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The Value of Air Pollution Co-benefits of Climate Policies: Analysis with a Global Sector-Trade CGE model called WorldScan

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Abstract

This paper uses the computable general equilibrium model called WorldScan to analyse the co-benefits of reduced emissions of air pollutants as a by-product of climate policies. WorldScan covers the entire world in five regions (two in the EU) and simulates economic growth in a multi-sector neo-classical recursive dynamic framework, and includes the modelling of emissions and abatement of greenhouse gases (CO_2, N_2O and CH_4) and air pollutants (SO_2, NO_x, NH_3 and $PM_{2.5}$). Abatement includes end-of-pipe controls removing pollutants without affecting the emission-producing activity itself. This paper shows that climate mitigation will significantly reduce the emissions of air pollutants. The economic value of the avoided air pollution damages can be estimated by the costs of the air policy that generates the emission reductions of air pollutants resulting from climate policies. Although the estimates of the value of the co-benefits are uncertain, it can be seen that trade may have a significant impact on the avoided costs of air policies, and therefore also has consequences on the value of the co-benefits of climate policies. Also, it is shown that the regional value of co-benefits can be substantial, and may provide an incentive to reduce GHG emissions.

Keywords: climate change, air pollution, energy, co-benefits, avoided air policy costs

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1. Introduction[2,3]

Emissions of GreenHouse Gases (GHGs) and Air Pollutant Gases (APG's) originate from fossil fuel combustion. Reducing CO_2 emissions can be handled by fuel mix changes and fossil energy savings. These *structural changes* also lower the emissions of air pollutant gases. There is a rapidly growing literature that recognizes the co-benefits of lower emissions of air pollutant gases induced by climate policies, see Rive (2010), Burtraw et al. (2003), Syri et al. (2001), van Vuuren et al. (2006), McCollum et al. (2012), and Rafaj et al. (2013).

Next to these structural changes induced by climate policy, the main historical response to mitigate air pollution consisted of 'end-of-pipe' (EOP) options, i.e. control technologies lowering emissions without affecting the emission-producing activity itself. This EOP solution of e.g. adding a flue-gas-desulphurization scrubber to a coal-fired power plant is often cheaper than fully replacing the coal-fired power plant by an APG-emission free electric power plant. For the future - despite that many EOP solutions have already been used in Europe - there are still EOP measures available to further mitigate air pollution, although they are more expensive than the historical measures, see Amman et al. (2011).

The hypothetical strategy that only achieves the lower level of emissions of air pollutant gases of a climate policy (but without any climate policy targets) will substitute some of the expensive structural responses of that climate policy with cheaper EOP options, The costs of such a hypothetical air pollution strategy can be avoided when implementing the climate policy. These (avoided) costs can serve as a proxy of the economic value of the co-benefit of reduced emissions of air pollutant gases induced by a climate policy. In Bollen et al. (2009a), local air pollution and global climate change policies are analyzed in an intertemporal framework. They

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[2] The views expressed in this paper are those of the author and should not be regarded as stating an official position of CPB Netherlands Bureau for Economic Policy Analysis.

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estimate the value of the co-benefits of climate policies, and also find that structural changes contribute to air pollutant mitigation, not only in China and India, but also in the OECD. Their analysis however lacks mechanisms on trade and impacts on specific sectors.

In this paper, a multi-sector, multi-region, global Computable General Equilibrium (CGE) model called WorldScan will be described that not only can simulate CO2 policies, but can also simulate the arbitrage of resources between EOP abatement and structural changes for cost-effective emission reduction strategies of four major air pollutants and/or all greenhouse gases (also non-CO2). The model analyses in the bottom-up study of Amann et al. (2008) also covers all those polluting substances. And it shows that structural measures, such as energy efficiency improvements, are part of cost-effective air policy strategies in China. But it does neither consider non-technical changes in the economy, such as a reallocation of resources towards production sectors that are less energy-intensive nor shifts to energy-extensive consumption.

