper. Whereas for carbon dioxide ($CO_2$) structural changes are the major way to achieve emission reductions, emissions of other GHG and all air pollutants can also be abated cost-effectively through 'end-of-pipe' (EOP) options, such as flue gas desulphurization techniques and dust filters on stacks of power stations. Since these emission control options are an 'add-on' to the production process, they remove pollutants largely without affecting the emission-producing activity itself. Air pollution policies in Europe have relied substantially on EOP abatement. Nevertheless, in the past, changes in energy prices themselves led to structural changes, thereby lowering air pollution. But, given the idea that the abatement of air pollutants primarily relies on EOP, while the mitigation of carbon dioxide

[5]This package sets climate and energy targets for 2020. This package plans to reduce the EU's GHG emissions by at least 20% below 1990 levels, to attain a 20% share of its energy consumption from renewable resources, and a 20% reduction in primary energy use compared with projected levels through improved energy efficiency. Plans for the EU's renewable target have yet to be elaborated at the national level.

mainly occurs through structural changes, it is no surprise that the EU chose to decide first on climate policies, and then to design air policy plans.

As the abatement potential of relatively cheap EOP abatement options has been exploited already in the past decades, further emission reductions through EOP have become more expensive. It may be more efficient to aim for reductions of air pollution through structural changes (for example, through a switch from oil to (more expensive but less polluting) natural gas in the transport sector, thus avoiding investments in expensive dust filters in cars and trucks).

This paper analyses cost-effective air pollution policies in the EU based on NEC directives. It shows that stringent air policy generates a structural change, which in turn will reduce the cost of EU climate policies, both for sectors within the Emission Trading System (ETS), the other Non-ETS sectors, and households (NETS).

The analysis employs WorldScan, which is a multi-sector, multi-region, global Computable General Equilibrium (CGE) model, to study the economic impacts of air pollution policies and interactions between climate and air policies. The choice was made for a CGE framework, as there is little knowledge on either the structural changes in the economy from air pollution policies, or from the interactions between climate and air pollution policy in this type of model. The model is set up in such a way that emission reductions can be obtained by both structural changes in the economy as well as by EOP. We argue that this type of analysis produces more realistic mitigation costs than those obtained as a result of relying solely on the direct cost estimates of bottom-up studies. The latter type of analysis may underestimate (or wholly lack) the element of structural change. But such studies also disregard the additional welfare losses from adding policy interventions in a distorted economy (carbon prices on top of existing energy taxes).

This analysis builds upon earlier work. To fully take into account the interactions between climate and air policies, WorldScan (Boeters and Korneef, 2010) was extended to include full coverage of all sources of emissions of non-$CO_2$ greenhouse gases $N_2O$ and $CH_4$, and emissions of air pollutants $SO_2$, $NO_x$, $NH_3$ and $PM_{2.5}$. We use data on emissions of non-$CO_2$ gases and air pollutants of the GAINS model (Wagner and Amann, 2009; Amann et al. 2011). The model here is suitable for simulating multiple emission abatement in a consistent economic modelling framework.

Further, this analysis adds to the work of Bollen et al. (2009a), Burtraw et al. (2003) and Rive (2009). Burtraw et al. (2003) also analysed interactions between climate and air policy, but focused only on the electricity sector. Rive (2009) also focused on the EU, but modelled only one EU region, and neglected emissions and EOP abatement of non-$CO_2$ gases, $NH_3$ emissions from agriculture and $NO_x$ emissions from transport services (either ships, freight, public transport and cars). Bollen et al. (2009a) present the most complete analysis, as they also accounted for the value of air pollution and put both policy issues in the context of an intertemporal cost-benefit analysis—but it lacks details with respect to countries within the EU and to sectors. Summarizing, this paper adds to the literature, as it puts multi-dimensional abatement in a CGE context with much sectoral/regional details.

A drawback of the type of model used is that we cannot simulate precisely the changes of the productions processes at the micro-level that could also be relevant for macro-emission abatement. We nevertheless closely calibrate substance- and time-specific emission coefficients and Marginal Abatement Cost curves (MACs) of bottom-up studies such as the GAINS model (Amman et al., 2009). Applying these, we can use our stylized production functions at the sectoral level (including EOP) to simulate structural changes in economies from combinations of air and climate policies.

Section 2 describes the version of WorldScan that is used for our analyses. This section focuses particularly on the extensions of the model with respect to emissions of non-$CO_2$ greenhouse gases and air pollutants. Section 3 presents the policy cases considered. The results of the simulations appear in section 4. Finally, section 5 discusses the main findings.

## 2. WorldScan

The macro-economic consequences of specific climate or air policy scenarios are assessed using the global applied general equilibrium model WorldScan (see Bollen et al., 2004; Lejour et al., 2006; Wobst et al., 2007; Manders et al., 2008; Hayden et al., 2010; and Bollen et al., 2011). WorldScan data for the base year 2004 were, for the most part, taken from the GTAP-7 database (Badri et al., 2008), which provides integrated data on bilateral trade flows and input-output accounts for 57 sectors and 113 countries and regions. Here we give only a brief sketch of the aggregation level with respect to regions, sectors and the main characteristics of the bottom-up representation of the electricity sector. We conclude with a description of the representation of bottom-up EOP mitigation technologies in the model, which allows simulating cost-effective reduction of emissions of $CO_2$ from non-energy sources and of $CH_4$, and of emissions of $N_2O$ from both energy and process-related sources. This extension allows WorldScan to also simulate what-flexibility with respect to the mitigation of Kyoto-gases. EOP options are implemented for all air pollutants, which is relevant for any air pollution policy.

The renewed version of the model enables simulation of the macro-economic impacts of climate and air policies. In this respect, the main instruments are taxes on pollution and emission targets on IET markets, permit trading in ETS and NETS markets, CDM, subsidies to promote renewable energy, and efficient prices of air pollution.

### 2.1 Overview

The aggregation of regions and sectors can be flexibly adjusted in WorldScan. The version used here features 23 regions and 18 sectors, listed in Table 1. Regional disaggregation is relatively fine within Europe, but coarse outside. The main reason is that the emission ceilings for air pollutants are region/country specific because of differences in the impacts of air pollution on human health and ecosystems. Moreover, the costs and the potential of control options may differ significantly between regions and/or countries.

Likewise, the study focuses on a set of sectors accurately representing the heterogeneous characteristics of activities causing emissions of GHGs and air pollutants, whereas non-polluting sectors are captured in a more aggregated manner. A distinction is made between sectors taking part in the EU emission trading system (ETS, consisting of the electricity and the energy-intensive sector) and sectors and household activities that do not participate in the emission trading system (NETS).

Further, we distinguish five agricultural sectors, because of distinct characteristics with respect to emissions and abatement of air pollutants and of non-$CO_2$ GHGs— and also to be able to appropriately model the production of biofuels (ethanol and bio-diesel). [6,7]

Coal , oil and gas are the primary energy sectors.[8,9] The electricity sector is refined with a detailed electricity technology specification developed by Boeters and Koornneef (2010). Renewable energy is characterised by technologies that are introduced as separate economic activities. Electricity generation technologies are represented by simple, linearly increasing supply functions and are calibrated using existing estimates of cost ranges and potentials. The technology split is determined by equalising marginal costs across technologies. WorldScan captures five concrete electricity technologies: (1) fossil electricity with a flat supply curve, and coal, gas and oil as imperfectly substitutable inputs, (2) wind (onshore and offshore) and solar energy, (3) biomass, (4) nuclear energy and (5) conventional hydropower.

<<<Table 1 around here >>>

WorldScan covers all relevant anthropogenic emissions of GHGs and main outdoor air pollutants. The former type of pollutant includes carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$); the latter category consists of sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), fine particulate matter ($PM_{2.5}$), and ammonia ($NH_3$).

[6] Rice cultivation, livestock production and fertilizer use are linked to the sector *Other agricultural activities*, which is hence a major source of emissions of $CH_4$, $N_2O$ and $NH_3$.

[7] Biodiesel is produced by the sector *Vegetable and oils and fats*, and ethanol by *Sugar beet* in Europe and *Sugar cane* in Brazil, and *Wheat and Corn* in the USA.

[8] The sector *Oil* delivers mainly to *Petroleum Coal Products*, which in turn delivers fuels for one of the two transport sectors or for consumption of the final good *Transport and communication*.

[9] A concordance matrix is used to relate aggregate production sectors to well-known aggregated consumption categories. These final good categories originate from Lejour et al. (2006), and include: [1] Food, beverages and tobacco, [2] Clothing and furniture, [3] Gross rent and fuel, [4] Other household outlays, [5] Education and medical care, [6] Transport and communication, [7] Recreation, and [8] Other goods and services consumed.

WorldScan is set up to simulate deviations from a "Business-As Usual" (BAU) path by imposing specific additional policy measures such as taxes or International Emissions Trading (IET) to it.[10] The emissions of the BAU of air pollutants are calibrated at the lowest region/sector level of WorldScan from an emissions pathway of the GAINS models.[11] All electricity technologies are calibrated to this BAU scenario, and nuclear and hydropower are exogenous in our policy scenarios. As individual electricity technologies are not represented in the input-output tables, the values in the aggregate electricity sector must be split up among them. This is done with three simple assumptions: (1) marginal costs (after taxes and subsidies) are equal across technologies, (2) fossil fuels are used as inputs in fossil electricity generation, but not for the other electricity technologies, (3) all other inputs (capital, labour, intermediate goods and services) are used in proportion to the aggregate shares (as in Boeters and Koornneef, 2010).

### 2.2 Modelling EOP mitigation technologies

*Basic principles of emissions and emission abatement*

$CO_2$ emissions can be easily estimated in a CGE model because $CO_2$ is emitted in fixed proportions to the volume of fossil fuels burned. This is not true for emissions of other pollutants, such as $SO_2$ and $NO_x$. Part of the emissions of these pollutants are not related to fossil fuel combustion, but are caused by, e.g., agricultural activities and waste disposal. A distinction can be made between emissions that are directly related to a specific input to production (such as fossil energy) and those inherent to the production process, independent of the inputs. These 'process emissions' are related to the output level of a sector.

Generally, emission reductions can be achieved not only by more efficient use of inputs (such as fossil fuels), substitution across different inputs (such as a switch from coal to natural gas) and investment in emission control technologies, but also by demand reduction and change in the structure of the economy.

[10] The BAU is not generated by WorldScan itself, but is calibrated to the World Energy Outlook 2009 (IEA, 2009). For more details on the calibration of the BAU, see Annex 1 and Bollen et al. (2011a).

[11] We calibrate emissions coefficients while simultaneously simulating sectoral activities of the BAU.

CGE models have their strength when it comes to demand shifts and changes in the production structure. For $CO_2$ mitigation these are most relevant, but for other pollutants EOP is more relevant.

*Alternative approaches to include emission control in a CGE framework*

The literature provides several approaches for including emission control in a CGE model. The general concept is that actors can choose between paying for emissions and investing in pollution control. Pollution control serves as a substitute to the pollutant emissions, which comes at a cost. The approaches differ in the way in which the abatement costs are incorporated in the model. Hyman et al. (2002) introduced emissions as an input to the production function. The elasticity of substitution between the emissions and the conventional inputs is estimated to match a marginal abatement cost curve that is derived from detailed bottom-up studies (see Hyman et al., 2002; Reilly et al. 2002). Gerlagh et al. (2002) and Dellink et al. (2004) introduced for each pollutant an abatement sector producing mitigation technologies in a region. Emission reductions can be achieved by increasing the input of abatement goods. The elasticity of substitution is estimated to fit the data on abatement cost of measures as available from various data sources. Rive (2010) included abatement in a CGE model by source-specific technology steps, each step representing groupings of abatement technologies with similar marginal abatement costs. This offers a flexible treatment that can incorporate activity- and pollution-specific marginal abatement cost curves of different shapes from bottom-up studies.

*Emissions and emission control in Worldscan*

Emissions from combustion of energy are calculated as a fixed proportion of the amount of fossil fuel use. Emissions related to the use of chemical fertilizer in agricultural production are similarly calculated, using the intermediary input from the chemical sector to the agricultural sector as a proxy for the amount of fertilizer used. This is illustrated by the nesting of the production function in Figure 2.1. Emissions that cannot directly be linked to a particular input into the production process are included in the model as process emissions (they are thus linked to the sectoral output, the top of the production function nest).

<<< Figure 2.1 around here>>>

Worldscan introduces the possibility of investing in emission control by modelling abatement technologies for each type of emission (input-related and process) in each sector. Omitting here indices for region-sector-activity-substance specifics, the supply function reads as follows:

$$c(a)=\left[\alpha\cdot\left(\bar{a}-a\right)^{-\beta}-\gamma\right]\cdot\sum_i \delta_i p_i \quad . \qquad (1)$$

*c(a)* gives the marginal cost of abatement as a function of *a*, the level of abatement as a percentage of ‘unabated emissions’, i.e. emissions as they would occur without emission control. $\bar{a}$ is the maximum level of abatement, $\alpha$ and $\beta$ are parameters (both > 0) and $\gamma$ is a constant that determines the initial level of the marginal cost $c(0)$. $\delta_i$ are input coefficients and $p_i$ prices of the inputs *i*, indicating the share of the various inputs required to produce abatement in the cost. The parameters $\delta_i$ are the fixed value shares of the inputs of the Capital goods sector. If wages rise, however, then this may also increase the marginal costs of abatement proportional to the labour share of production of the Capital Goods sector. This functional form is used because it offers adequate flexibility to approximate empirical abatement cost curves.[12] The total cost curve is

$$C\left(a\right)=\bar{e}\cdot\left[\alpha\cdot\frac{\bar{x}^{1-\beta}-\left(\bar{x}-x\right)^{1-\beta}}{1-\beta}-\gamma\cdot x\right]\cdot\sum_i \delta_i p_i \quad , \qquad (2)$$

with $\bar{e}$ the level of emissions as they would occur without emission control. These unabated emissions are calibrated to a BAU, derived by a bottom-up model (GAINS, in this paper), and emission coefficients are equal to the ratio between the emissions of a specific activity and the simulated level of that particular activity. However, in a policy scenario, we fix the emission coefficient, but not the activity, and therefore the unabated emissions level $\bar{e}$ may change. This feeds into equation 2, and therefore a fixed set of abatement options may yield different levels of abatement depending on whether $\bar{e}$ changes compared to the base year.

[12] More details on an example of the calibration of MACs are provided in Annex 1.

The functional form is flexible, in order to approximate a large range of MAC curves. The values of the parameters $\bar{a}$, $\alpha$, $\beta$, $\gamma$ and $\delta_i$ are estimated from a set of MAC curves from GAINS, which is based on the set of mitigation options of the ranges spanned by Maximum Feasible Target Reductions (MFTR) in addition to those measures necessary to comply with the Current Legislation in 2020 (see Amman et al., 2010).

Using sector-specific abatement supply makes it possible to take into account differences between sectors with regard to the possibilities and costs of reducing emissions. This seems to be of particular interest if environmental policies are differentiating between sectors—such as is the case in the EU, where climate policy sets different targets for sectors within ETS and NETS. Moreover, as emission reductions are expressed relative to 'unabated' emission levels, changes in emissions that result from changes in production structure or output levels will proportionally lead to changes in the abatement potential by emission control options.

Rive (2010) limited EOP abatement to a small number of discrete steps and disregarded sources of emissions of e.g. the transport sector. By using equation 1 as our format for a MAC, we can deal with many curves and a wider domain of abatement in sectors and countries without an excessive computational burden. Hence, we can put real numbers to the economy-wide allocation of resources between EOP and structural changes—i.e. to consider air pollution that covers all anthropogenic emission sources, not just those of some major electric power stations. We realize that the equations above are an approximation, we think that we gain in terms of realism of the analysis by also mimicking the EOP costs of very expensive options (the MFTR potential and beyond).

## 3 Policy cases

We assess the impacts of several policy cases up to the year 2020, with a particular focus on emissions and prices of emissions on ETS and NETS markets, on country specific air pollutant prices that meet a pre-specified set of NECs, and on competitiveness and welfare. In this paper, welfare is the Hicksian Equivalent Variation (HEV) to compensate for any losses of utility with respect to the baseline without any policies, and measured as a percentage of National Income. Any damage valuation of the environmental state or benefits from improved environmental quality of policy interventions is not included in this indicator.

<<<Table 2 around here>>>

The air pollution policies are variants of the TSAP, which are presented for EU-27 in Table 2. We chose three variants of Amman et al. (2007), in increasing order of stringency compared to the BAU: European Commission (EC), European Parliament (EP), or Cost-Benefit Analysis (CBA).[13] The variants serve to achieve multiple goals of mitigating mortality from the chronic exposure to particulate matter and ozone, and the more traditional environmental problems of acidification and eutrophication (see EC, 2011). The targets are formulated in improvements with respect to the year 2000. The last row of Table 2 refers to an emissions index of Particulate Matter Surrogate (PMs).[14] This indicator reflects the emissions of air pollutants $SO_x$, $NO_x$, $NH_3$ and $PM_{2.5}$ relevant for the build-up of outdoor concentration of fine particulate matter. We chose to present this single indicator because it summarizes the emissions of air pollution. Further, Holland et al. (2007) show that the value estimate of avoided mortality impacts from lower concentrations of particulate matter from policy interference accounts for 80% of all the air pollution benefits in Europe. Although we present here only the emission targets for EU27, it should be noted that country- and substance-specific targets are below this aggregate index (more details in section 4.1).

Mortality from the chronic exposure to ozone is also relevant for air pollution, but is a global externality and hence will be less affected by EU mitigation plans.[15] Table 2 also shows that acidification of

[13] The variants EC, EP, and CBA were taken from Wagner et al. (2010), Amman et al. (2008), and Amman et al. (2005), respectively. The CBA variant equalizes the difference of direct costs from GAINS and benefits of stringent air policy at the margin, as reported in Holland et al. (2005). These numbers can be provided upon request.

[14] PM surrogate (PMs) is the weighted sum of air pollutants with weights 0.54, 0.88, 2.0, and 0.64 for $SO_x$, $NO_x$, $PM_{2.5}$, and $NH_3$, respectively. The weights are based on de Leeuw (2000).

[15] Although part of the TSAP, the VOC emission reduction plans relevant for ozone formation are disregarded here because they hardly affect the analysis. Ozone formation is driven by global changes in concentrations of

ecosystems in Europe will improve considerably when implementing EC, but it's worth noting that around 55% reduction is already foreseen in the existing reduction plans (Current Legislation Emissions scenario in Amman et al., 2004). Other options than mitigation of emissions will be necessary to further lower acidification in Europe. Eutrophication is more than acidification driven by the deposition of nitrogen, and as $NH_3$ mitigation is relatively more expensive than $SO_2$ mitigation, the eutrophication improvements (% ecosystem area exceeded) are lower.

Although we realize that the EU's Climate and Energy package has already been promoted to legislation, we start with the analytical "clean" option of only air pollution variants based on EU countries pursuing multiple national ceilings for air pollutants without having to reduce any GHGs. We show here the impacts of the most stringent set of proposed NECs (i.e. CBA and the more relaxed variant of EP).