Only Rive (2010) integrates EOP emission control options of air pollutants in a CGE model of the EU. But he limits to a static model analysis of the year 2020, one aggregate EU region, one of the Kyoto gases (CO_2) and air pollution only from large stationary energy sources (which is only half of the air pollution problem). The air pollutant gases considered in this paper are sulphur (SO_2), nitrogen (NO_x) Particulate Matter (PM), and ammonia (NH_3) and cover all known anthropogenic sources. This paper also extends on Bollen and Brink (2012) with an analysis of global coverage (instead of only the EU27) and a longer time horizon up to 2040 (instead of up to 2020). And unlike Rive (2010), this paper also takes into account more emission categories and more known abatement options of non-CO_2 greenhouse gases, small point and mobile sources, and is more up-to-date with current policies.

The analysis here adds to the literature, because this paper describes the extension of WorldScan that enables to calculate emissions of the substances sulphur (SO2), nitrogen (NOx), fine particulate matter (PM2.5), ammonia (NH3), methane (CH4) and nitrious oxide (N2O). WorldScan can now simultaneously simulate the most relevant emissions and abatement of emissions of different air pollutants and greenhouse gases. The extension of this CGE model with all these different types of emissions requires detailed data on emissions and costs of EOP measures when reducing these emissions. The data are taken from the detailed bottom-up technology model called GAINS (Amann et al., 2009; Amann et al., 2011; Klimont, Z. et al., 2009). How these data are used is explained in the methodology section. But the main research question will be to what extent emission reductions can be obtained by structural changes in an economy or by EOP measures induced by a climate policy. The next question will be to estimate how structural changes will affect the emissions of air pollutant gases, i.e. to estimate the co-benefit of reductions of emissions of these air pollutants. The other major research question is to estimate the macro-economic impacts of these climate policies, to define the air policies yielding only and precisely the same co-benefit of the climate policy, to estimate the macro-economic impacts of these air policies, and finally to compare the macro-economic impacts of both policies.

Section 2 describes WorldScan, the model used for this analyses, focussing on how to model air pollution policies. Section 3 presents the policy cases considered. The main results of the simulations appear in section 4. Finally, section 5 concludes.

2. WorldScan[4]

The economic impacts of climate and air policy scenarios are simulated with WorldScan (Lejour et al., 2006; Bollen and Brink, 2012), which is a recursive dynamic multi-sector multi-region computable general equilibrium model in the neoclassical tradition of growth models. The WorldScan model fits in the category of CGE models as GEM-E3 (Ciscar et al., 2013), OECD

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[4] This part of the paper is an overview of WorldScan as in Bollen and Brink (2012). WorldScan is flexible with respect to regions and sectors. In this paper only a 5 region model version is used instead of 24 region version in Bollen and Brink (2012). Here, climate policies are simulated for the years beyond 2030, and a mechanism is added on declining costs of electric technologies from learning-by-doing.

Env-Linkages (Dellink et al., 2010), and DART (Weitzel et al., 2013).The WorldScan model is calibrated to GTAP-7 (Badri and Walmsley, 2008), and the regions, production sectors, consumption categories, inputs, and energy technologies are listed in Tables 1.

Table 1a Regions in WorldScan

Regions	Abbreviations	
- Old Member States	EU1	EU27
EU - New Member States	EU2	
Rest of Annex-1	RA-1	All Annex-1 countries minus EU27
Non Annex-1 Energy Importing Countries	NA-1 EI	Rest of Former Soviet Union, Rest of North Africa (with Algeria and Libya), Rest of Western Asia (with Iraq and Saudi Arabia, etc.), Egypt, and Venezuela
Non Annex-1 Energy Exporting Countries	NA-1 EE	NA-1 minus NA-1 EI (see above)

Regional disaggregation within Europe concerns old (EU1) and new member states (EU2), the ‘Rest of Annex-1’ countries (RA-1), the ‘Non Annex-1 Energy Importers’ (NA-1 EI), and the ‘Non Annex-1 Energy Exporters’ (NA-1 EE), see Table 1a. The sectors in the model represent heterogeneous activities causing emissions of greenhouse gases and air pollutant gases, see Table 1b. ETS (electricity and the energy-intensive sector) participating in the EU emission trading system and the other sectors (NETS) can be distinguished separately. Coal, oil and natural gas are primary energy sectors.[5]