Further, the next three cases introduce the ambitious climate-change-related pledges made by countries up to the Copenhagen Climate Change Conference in December 2009 (thus, the third AMBITIOUS PLEDGES (without air policies) scenario, the fourth AMBITIOUS PLEDGES + CBA variant, and the fifth policy case relaxes on the ambitions of the air policy: AMBITIOUS PLEDGES + EP).[16]

Next, we analyze the less stringent climate policy of the EU solely implementing its Energy and Climate Package with the renewable target (EU PLEDGE) and without this target (EU GHG).[17] These climate policies are combined with the two earlier air targets, but also extended with EC. Thus, eight cases are designed: EU PLEDGE + CBA, EU PLEDGE + EP, EU PLEDGE + EC, and EU PLEDGE and likewise without EU's renewable target: EU GHG + CBA, EU GHG + EP, and EU GHG + EC, EU GHG.

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tropospheric CO, from emissions of $CH_4$, $CO_2$, and then at the regional level at the stratosphere affected by emissions of $NO_x$ and VOC; see also Bollen et al. (2009b).

[16] Annex I countries ambitiously adopt relatively low caps on GHG emissions and allow free permit trade amongst each other. Further, in this scenario China and India impose relative targets for $CO_2$ emission intensities of 45% and 25% below 2005 intensities. The EU imposes a 30% GHG emission target, and a 20% share of renewable energy in final energy use.

[17] The EU PLEDGE excludes the use of CDM, but assumes permit trade with one uniform carbon price in ETS and one in NETS markets in the EU. Again, the EU imposes a targeted 20% share of renewable energy in final energy use.

The AMBITIOUS PLEDGES scenario assumes a completely different institutional setting of climate policies than EU PLEDGE (i.e. all Annex-1 countries establish an international IET system leading to a single uniform carbon price throughout Annex 1). For analytical purposes, we introduce the EU25% scenario that assumes that the EU's GHG reduction is equal to 25% (instead of 20% of EU PLEDGE).

# 4 Results

Section 4.1 analyzes the marginal costs of abatement of stringent air policies (CBA) for different air pollutants and the welfare impacts for countries. Then, we relax the stringency of the air targets, and show how structural changes in the economies of the EU-27 induced by air targets serve to reduce the GHG emissions, and how this compares with Europe's GHG emission reductions of the EU PLEDGE and AMBITIOUS PLEDGES. Next, section 4.2 explicitly introduces climate policies, which makes it possible to analyze the interaction between air pollution and climate policies. We show how not only prices in ETS and NETS markets in Europe but also welfare are affected through combinations of ambitious and less ambitious targets for climate policy (30 and 20% targets for GHG, and with or without a renewable target for final energy) and air policy (based on CBA, or proposals by the European Parliament or the European Commission). Finally, section 4.3 brings together the results of all policy variants.

## 4.1 Co-benefits of stringent air targets significant

This section presents an overview of what the impacts in 2020 will be of imposing national ceilings in different EU countries based on CBA. We illustrate here the extent to which air policies alone may provoke structural changes in economies in the EU. While we realize that the EU designed its Climate and Energy Package for 2020, this case nevertheless serves as a benchmark for the results of the other cases presented in this paper. Figure 2 presents the marginal costs of abatement of $SO_2$, $NO_x$, $PM_{2.5}$, and $NH_3$, and the welfare losses measured as a percentage of national income.

<<<Figure 2 around here>>>

The figure shows clearly that welfare losses will be the largest in the new Member States of the EU (Poland: 3%; rest of EU-27: 2%). The main reason is that emissions per unit of GDP in these countries will be higher by a factor of four compared to average of the EU27.[18] Hence, the relatively low marginal costs of abatement (non-zero for all substances) necessary to meet the national ceilings will generate

[18] For all countries we weigh emissions of the different substances according to de Leeuw (2000) to represent emissions relevant for mortality from the chronic exposure to $PM_{2.5}$, and divide this emission index by BBP.

large distortions in these economies. The next group of countries with more moderate welfare losses are Italy (1%) and Spain (0.8%). The losses in these countries are mainly stemming from the high marginal costs of abatement compared to the other countries. Germany also has high marginal costs for $SO_2$, but their welfare losses are less than those in Italy and Spain. In Germany, the air policy mainly affects the electricity sector, whereas in Italy and Spain more gases are taxed and there are higher costs associated with transport services. The latter factor will push up the welfare losses because of interactions of the air policy with existing oil taxes in the baseline. The numerical importance of this argument is provided by Klepper and Peterson (2006).

<<<Figure 3 around here>>>

Figure 3 presents for all EU countries in WorldScan the changes in emissions of GHGs and air pollutants as a consequence of of the air policy to match the ceilings of the CBA variant for the same countries as in Figure 2. The circles represent the emissions reductions implied by the targets of the EU Energy and Climate Package (20%) and Ambitious Pledges (30%).

It can be seen that stringent air goals have a large indirect impact; such a policy leads to reductions of the GHG emissions. The air policy targets of reducing 20% of the emissions of $NO_x$, $PM_{2.5}$, and $NH_3$, and 45% of $SO_2$, lead to a 25% GHG emission reduction alone! The reason why (the exogenous) $SO_2$ emissions reductions are much larger than for the other pollutants is that they contribute more significantly to health than the other substances. The emission reductions for $NH_3$ are significant as well, because ammonia per kg contributes more significantly to health damages than $NO_x$, and hence EOP options in agriculture are effective as well (de Leeuw, 2000; Holland et al., 2005). Stringent air policies generate a climate change co-benefit that is larger than what climate targets of the Energy and Climate Package aim at. For each substance it can be seen that the share of the contribution of EOP to abatement is limited, keeping in mind that the maximum feasible reduction potential is at most a factor of two higher than the actual reduction. Sixty-six percent of the $SO_2$ emission reductions are generated from structural changes. Rive (2010) estimated this to be a 30-50%. The reason why we produce more structural changes is that the marginal costs of end-of-pipe abatement are higher. The main reason is that the $SO_2$ emissions reduction effort in this paper is higher by about a factor of three. Next to that, there is also more abatement in our BAU. The low-hanging fruit is excluded from our policy simulations, thus leaving Europe with more expensive reduction options.[19] .Consequently, it is hardly surprising that there are significant GHG emissions reductions as a co-benefit from these policies.

The indirect GHG emission reduction (co-benefit) of stringent air policies come from Germany, Poland and the other accession countries, because air pollution abatement in these countries is cheaper. Actually, the indirect co-benefit of the air policy is larger than the GHG emission reductions pledged by the EU. The other countries can be seen to do less GHG abatement from their air policies (especially the Netherlands) because they already implemented the cheap abatement options. Despite the fact that EOP to total abatement is large in Eastern European countries, there are sufficiently low (energy) prices of polluting activities in the economy to generate a substantial structural improvement, which in turn leads to the significant co-benefit to climate change.

### 4.2 Even moderate air targets have impacts on climate change policies

The previous section argued that structural changes in the economy unfold only if only air pollution policies were to take place (and no additional climate change policies). This section abandons this assumption, and analyzes the impacts of air targets on climate change policies. Figure 4 presents the changes of emissions in EU27 related to the GHG's and air pollutants of various policy scenarios. These scenarios are the air policies to meet the ceilings of the CBA and EP, and the combinations with climate policy: i.e. AMBITIOUS PLEDGES with air targets (+EP, +CBA, or no air targets). The circles represent the emissions reductions implied by the targets of the AMBITIOUS PLEDGES and EU PLEDGE.

[19] The SO2 emission level of NEC in Rive (2010) is comparable to the level of our BAU. Hence, the NEC10 calls for an extra 15% SO2 emission reduction compared to NEC. This paper follows CBA and EP, which leads to a 40-50% emission reduction.

<<<Figure 4 around here>>>

The AMBITIOUS PLEDGES scenario yields a 15% GHG emission reduction (that is, half of the necessary emission reductions will be imported from international permit markets at a price of approximately 10 €/t$CO_2$ eq.). Hence, unsurprisingly, CBA provokes a larger climate co-benefit (a 22% GHG emission reduction) than EU's contribution to the climate in the AMBITIOUS PLEDGES scenario (18% GHG emission reduction). Note also that EP approximates the GHG emission reduction of the AMBITIOUS PLEDGES case. Adding climate to air policies magnifies GHG emission reductions of the air policy (compare AMBITIOUS PLEDGES + CBA with CBA and AMBITIOUS PLEDGES + EP with EP). AMBITIOUS PLEDGES + CBA eliminates EU trade in permits. The domestic marginal costs of $CO_2$ abatement go down and come close to the international permit price.

Finally, whereas stringent air targets have climate change co-benefits in the range of the GHG reductions of the variants of EU PLEDGE and AMBITIOUS PLEDGES, the air quality co-benefits of climate change policies are 50% of the benefits of the EP variant. In other words, the EU policymaking concentrates on climate change policy, which will reduce only half of the potential number of premature deaths from air pollution policies of CBA; it is the other policy perspective of air pollution that will lower the number premature deaths much more, and will generate GHG emissiobn reductons as envisaged by EU's climate pledges.

Next, Figure 5 presents the changes in primary energy use in EU27 from the more relaxed climate policy (EU PLEDGE), combined with air ceilings of either the CBA or EP variant. Primary energy use is split up in oil, gas, coal and non-fossil energy carriers (nuclear, wind, sun and biomass).

<<<Figure 5 around here>>>

The figure confirms the main result of this paper that seeking only to achieve air targets without pursuing any climate policy goals will already substantially restructure the economy of the EU27. The response is to switch away from fossil fuels and save on energy by 10-15% of total primary energy use (EP and CBA variant). The structural changes of the CBA variant can be seen to be larger than those of the EU Pledge. Also, we see that imposing air targets in line with CBA generates reductions in coal (from 5 to 8%) and oil (from 1.5 to 3%), which is driven by the stringency of the $SO_2$ target for ETS and the $NO_x$ and $PM_{2.5}$ targets for oil in transport sectors. The increase of non-fossil energy demand occurs only when the renewable target is explicitly applied. Otherwise, energy saving seems to be cheaper and dominates the impacts on energy markets, see also Boeters et al. (2010). Finally, it can be seen that gas is affected more than oil in all variants, whereas oil contributes relatively more to pollution (carbon intensity is approximately 1/3 higher, and for air pollutants this is often much higher). The reason is that current energy taxes on oil are generally higher; additional taxation therefore has a lower impact on end-user prices, thus lowering also its impact on demand.

<<<Figure 6 around here>>>

Figure 6 brings together the impacts on welfare and prices on ETS and NETS markets of air policies in addition to the climate policies (AMBITIOUS PLEDGES and EU PLEDGE with and without the renewable target). The left-hand panel of Figure 6 shows the impacts of air policies on welfare, whereas the right-hand panel shows them on the prices in €/ t $CO_2$ eq. The stringency of the air targets are plotted on the x-axis of both panels; the left-hand side starts with no air policies (0%), then the EC variant (at around 60% of the total CBA abatement effort), the EP variant (around 70%), and finally the CBA variant (100%).

Clearly, constraining emissions of air pollutants of the EC variant in addition to climate policies has little impact on welfare and carbon prices (only NETS will go down from 8 to 3 €/ t $CO_2$ eq.). The left panel of figure shows that the welfare losses will be 0.1%-point lower without the renewable target. The reason is that this target is binding, and comes at the expense of  an additional subsidy on sustainable energy carriers (solar, wind, and biomass) amounting to as much as 20-24% of the user price (either electricity or biofuels).[20] The losses of the AMBITIOUS PLEDGES and EU PLEDGE are approximately the same. On the one hand, the carbon price of the AMBITIOUS PLEDGES is lower than that in the EU PLEDGE, but on the other hand, the terms of trade gains diminish and the compliance costs (at fixed reductions) increase as other countries also impose a climate policy.

Only more stringent air targets generate significant impacts. The welfare losses of the climate policies (0.4-0.5%) are increased greatly when an air target is imposed (another 0.2%-point loss at the most in the CBA variant). In those scenarios the air targets are binding, and even replace the tax distortions of the climate policy. The ETS price drops from 17 to 11 and 0 €/ t $CO_2$ eq by moving from no air targets to EP and CBA. ETS as an instrument of climate policy may even become obsolete. This doesn't mean that innovation in sustainable energy grinds to a halt— as the renewable subsidy will remain at least at 20% of the end-user price— but the tax distortion becomes different in nature (switching from $CO_2$ to $PM_{2.5}$ and $NO_x$).[21] The NETS sectors' price response is relatively large to air pollution policies. The main reason is that the transport sector as part of NETS will be confronted with more binding targets than ETS sectors when also confronted with air policies.

Summarizing, air targets will lower carbon prices substantially—and especially when air targets are more binding than EP, ETS markets stop functioning. Welfare losses depend on the stringency of the air target, and those of the air policies analysed in this paper are lower than those of the climate change policy options, especially if analysed in addition to the current climate policies.

## 5. Discussion

[20] Boeters et al. (2010) also estimated the climate costs of the renewable target to be in the range of 0-30% of the total welfare loss. This paper produces a slightly higher cost estimate than their benchmark case because of lower shares of renewable energy in the BAU (10 versus 15%).

[21] See also a detailed example of coal-fired powerplants in New Member States (excluding Poland) in Annex 1.

Here we  bring together the results of the main policy variants. Table 3 presents the impacts of the various scenarios on welfare, emissions of PMS in the EU (resembling the aggregate representative air pollutant in this region) and of the global $CO_2$eq, and the ETS permit price.

<<<Table 3 around here >>>

From the climate policy perspective, the EU PLEDGE is the benchmark. The next steps for the year 2020 in EU policy could involve extra climate policies or air policies, or a combination of both. In the case of climate change policies there are two realistic possibilities. There may be a 25% cut in GHG emissions in the same institutional setting as the EU PLEDGE scenario or there may be a 30% cut in GHG emissions as in the AMBITIOUS PLEDGES scenario. The latter scenario also assumes the most stringent targets as pledged by the other Annex-1 countries with full free permit trading amongst these countries. Table 3 reveals that the impact on global GHG emissions in 2020 in any scenario is limited, implying that little substantial climate change improvements. The co-benefits are changes in stylized indicator labelled PMS, with an extra 2% reduction if the EU moves from a 20 to 25% cut in GHG emissions. If, however, the EU switches to free permit trading once the carbon coalition expands, then the trade-off occurs with an extra global GHG emission reduction of 2.3%, while PMS emissions increase by 2%-points because where-flexibility enables to reduce less on carbon. The magnitude of the impacts on emissions may be uncertain, but the trade-off is robust if where-flexibility holds. The ETS carbon price drops in the AMBITIOUS PLEDGES scenario to 10 €/ $tCO_2$, while welfare is unaffected, because lower mitigation costs are offset by lower terms-of-trade gains.

Next, we observe that the EP scenario reduces the ETS price by 40% and the emissions of PMS by 10% at lower costs (only 0.05% of NI). The benefits of avoided air pollution damages will be significant as well. The EP air pollution policy seems to be superior to additional climate policies. The EP policy aims to bring significant improvements in air quality in Europe in areas that affecting people's health directly, whereas EU25% is almost as expensive, but brings fewer gains. This stylized fact also is confirmed by a cost-benefit analysis on climate change and air pollution in Bollen et al. (2009a), and Bollen et al. (2010).

The EU PLEDGE + CBA scenario is a further reduction of PMs emissions, and represents an ambitious step in environmental policy. At the same time, it can be argued that this step needs to be taken in order to come into line with the EU's already ten-year-old ambition of fully clean air for all European citizens. The EU PLEDGE + CBA scenario entails a further reduction of the global GHG emissions (0.1% $CO_2$ eq.) with non- binding GHG targets on ETS markets (more coal reductions) and non-ETS sectors (more oil reductions in transport) and a binding renewable energy target. Nevertheless, the renewable subsidy reduces by 10%, as more fossil energy reductions make it possible to reduce also on biomass because the target is formulated as a 20% share and it produces PM emissions. However, the CBA strategy lowers the ETS market price considerably. Companies under ETS have to comply also with binding targets on $SO_2$, $NO_x$ and $PM_{2.5}$, and hence new coal-fired power stations become too expensive compared to the non-fossil alternatives.

The negotiations within the EU and UN-ECE on air pollution will start this year and be finalized by 2014, and some options for policy can be investigated with the model designed for this paper. With some modifications, the model can also be used to optimally allocate emission ceilings across EU countries that maximize the health benefits of avoided premature mortality associated with the chronic exposure to outdoor PM. Although we cannot fully address all of the detailed impacts of bottom-up models such as GAINS, we nevertheless can shed some light on the structural adjustments in energy markets and the EU-economy from climate and air policy variants.

Recall from Table 3 that the ceilings based on CBA reduce by 53% the number of Years of Life Lost (YOLL) in EU27 in the year 2000. The reduction of the number of YOLL in the CBA scenario (compared to the EU PLEDGE scenario) is equal to ?? mn YOLL in a period of ten years. This improvement, multiplied by the very conservative estimate median value of YOLL (52000 € per YOLL) is equal 0.?% of NI, which is a factor x higher than the compliance costs of 0.25% NI. The CBA in addition to the EU PLEDGE generates more benefits than costs, and further reductions may show the same . This is also confirmed by Bollen et al. (2009a). Additional climate policy will be less effective than air policies, because the air pollution improvements are much smaller (almost nothing), and the climate impact (i.e. on global $CO_2$ eq. emissions) is insignificantly different from that achieved by the air policy.

This paper focussed on Europe, but employed the WorldScan model, which has global coverage. The database developed for this paper also calibrates air pollution emission coefficients and EOP abatement options for China and the US, and can also be used to investigate air pollution policies in all of these regions in a global international trade context. We would expect, in particular, that air pollution policies in China impact fossil energy markets and prices, and hence may have an effect on other countries' economies and environmental policies. This topic will certainly have to be addressed in future research.

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## Annex 1: Calibrating WEO 2009 as a Business-As-Usual Scenario

The effects of climate policy depend strongly on the underlying baseline. The policy scenarios developed in this paper are based on the baseline of the 2009 World Energy Outlook (WEO, IEA, 2009). With our baseline we deviate from the WEO-baseline in one respect, however. We removed the ETS-caps from the WEO in order to establish a level playing field for our assessments of the mitigation pledges in an international context.

The baseline calibration employs trends for population and GDP by region, energy use by region and energy carrier, and world fossil fuel prices by energy carrier. Population is exogenous, but the other time series are reproduced by adjusting the model parameters. GDP is targeted by total factor productivity (differentiated by sector), energy quantities are targeted by energy efficiency, and fuel prices are targeted by the amount of natural resources available as input to fossil fuel production. In policy variants, total factor productivity, energy efficiency, and natural sources are fixed exogenously, and GDP, energy use, and energy prices are endogenous variables.