In WorldScan, consumers save a fixed portion of their earned income. The income available for consumption is allocated to purchasing consumer goods and services. This is modelled as a Linear Expenditure System (LES) with consumers maximizing utility they derive from the consumption of goods and services, subject to a budget restriction and taking into account

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[5] The sector *Oil* delivers mainly to *Petroleum and coal products*, which in turn delivers fuels to various sectors (in particular the transport sectors) and to households.

subsistence levels, i.e. the minimal quantity of a consumption good necessary to survive (see Lejour et al., 2006). The consumption categories are listed in Table 1b in the right column.[6]

Table 1b Production Sectors, Consumptions Categories in WorldScan

Production Sectors	Consumption Sectors
Agriculture	Food
Minerals NEC	Beverages and tobacco
Oil	Clothing and furniture
Coal	Gross rent and fuel
Petroleum Coal Products	Other household outlays
Natural Gas (incl. gas distribution)	Education and medical care
Electricity	Transport and communication
Energy Intensive (+ Chemicals)	Recreation
Transport (water and air)	Other goods and services consumed
Services	
Capital Goods and Durables	

The production technology is represented by a production function, which relates factor inputs and intermediate inputs to output, and is a nested structure of constant elasticities of substitution functions. For more details, see Lejour et al. (2006). The main factor inputs are high- and low-skilled labour, and capital. Intermediate inputs are goods, services and energy. The inputs are to some extent substitutable, see Table 1c for an overview of the inputs.

International markets for goods and services are linked to each other by employing the Armington assumption, see Armington (1969). Firms in each region produce a unique variety of a particular good with the number of varieties equal to the number of regions. Regional varieties are imperfect substitutes (through the use of Armington elasticities). Therefore, firms have monopoly power over their own variety and can choose their price.

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[6] The modeling of a sectoral consumption demand system in WorldScan is founded on different categories than the production sectors. This is done for empirical reasons, and more details on this issue can be found in Lejour et al (2006). WorldScan employs a concordance matrix with statistical weights that translates output of producing sectors to consumption categories.

Table 1c Inputs in Sectoral Production Functions in WorldScan

Value Added Factors	Other non-energy intermediary	Other Energy Intermediary
Low-skilled labour	Agriculture	Coal
High-skilled labour	Minerals NEC	Petroleum Coal Products
Capital	Energy Intensive (+ Chemicals)	Natural Gas (incl. Distribution)
Land	Transport (water and air)	Electricity
Natural resources	Services	Oil
	Capital Goods and Durables	Biodiesel
		Ethanol

WorldScan simulates deviations from a “Business-As-Usual” (BAU) path by imposing specific additional policy measures such as taxes, emission prices of greenhouse gases or air pollutant gases, or renewable energy subsidies to mitigate emissions. The WorldScan simulations of this paper - i.e. the climate policy scenarios - are part of the AMPERE project. For an overview paper on a multi-model exploration of this project on staged accession scenarios to a global climate regime, the reader is referred to Kriegler et al. (2013). WorldScan reproduces the main characteristics of the ‘RefPol’ scenario. This scenario includes climate and renewable policies, and is based on the unconditional Copenhagen pledges of countries for 2020, and extends on the climate policy efforts beyond 2020. For more details, see section 3 when discussing scenario design and see Kriegler et al. (2013). The BAU used in the paper here, is the simulation of the ‘RefPol’ scenario, but without any climate and energy policies.

The developments of emissions of CH_4, N_2O, and of air pollutant gases are taken from the implementation of the World Energy Outlook 2009 in GAINS models.[7] Basic inputs for the ‘RefPol’ scenario calibration are time series for population and GDP by region, energy use by region and by energy carrier, world fossil fuel prices by energy carrier, and emissions of air

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[7] Emissions are based on GAINS model scenarios, and extracted from http://gains.iiasa.ac.at/models/. The BAU scenario is ‘BL_WEO_2009’, which is a Current Legislation (CLE) Scenario. For Europe, see Capros et al.(2010). For the regions and years (beyond 2030) not covered by GAINS, the emissions are in line with the OECD Environmental Outlook scenario to 2050 (OECD, 2012). More on this issue when discussing the calibration of emission factors.

pollutants. Appendix A (supplementary material) describes in detail the calibration of the ’RefPol’ scenario.

Table 1d Energy Technologies in WorldScan

Electricity Technologies	Biofuel technologies
Conventional fossil (without CCS)	Ethanol
Fossil with CCS	from sugar beet
Nuclear	from sugar cane
Wind	from wheat
Biomass	from corn
Hydropower	Biodiesel

Crucial for emissions – either greenhouse or air pollutant gases - is the demand for specific electric technologies. The electricity technology specification is taken from Boeters and Koornneef (2011). As illustrated in Table 1d, WorldScan distinguishes five electricity technologies: (1) fossil electricity, (2) wind (onshore and offshore) and solar energy, (3) biomass (produced by the other Agricultural sector), (4) nuclear energy and (5) conventional hydropower. Biofuels and biomass are both produced by the other Agricultural sector, and can be used to lower emissions of liquid fuels. WorldScan does not model vintages explicitly. The adjustment to emissions prices is instantaneous, and hence there are little insights from the timing of adopting new equipment. Although this may seem an oversimplifying assumption, Brink et al. (2013) compare the impact of carbon prices on CO2 emission reductions of a similar version of WorldScan (without air pollutant gases but more regions) with TIMER (energy system dynamics model) with vintages in the electric sector (see van Vuuren, 2006). Brink et al. (2013) conclude that the order of magnitude of emission response for 2030 is similar across models.[8]

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[8] In this analysis, Russia and China show higher emission reductions in WorldScan. High economic growth argues against the vintage structure explaining these differences (the new vintage is relatively large). Instead, the low energy prices will account for the large emission reductions, which in turn are driven by energy savings, sectoral changes, production losses, and fuel switches from coal to renewable energy.

The fossil combustion plants can be retrofitted with Carbon Capture and Storage (CCS) technology, like EOP (see later on Equations 2 and 3). CCS is assumed to be paid by the electricity sector. Moreover, the specification of the production function of CCS is assumed to be equal to the production function of the capital goods sector. The endogenous abatement fraction includes an energy penalty with marginal cost data based on TIMER (van Vuuren, 2006). The cost of CCS technology is comprises the costs of capture, transport, and storage.[9]

To be able to run reasonable climate and energy policy scenarios up to 2040, WorldScan assumes the long term costs of electricity technologies and CCS to decline through learning-by-doing. The approach follows Manne and Richels (2004). The regional costs of electricity technologies decline from the global cumulative production relative to the level in the base year (2004). But learning is limited by introducing the floor cost parameter (the very long-term cost level of a specific technology). This means that for the purpose of the analyses in this paper that the cost reductions will mainly occur for CCS, wind and biomass. The cost reductions of the 'RefPol' scenario reproduce the ordering of the reductions of the cost of electricity technologies of the 'reference' scenario of IEA (2010).[10]

While the 'RefPol' scenario in WorldScan is calibrated to reproduce the shares of electric technologies in total electricity production, in all other scenario simulations, all fossil electricity technologies (including CCS), wind and biomass change endogenously. Nuclear and hydropower are kept at their BAU levels. The supply of nuclear is considered to be mostly a political decision depending on the risk assessment of nuclear accidents and nuclear waste disposal. Also Boeters and Korneef (2011) concluded that hydro energy can only be extended at very high costs, which means that not much action will be expected to take place here.

Sectoral emissions are simulated by either multiplying emission coefficients with simulated outcomes of specific inputs (only energy inputs or fertilizer use) of production or simulated