According to our baseline, the global population will continue to expand. Combined with worldwide economic growth of 2.7% per year, global demand for energy will be almost 30% higher in 2020 than in 2004. As described in WEO2009, the effects of the financial and economic crisis are included and have a large impact on medium-term economic growth rates. This expansion predominantly takes place in Non-Annex I, thus partially reducing the gap in energy consumption per capita with the industrialized countries. Table 2.1 gives some key overview characteristics of the baseline for the 2004-2020 period. The table indicates that in the baseline energy- and GHG intensities are declining worldwide and especially in Non-Annex I. In principle, our baseline follows the fossil fuel price projections of WEO2009 (e.g. the oil price will reach 100 US$ per barrel in 2020). In Europe, the gas price is expected to lag behind the oil price. Regional coal prices are expected to remain constant at their 2009 level.

Basically, the main difference between the WEO baseline and our baseline is increased energy consumption in the EU (due to the lifting of ETS caps) and reduced energy consumption elsewhere (due to somewhat higher fossil fuel prices). Table A.1 in the Annex provides the differences in characteristics of both baselines.

<<Table A.1 around here >>>

PM

## Annex 2: How EOP works in WorldScan: an example

Environmental policies are implemented in the model by introducing a price on emissions (Lejour et al., 2006). This emission price makes polluting activities more expensive, and provides an incentive to reduce these emissions. For emissions directly related to the use of a specific input, such as fossil fuels, the emission price in fact causes a rise in the user price of this input. Consequently, this leads to a fall in the demand for it and hence a reduction in emissions. For emissions related to sectoral output levels, the emission price causes a rise in the output price of the associated product. Consequently, this leads to a fall in demand for it and hence in a reduction in emissions. Moreover, if emission control options are available, these will be implemented up to the level where the marginal cost of emission control equals the emission price. The emission price can be introduced exogenously, but it is also possible to set a restriction on emissions in the model. In this case, the emission price is endogenously determined in the model at the level needed to reduce emissions to the predetermined emission target.

For illustrative purposes, we elaborate on the effect of a restriction on emissions of greenhouse gases and on $SO_2$ emissions for a specific sector (coal-fired power plants in the New Member States (excluding Poland)). Table A.2 presents some relevant results for this sector. In the baseline, 2020 emissions of greenhouse gases are 109 Mton. The EU PLEDGE scenario leads in permit trade in ETS markets, leading to a price on GHG emissions of €17/ton $CO_2$-eq, but likewise the renewable target leads to a renewable price equal to 24% of the user price (not shown in Table A1, but important to keep in mind) . This emission price is translated into a mark-up on the market price of fossil fuels of 71% (i.e. the user price of coal for coal-fired power plants in Italy doubles). Also the price of oil and gas rises, so electricity becomes more expensive and hence the demand for electricity in the New Member States (excluding Poland) declines by 7%. Because $CO_2$ emissions per energy unit are larger for coal than for oil and gas, the demand for coal will fall more than proportionally: 63% (16 Mtoe). As a result of the decline in the use of coal, the associated GHG and emissions will decline by 65%. As a co-benefit of climate policy, $SO_2$ emissions will also be reduced.

Reductions in emissions of GHGs from coal-fired power plants in the new Member States (excluding Poland) can also be achieved (to some extent) by end-of-pipe abatement. The abatement cost curve in Figure A.1 shows that at a marginal cost of €31/ton $CO_2$-eq., the $N_2O$ emissions from coal-fired power plants can be reduced by 74%. $N_2O$ emissions in the climate policy case amount to 2.4 Mton $CO_2$-eq., so a reduction of 1.8 Mton can be achieved by implementing end-of-pipe control. So, the overall reduction of GHG emissions from coal-fired power plants is 75%, which consists of a 74% reduction as a result of reduced use of coal and an additional 1% reduction as a result of end-of-pipe abatement of $SO_2$ emissions.

<<<Table A1 around here>>>

Policies for air quality improvements are implemented by introducing, in addition to the GHG emission reduction target, a restriction on emissions of $SO_2$ in the new Member States (excluding Poland). This results in an emission price for $SO_2$ of €13/kg $SO_2$. Coal being an important source of $SO_2$ emissions, the price on $SO_2$ emissions causes the price of coal to increase by 44%. As a result, the demand for coal falls by another 11% (74-63%), and consequently also the associated emissions of $SO_2$. As a co-benefit of this air policy, also emissions of GHGs fall by the same percentage.

The $SO_2$ emission price also induces investment in $SO_2$ emission control. The abatement potential is limited (about 30% of total $SO_2$ emissions from coal-fired power plants) because to a large extent emission control already is implemented in the baseline. The abatement cost curve in the right-hand panel of Figure A.1 indicates that at a marginal cost of €86/kg, 19% of the $SO_2$ emissions (i.e. the emissions that remain after the fall in coal use) can be reduced by emission control.

The fall in GHG emissions makes it much easier to meet the GHG emission reduction target. An emission price of €11/ton $CO_2$-eq. now is sufficient to meet the ETS reduction target (note that since the ETS target concerns not only power plants in the new Member States (excluding Poland), but also emissions from all ETS sectors in the EU, this price fall is not uniquely caused by the co-benefit of $SO_2$ reduction in the coal-fired power plants in the new Member States (excluding Poland); similar co-benefits occur in other sectors and other countries). Since this price is below the initial marginal cost for end-of-pipe abatement of $N_2O$ (see left-hand panel of Figure 3.1), no end-of-pipe abatement of GHG emissions takes place. Note that with climate and air policies together, the coal-fired power plants contribute more to the total ETS reduction target (i.e. they will have to purchase fewer emission permits) than in the case with climate policy only (28 vs. 38 $CO_2$-eq.).

## Annex 3: Mapping from GAINS to GTAP-VII

<<<here Table A.3>>>

**Table 1 Overview of regions, sectors and technologies and production inputs in WorldScan**

| *Regions*[a)] | *Sectors*[b)] | *Inputs*[b)] |
|---|---|---|
| Germany | Cereals (Wheat and Cereal Grains NEC) | *Factors* |
| France | Oilseeds | Low-skilled labour |
| United Kingdom | Sugar Crops (Sugar Cane, Sugar Beet) | High-skilled labour |
| Italy | Other Agriculture | Capital |
| Spain | Minerals NEC | Land |

| | | |
|---|---|---|
| Netherlands | Oil | Natural resources |
| Other EU15 | Coal | |
| Poland | Petroleum Coal Products | *Primary energy carriers* |
| Rest of EU-27 | Natural Gas (incl. gas distribution) | Coal |
| Norway | **Electricity** | Petroleum, coal products |
| Switzerland | **Energy Intensive (incl. Chemical Products)** | Natural gas |
| Russia | Vegetable Oils and Fats | Modern biomass |
| Ukraine | Consumer Food Products | |
| USA | Other Consumer Goods | *Other intermediates* |
| Canada | Capital Goods and Durables | Cereals (Wheat & Cereal Grains) |
| Japan | Road and Rail Transport | Oilseeds |
| Australia | Other Transport (water and air) | Sugar Crops (Sugar Cane&Beet) |
| New Zealand | Other Services | Other Agriculture |
| *Brazil* | | Minerals NEC |
| *Middle East and North Africa* | *Electricity Technologies* | Oil |
| *China (incl. Hong Kong)* | Conventional fossil (without CCS) | Coal |
| *India* | Fossil with CCS | Petroleum Coal Products |
| *Rest of the World* | Nuclear | Natural Gas (incl. Distribution) |
| | Wind | **Electricity** |
| | Biomass | **Energy Intensive (incl. Chemical Products)** |
| *Substances* | Hydropower | Vegetable Oils and Fats |
| $CO_2$ | | Consumer Food Products |
| $CH_4$ | *Conventional biofuel technologies* | Other Consumer Goods |
| $N_2O$ | Ethanol | Capital Goods and Durables |
| | from sugar beet | Road and Rail Transport |
| $SO_2$ | from sugar cane | Other Transport (water and air) |
| $NO_x$ | from wheat | Other Services |
| $NH_3$ | from corn | Biodiesel |
| $PM_{2.5}$ | Biodiesel | Ethanol |

[a] Non-Annex I regions are denoted in italics
[b] ETS-sectors and inputs denoted in bold