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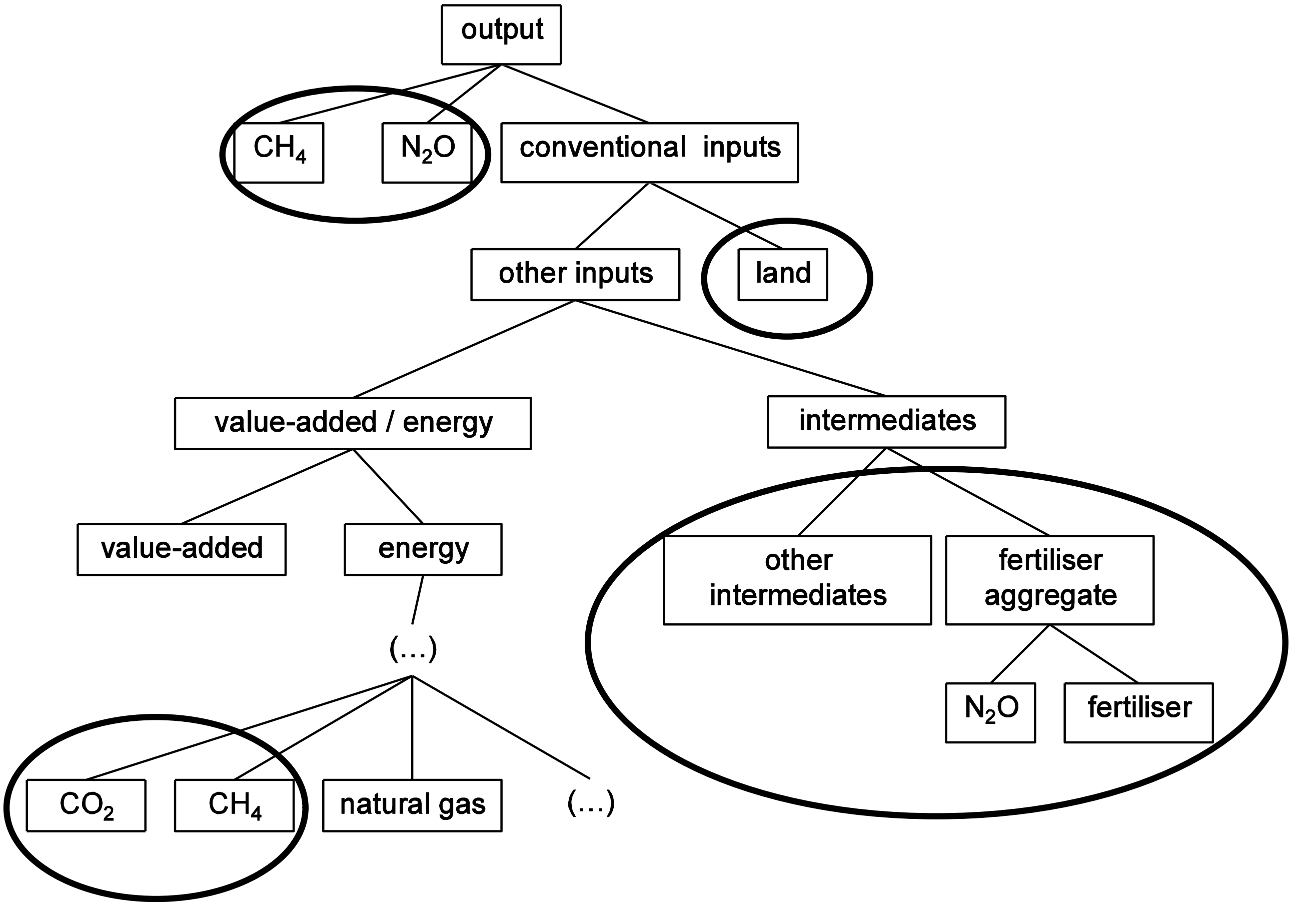
[9] The regional reservoir availability and storage costs for various options range from 7-70 2004US$/tCO2. The total maximum feasible reduction (including the energy penalty) is 85%

[10] The actual learning rates are exogenous and can be found in Appendix A.

outcomes of output. Emissions from energy use are calculated using a fixed emission coefficient (i.e. a fixed amount of emissions per unit of coal, oil, natural gas, or biomass used). The use of chemical fertilizer in agriculture is a significant source of emissions of N_2O and NH_3. Emissions related to the use of chemical fertilizer are calculated using the intermediary input from the energy-intensive (chemical) sector to the agricultural sector as a proxy for the amount of fertilizer used (see Figure 1).

Figure 1 Production structure with CO_2, CH_4 and N_2O emissions in the other agricultural sector



Note on circles:

[1] The circled part at the low right is not applicable in other sectors.
[2] Land is the fixed factor in agricultural sectors, but does not prevail as a fixed factor in other sectors. In primary energy sectors it is replaced by proven reserves of coal, oil and gas in the coal, oil, and gas distribution sector, respectively. In other sectors there is no fixed factor, and therefore omitted.
[3] GHG Emissions should be replaced by APG's in other sectors

Process emissions are linked to the sectoral output, the top of the production function nest. The production structure as shown in figure 1 for the agricultural sector is similar for other sectors. The main difference with other sectors is that these sectors don't have fertiliser and land as an input.

For CO_2, the emission factors link energy use per fuel type to emissions, but is independent of sectors and regions. Emission factors for other substances are sector-specific and region-specific. Emission factors up to 2030 for both non-CO_2 greenhouse gases and air pollutant gases are calculated such that emission levels by region, sector and activity in the BAU reproduce the corresponding emission levels of GAINS (WEO-2009 scenario). When calibrating emission factors in WorldScan, it is necessary to map the emissions of GAINS sectors/activities to WorldScan sectors and consumption categories, see Appendix B.

Further, these sectoral emissions are also allocated to either the burning of [1] coal, [2] gas, [3] oil, or [3] biomass, or [5] to fertilizer use, or [6] to production (process emissions).[11,12] Technically, the 'RefPol' scenario is calibrated in three steps:

1. emission factors are kept constant at the base year level (2004), and
2. emission factors of the years between 2005-2030 are equal to the mapped GAINS data - the Current Legislation scenario labelled 'BL_WEO_2009' in Amann et al. (2011) - divided by the simulated activities of the scenario of step1. For the years not available in GAINS, the data are interpolated between two consecutive observations.[13]
3. For the years between 2030 and 2040 not the level but the trends of emission coefficients of WorldScan are equal to those from TIMER (van Vuuren, 2006) as used in OECD (2012).

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[11] All anthropogenic (except land-use related) emissions of greenhouse and air pollutant gases are covered.

[12] The end-use categories are: 'Gross rent and fuel' (coal and gas), 'transport and communication' (Petroleum Coal Products), and 'Other goods and services consumed' (Petroleum Coal Products). Fuel-switching is handled within 'Gross rent and fuel', and the blending of bio-fuels for 'Petroleum Coal Products' in 'transport and communication' and 'Other goods and services consumed'. Electric cars are not employed in this paper.

[13] The 'Non Annex-1 Energy Exporters' region is incomplete in GAINS (only some Russian energy exporters are included). For the base year, emissions of the IMAGE model are used, and for the years up to 2030 the development of emission coefficients in GAINS for this region is used to determine the emissions levels.

> The BAU assumes a mild reduction of emission coefficients in the OECD. Outside the OECD, future emissions are very uncertain, but it may be expected that non-OECD countries respond to serious air pollution problems. A reasonable assumption is that the gap between emissions coefficients of developing countries and the OECD closes at the same speed at which the income gap of developing countries is reduced between the non-OECD and the OECD (in purchasing power). Note that there are many other reasonable assumptions possible on this issue.

It should be noted that the historical EOP controls and those measures to be implemented for CLE (future years) are not explicitly modelled in WorldScan. Historical EOP controls are assumed to be reflected in the base-year prices of both GTAP and WorldScan, and for future years CLE should be reflected by the GDP path of the 'RefPol' scenario.[14] In this paper, all other scenarios than the 'RefPol' scenario fix emission coefficients to the levels calibrated for the 'RefPol' scenario.

Emissions of a particular pollutant by sector *s* are modelled as:

$$UEM_s = \sum_i \varepsilon_{i,s} q_{i,s} + \varepsilon_{Q,s} Q_s \qquad (1)$$

with UEM_s the level of emissions without EOP abatement, $q_{i,s}$ the volume of input i used in production of sector s (such as fossil fuels and chemical fertilizer), $\varepsilon_{i,s}$ the emissions per unit of this input used, and $\varepsilon_{Q,s}$ the emission factor for process emissions by sector s, i.e. the emissions per unit of sectoral output Q_s.