**Figure 1 Production structure with $CO_2$, $CH_4$ and $N_2O$ emissions**

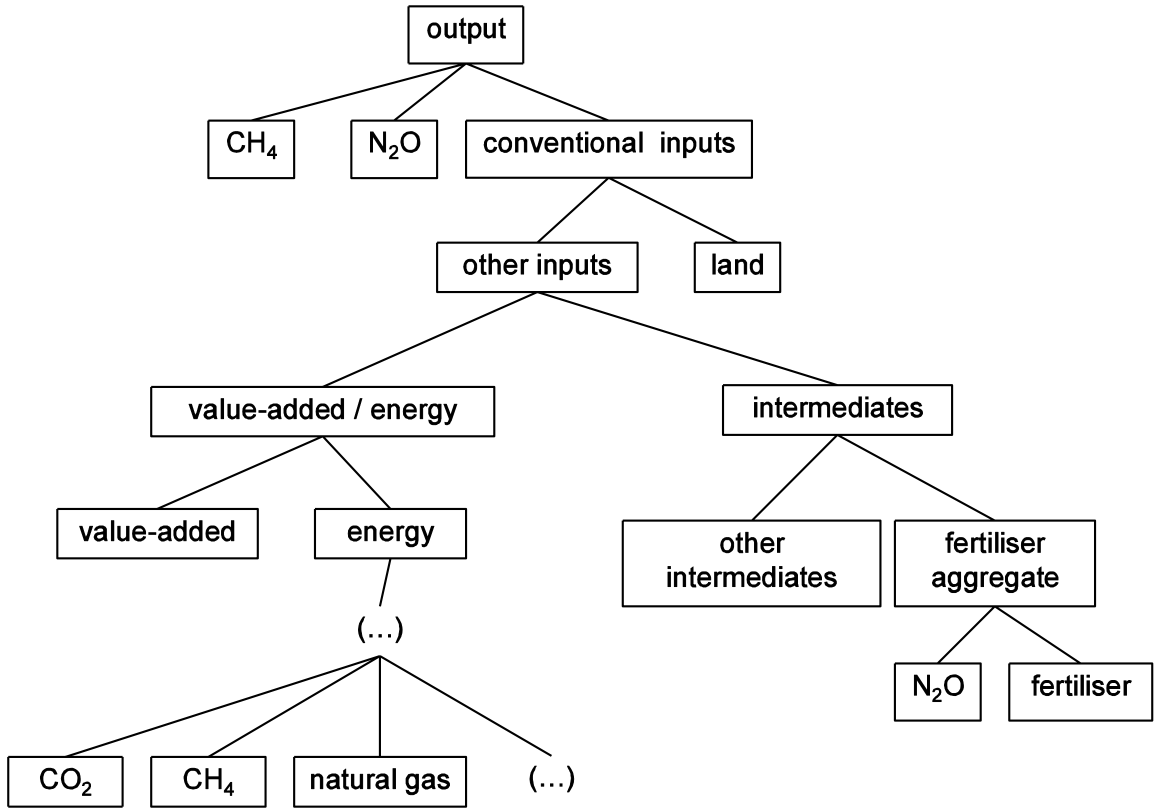
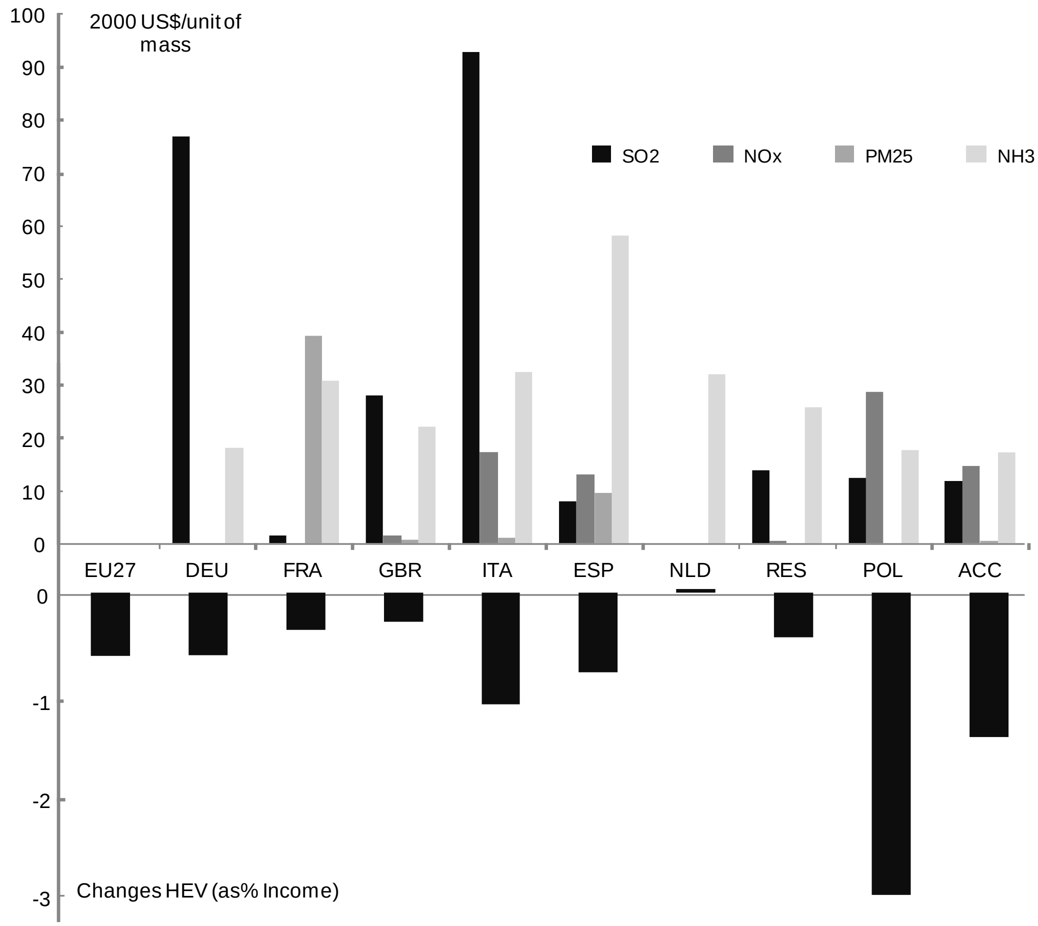


**Table 2 Ambition levels for TSAP strategies (% reductions compared to the year 2000)**

| | EC | EP | CBA |
|---|---|---|---|
| Life Years Lost from particulate matter | 47 | 50 | 53 |
| Acute mortality from ozone | 10 | 16 | 24 |
| Acidification - ecosystem forest area exceeded | 74 | 79 | 79 |
| Eutrophication - ecosystem area exceeded | 43 | 46 | 53 |
| PMS* | 55 | 58 | 62 |

Source: Own calculations based on EC (….); PMS is weighted sum of air pollutants with weights equal to 0.54, 0.88, 2.0, and 0.64 for $SO_x$, $NO_x$, $PM_{2.5}$, and $NH_3$, respectively.