EOP abatement reduces emissions below the BAU for all non-CO2 greenhouse gases and air pollutant gases in each sector for all energy inputs (if applicable), for fertilizer use (energy-intensive goods) or related to production (process emissions):

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[14] The additional EOP emission controls are from the same CLE scenario. This means that emissions factors include other (cheaper) EOP controls than the more (expensive) additional EOP controls represented in the Marginal Abatement Cost (MAC) curves (see later when discussing equation 3).

$$EM_s = \sum_i \left(1 - x_{i,s}\right) \varepsilon_{i,s} q_{i,s} + \left(1 - x_{Q,s}\right) \varepsilon_{Q,s} Q_s \tag{2}$$

with $x_{i,s}$ and $x_{Q,s}$ the relative abatement level due to emission control applied to input-related emissions and output-related emissions, respectively. Omitting indices for region-sector-activity-substance specifics, the total abatement costs reads as:

$$C(x) = UEM_s \cdot \left\{ \frac{\beta}{1-\chi} \left[\bar{x}^{1-\chi} - \left(\bar{x} - x\right)^{1-\chi} \right] - \gamma x \right\} \cdot \sum_i \delta_i p_i \tag{3}$$

C(x) gives the cost of abatement as a function of x, $\bar{x}$ is the maximum share of emissions that can be reduced by emission control options, β and χ (both > 0) determine the shape of the supply function, and γ is a constant that determines the initial level of the marginal cost $c(0)$.[15] Emission control requires the inputs of energy, capital, labour, intermediate goods and services. Parameter δ_i is the share of input i of the capital goods sector in the base year.[16] If e.g. wages were to rise, then the marginal cost of abatement will also increase. There is no learning in EOP abatement, and abatement costs lower the value added of that particular sector.

EOP is applied to output (if the process emission factor is larger than 0) and/or each input (if the input-specific emission factor is larger than 0) of all sectors. Further, EOP is applied up to the level where marginal cost equals the endogenous emissions price resulting from a constraint on emissions. Conceptually, the emission prices of air pollutant gases are not treated differently in WorldScan from emissions prices of greenhouse gases or carbon taxes.[17] It is assumed that the government deficits are unchanged when introducing taxes on carbon, or emissions prices of air pollutant gases or greenhouse gases, or subsidies on renewable energy. Further, it is assumed that unemployment is unchanged at the macro-level.

The additional more expensive EOP controls options of GAINS are mapped to WorldScan sectors in the same was as emissions, and the options are ranked according to marginal costs.

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[16] As emission control measures will in many cases be capital goods, on average the production and implementation of these measures will be similar to that of capital goods.

[17] This also applies to the way renewable subsidies are treated in the model.

The maximum feasible reduction can be derived from the GAINS data through the mapping procedure as followed for emissions. The derivative of equation 3 (MAC curve) is estimated by Ordinary Least Square (OLS) estimators. Appendix C shows by means of Figure A.1 that a wide range of shapes of a MAC curve can be estimated. In the GAINS databases there are only MAC curves presented for 2020 and 2030. Appendix C also shows the maximum feasible reduction for fossil combustion driven sectors (Table A.2). It can be seen that – after conducting the mapping procedure - only 15-20% of the number of all potential activities (i.e. all combinations of sectors and inputs) can yield significant emission reductions through EOP.

Summarizing, WorldScan can simulate an efficient response to emission prices of air pollutants and greenhouse gases through arbitrage of resources to EOP abatement on inputs (combustion of fuels) and production (process related emissions) on the one hand, and on the other hand on structural changes in an economy through reallocating resources from high to low emission activities (across sectors and within a sector), and through consumption away from pollution-intensive to pollution-extensive commodities. The model simulates an emissions price in a multi-sector- multi-region CGE framework with trade, but it is good to realize that technology is only explicitly represented in the electricity sector. In all other parts of the model, technology is implicitly represented by CES substitution functions – either in production or consumption. For example, energy savings can be induced by price changes of energy (through emission prices), but are only implicitly represented. At the sectoral level, energy savings may occur from a reduction of output or the switch between inputs at constant substitution elasticities (between energy and non-energy inputs). At the macro-level, energy savings may be induced from reallocating labour and capital from energy-intensive to energy-extensive sectors. Finally, energy savings may also occur by lowering consumption, or through the substitution between energy-intensive and energy-extensive commodities (e.g. from transport services to non-transport services. EOP abatement is put in a CGE perspective. The EOP technologies are only implicitly represented, although they can be traced in a simulation. The simulated level of the emission prices is equal to marginal costs of abatement, And hence all collected options with lower marginal costs than the emission price are part of the EOP abatement port-folio.