**Figure 2 Impacts of CBA Ceilings on Emissions price and National Income**




Note: SO2 price in / kg SO2

**Figure 3 Impacts of CBA Ceilings on Air Pollutant and GHG Emissions**

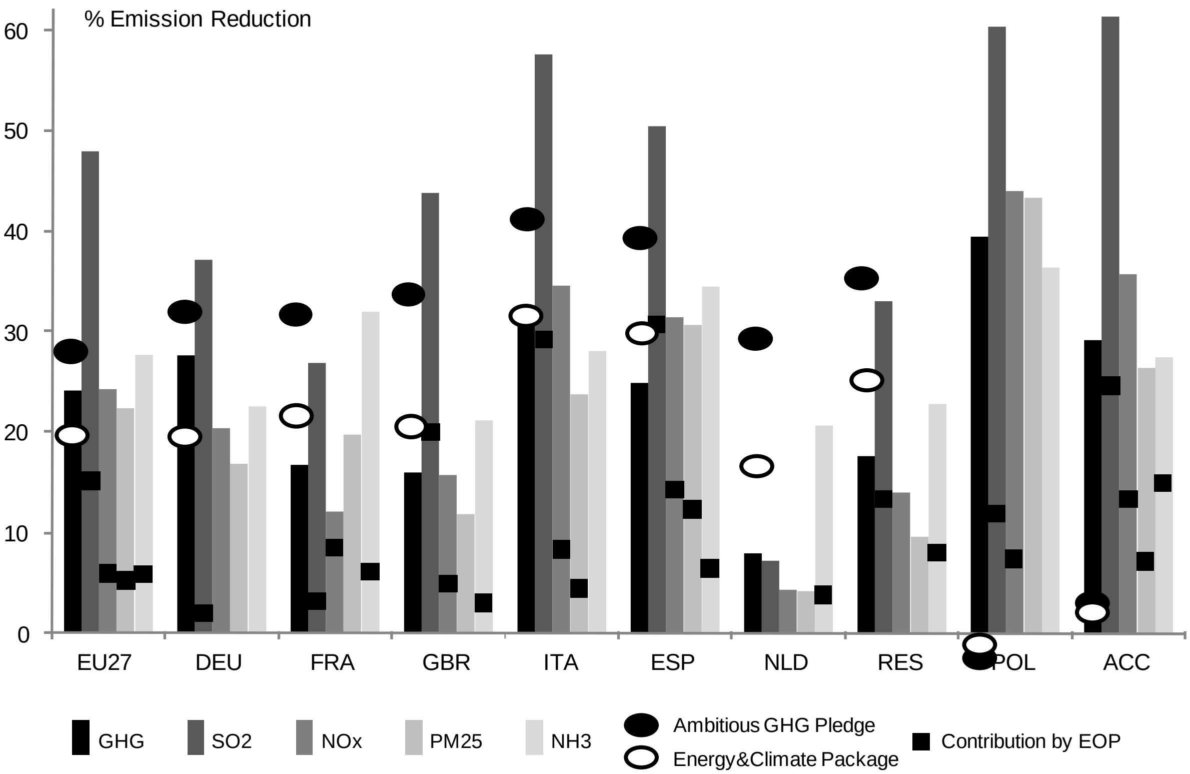


**Figure 4 Impacts of Different Policy Scenarios on Air and GHG Emissions in EU-27**

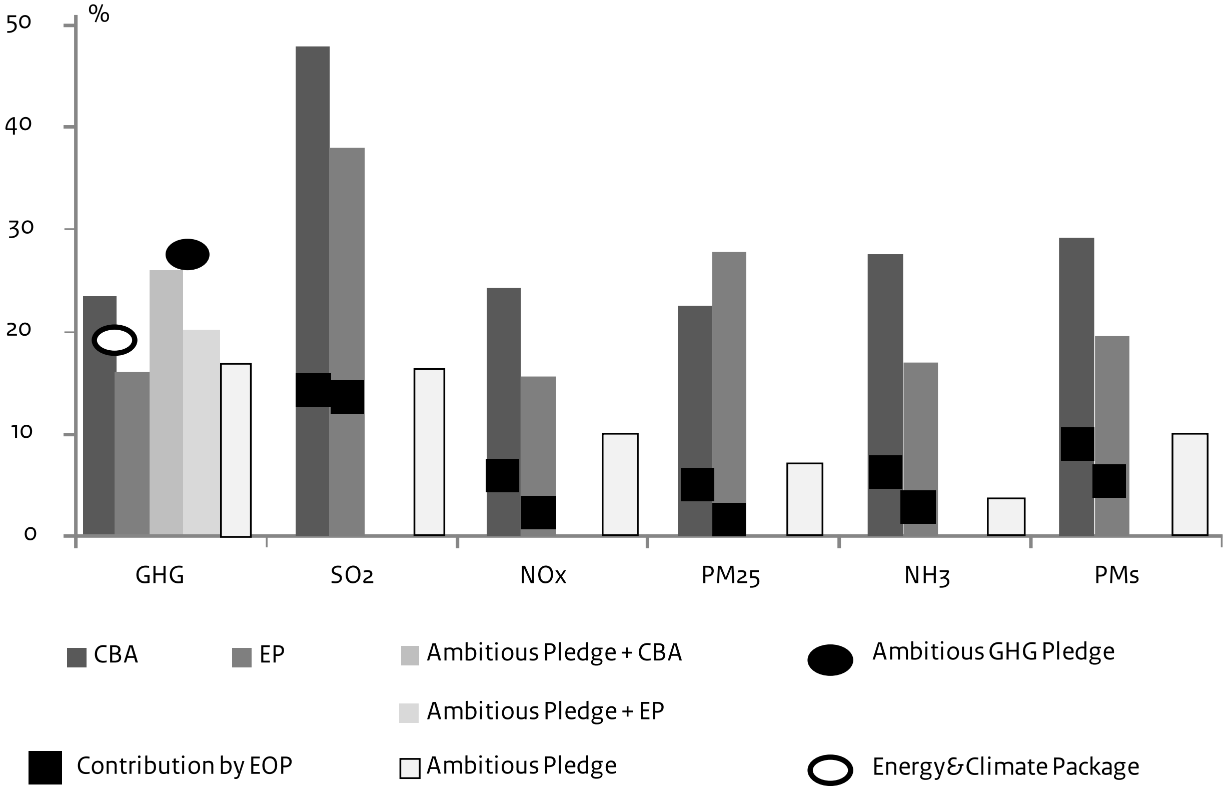


**Figure 5 Impacts of Different Policy Scenarios on Primary Energy Demand in EU-27**

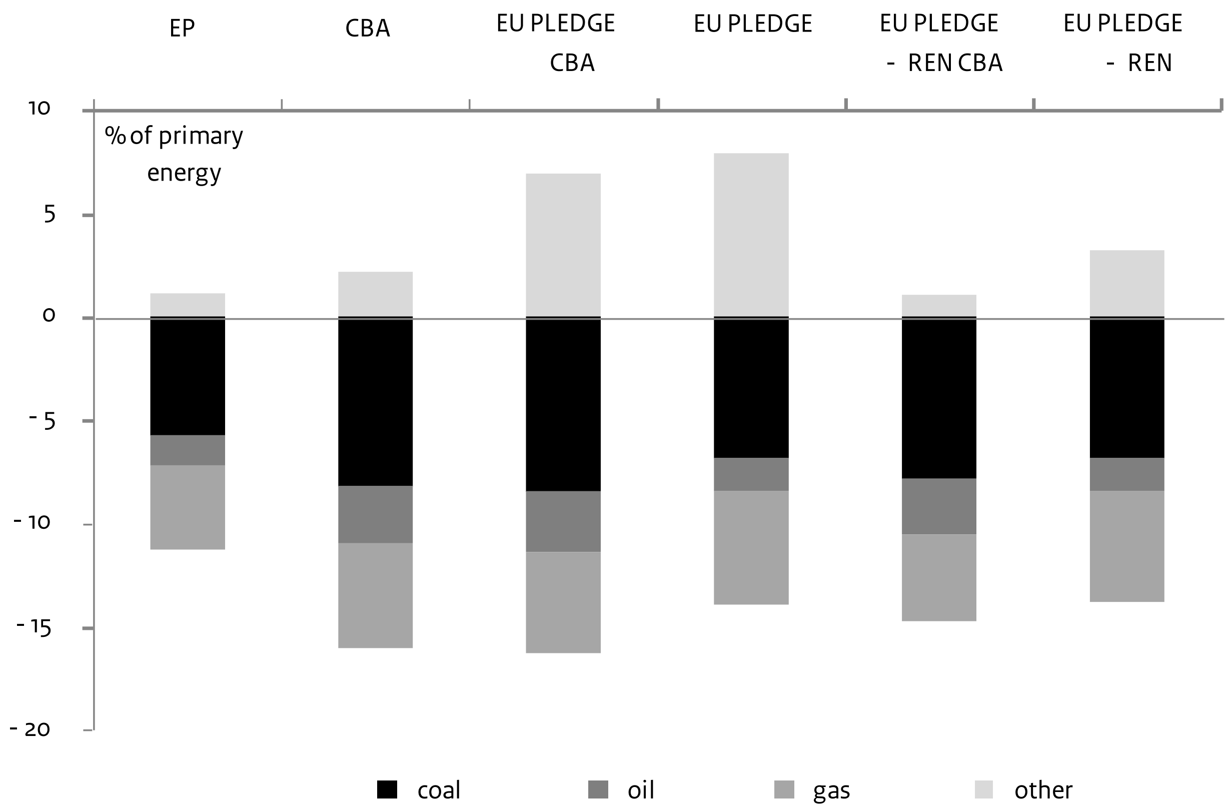
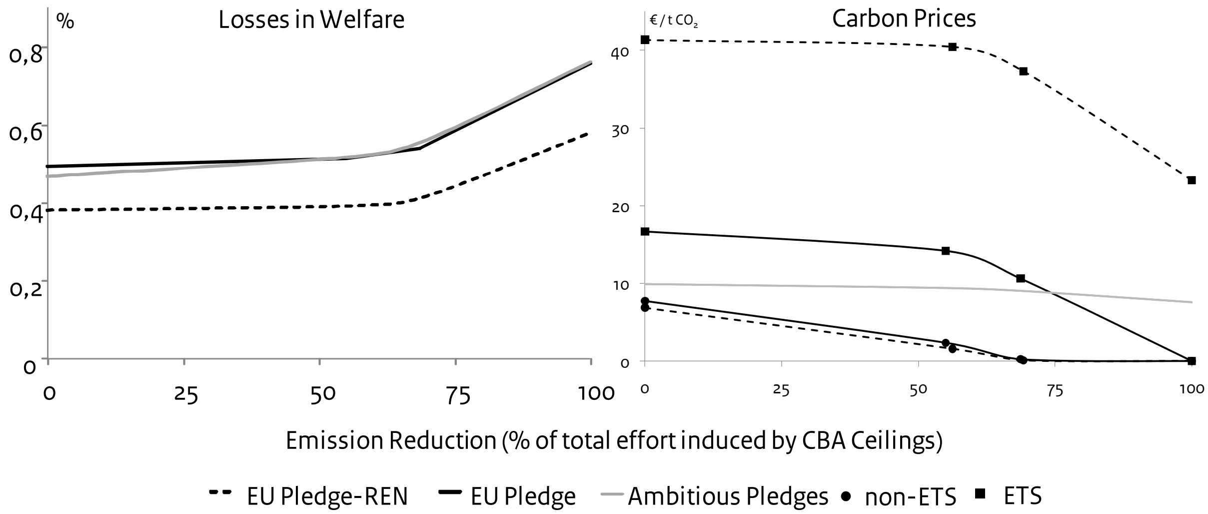


**Figure 6 Impacts of Climate & Air Policies on Welfare and Carbon prices in EU-27**




N

ote: 0= no air policies, ≈60%=EC, ≈70% = EP, 100%=CBA

**Table 3 Summarizing Climate and Air Policies**

| | PMS (%) | $CO_2$ eq. (%) | Welfare (%) | ETS Price (€ / $tCO_2$ eq.) |
|---|---|---|---|---|
| Climate Policy | | | | |
| EU Pledge | -11 | -0,9 | -0,5 | 17 |
| additional changes compared to EU Pledge | | | | |
| + EU 25% | -3 | -0,3 | -0,08 | 8 |
| + Ambitious Pledge | 2 | -2,3 | 0,02 | -7 |
| + EC | -5 | 0,0 | -0,02 | -3 |
| + EP | -10 | 0,0 | -0,05 | -6 |
| + CBA | -20 | -0,1 | -0,27 | -17 |
| Air Policy | | | | |
| CBA | -29 | -0,7 | -0,6 | - |

**Table A.1 Overview characteristics of the BAU, average annual growth (%), 2004-2020**

| | Population | GDP volume | Energy consumption [a)] | GHG emissions | Energy intensity | GHG intensity [b)] |
|---|---|---|---|---|---|---|
| Annex I | 0.3 | 1.8 | 0.0 | 0.1 | -1.8 | -0.0 |
| EU-27 | 0.3 | 1.5 | 0.6 | 0.5 | -1.0 | -0.1 |
| Non-Annex I | 1.3 | 5.4 | 3.2 | 3.0 | -2.2 | -2.9 |
| China (incl. Hong Kong) | 0.7 | 8.2 | 4.4 | 3.3 | -3.7 | -1.1 |
| India | 1.3 | 7.1 | 4.6 | 3.2 | -2.5 | -1.4 |
| World | 1.1 | 2.7 | 1.6 | -1.6 | -1.1 | -1.7 |

| | $SO_2$ emissions | $NO_X$ emissions | $PM_{25}$ emissions | $NH_3$ emissions |
|---|---|---|---|---|
| Annex I | PM | | | |
| EU-27 | | | | |
| Non-Annex I | | | | |
| China (incl. Hong Kong) | | | | |
| India | | | | |
| World | | | | |

a) Total of coal, refinery products, natural gas, biofuels, commercial biomass and renewable energy

b) GHG-intensity represents the ratio of GHG-emissions and energy consumption

Source: WorldScan

**Figure A2 Sectoral Contributions to Total Emissions in EU-27**

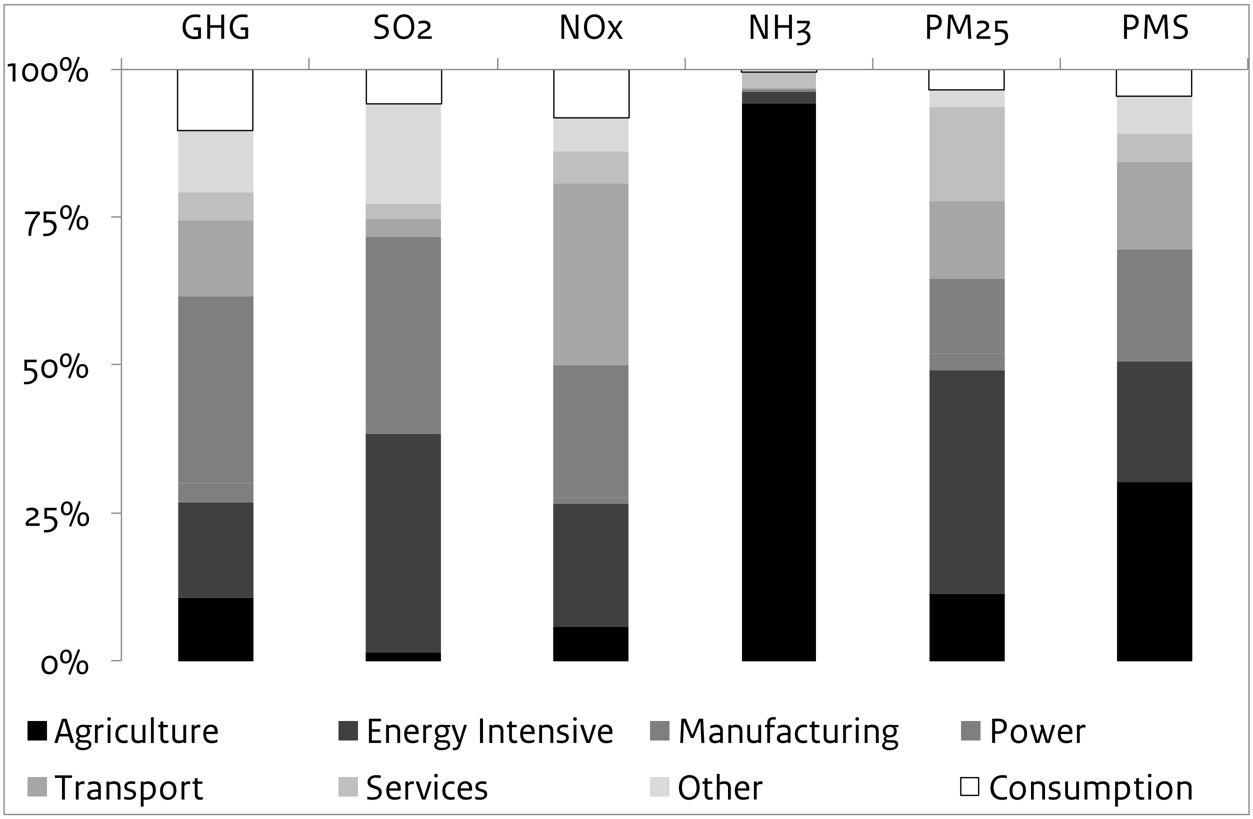
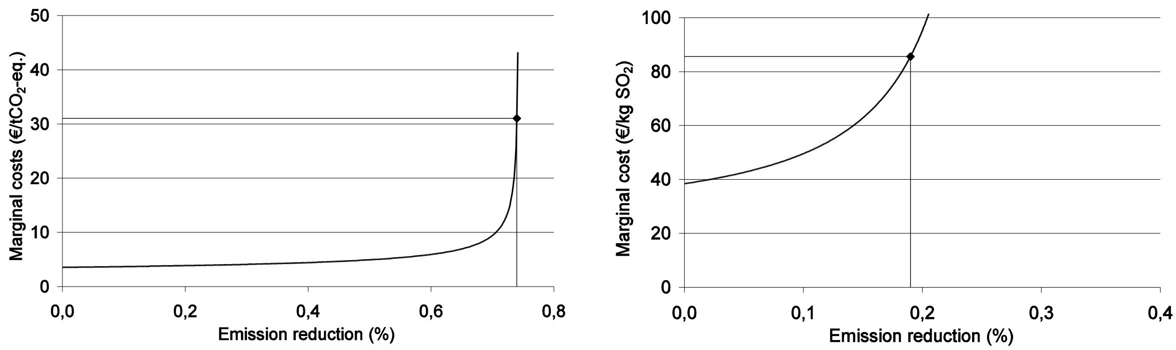


**Table A.2 Effects of a restriction on emissions of $CO_2$ eq. and $SO_2$ for coal-fired power plants in New Member States (excluding Poland)**

| | | BAU | EU PLEDGE | EU PLEDGE+EP |
|---|---|---|---|---|
| Coal use | (Mtoe) | 26 | 10 (-43%) | 7 (-52%) |
| Emission price | GHG (€/ton $CO_2$-eq.) | | 17 | 11 |
| | $SO_2$ (€/kg SO2) | | 0 | 13 |
| Mark-up price coal | related to price GHG | | 71% | 47% |
| | related to price $SO_2$ | | - | 44% |
| Emissions | GHG (Mton) | 109 | 38 | 28 |
| | $SO_2$ (kton) | 173 | 63 | 45 |
| Change emissions | GHG | | -71 (-65%) | -82 (-75%) |
| of which | *- end-of-pipe* | | -2 | -1 |
| | *- structure effects* | | -69 | -81 |
| Change emissions | $SO_2$ | | -109 (-63%) | -128 (-74%) |
| Of which | *- end-of-pipe* | | 0 | -1 |
| | *- structure effects* | | -109 | -127 |

**Figure A.1 Abatement cost curve $CO_2$ and $SO_2$ for coal-fired power plants in Italy**



## Table A.3 Mapping of GAINS sectors to WorldScan sectors

| Worldscan sectors | GAINS sectors |
|---|---|
| Cereals, Oilseeds, Sugar crops, Other agriculture | Agriculture: Ploughing, tilling, harvesting |
| | Crops left on field |
| | Other transport: agriculture and forestry |
| | Domestic sector - other services, agriculture, forestry, fishing, and non-specified sub-sectors |
| Cereals | Storage and handling: Agricultural products (crops) |
| Other agriculture | Rice cultivation |
| | Agriculture: grassland and soils / organic soils / Livestock / Other |
| | Manure treatment and manure distributed on soils |
| | Forestry |
| | Waste: Agricultural waste burning |
| | Use of mineral N-fertilizer |
| Minerals NEC | Mining: Bauxite, copper, iron ore, zinc ore, manganese ore, other |
| | Storage and handling: Iron ore |
| Coal, Oil, Natural gas, Petroleum, coal products | Fuel combustion in furnaces used in the energy transformation sector |
| Oil, Natural gas | Waste: Flaring in gas and oil industry |
| Natural gas, Petroleum, coal products | Own use of energy sector and losses during production, transmission of final product |
| Oil | Extraction of crude oil |
| Natural gas (incl. distribution) | Extraction, proc. and distribution of gaseous fuels |
| | Transportation of gas |
| Coal | Mining: Brown coal, Hard coal |
| | Storage and handling: Coal |
| Petroleum, coal products | Crude oil & other products - input to Petroleum refineries |
| | Ind. Process: Briquettes production |
| | Conversion: Combustion in boilers |
| Electricity | Power and district heating plants |
| | Industrial power and CHP plants |
| Energy intensive sectors (incl chemical products), Consumer fc | Other Industry |
| | Ind. Process: Carbon black production / Open hearth furnace / Agglomeration plant - pellets / Sm |
| Energy intensive sectors (incl chemical products) | Iron and Steel Industry |
| | Chemical Industry |
| | Non-Ferrous Metals |
| | Building Materials Industry |
| | Paper and Pulp Industry |
| | N - fertilizer production |
| | Storage and handling: N,P,K fertilizers |
| | Wastewater from organic chemical (non-food) manufacturing industry |
| | Nonenergy use of fuels |
| | Storage and handling: Other industrial products (cement, bauxite, coke) |
| | Ind. Process: Production of Cement / Lime / Glass / Bricks / Basic oxygen furnace / Cast iron / Coke o |
| Vegetable oils and fats, Consumer food products | Food (incl. beverages and tobacco) manufacturing industry |
| Vegetable oils and fats | Fat, edible and non-edible oil extraction |
| Consumer food products | Meat produced |
| Other consumer goods | Textile industry |
| | Wood and wood products industry |
| Road and rail transport | Road transport - Heavy duty vehicles / Light duty vehicles / Motorcycles / Motorcycles, mopeds and ca |
| | Other transport: rail / offroad / other off-road |
| Other Transport (water and air) | Other transport: domestic air traffic - civil aviation / inland waterways / maritime activities |
| Other services | Domestic sector - commercial and public services |
| | Waste treatment and disposal |
| | Waste water treatment (domestic) |
| | Municipal solid waste |
| | Waste: Open burning of residential waste |
| | Gasoline distribution |
| | Construction activities |
| | Other transport: mobile sources in construction and industry |
| | |
| Consumption categories | |
| Gross rent and fuel, Other goods and services consumed | Domestic sector - residential |
| Transport and communication | Road transport - Light duty vehicles: cars and small buses with 4-stroke engines |