3 Scenario Design

The analysis in this paper is based on a set of scenarios that are characterized by different climate efforts from different front runner regions – the EU alone or the 'Non Annex-1 Energy Importers' jointly – and the 'Non Annex-1 Energy Exporters'. The front runners adopt ambitious climate policies, while others continue to implement moderate climate policies. The front runner scenarios deviate in two variants beyond 2030 in either a stringent '450P-CE' scenario or moderate 'RefP-CEback' scenario, depending on the success of engaging the rest of the world to climate policy. The analysis presented here focuses for the years of 2030 and 2040 on the indirect benefits of climate policies (reduction of emissions of air pollutant gases). The climate policy scenario setup is summarized in Table 2, and a more thorough discussion of individual scenario classes can be found in Kriegler et al. (2013). The 'RefPol' scenario includes emissions reduction commitments and renewable policies based on the unconditional Copenhagen pledges of countries. The EU's climate policy follows -20% GHG cap for 2020 (compared to the emissions in 1990, and a target of 20% of EU energy consumption to come from renewable sources from 2020 till 2040 in each year. There is an EU-wide cap on GHG emissions from sectors within the Emission Trading System (ETS), and reduction targets for emissions from households and sectors not covered by the ETS (NETS). The EU countries are allowed flexibility in meeting their NETS targets through emission reallocation for a given year between EU1 and the EU2 region.

Beyond 2020, regions in the 'RefPol' scenario are assumed to continue with emissions reductions that sustain their average emissions intensity improvements at a rate that it is roughly consistent with their pre-2020 action or slightly strengthened for regions without emissions targets until 2020. This means a GHG intensity yearly reduction rate equal to 3% for EU27 and ‘Non Annex-1 Energy Exporters’, and 2.5% reduction rate for ‘Rest of Annex-1’ and ‘Non Annex-1 Energy Importers’ (derived from detailed country assumptions in Kriegler et al, 2013). The technology targets apply to all policy scenarios, and they are 20% for the EU (as for 2020), and a 15% target for the ‘Non Annex-1 Energy Importers’.[18]

Table 2: Scenario design on staged accession scenarios

Scenario Type	Short Name	Global Target	Tech. Targets	Regions	Carbon Price until 2030	Carbon Price after 2030
No-Policy	Base	None	None	All	None	None
Reference policy	RefPol	None	Yes	All	Derived from regional targets (where existing)	
Climate Policy Benchmark Scenarios	450	450 ppm	Yes	All	Globally harmonized to meet 450 ppm	
	550	550 ppm	Yes	All	Globally harmonized to meet 550 ppm	
Staged Accession	‘450P-CE’	None	Yes	EU+Energy-Imp NA1	EU Roadmap	Globally harmonized price from 450
				Other regions	Regional prices from RefPol	
Reconsideration Scenarios	‘RefPEUback	None	Yes	EU	Price derived from EU Roadmap targets	Regional prices from RefPol
				Other regions	Regional prices from RefPol	

Climate policy scenarios as the ‘450’ and the ‘550’ cases simulate GHG emission prices to approximate a global CO2 eq. emissions profile of the climate target 450/550 ppmv in the atmosphere (where-flexibility allows regional GHG emissions to be endogenous). The ‘450’ and the ‘550’ climate policy cases are an approximation of the true 450/550 CO2 eq. ppmv scenarios, because the climate policy is implemented as a cumulative budget of global CO2 emissions for the period 2010-2050 (as described in Kriegler et al. 2013) and assumes a ‘consistent’ emissions price for the other important non-CO2 gases (CH4 and N2O). The time profile of the global CO2 emissions - in the recursive dynamic framework employed for the

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[18] China alone has a 25% target, but other countries in ‘Non Annex-1 Energy Importers’ region have no renewable target, see Kriegler et al. (2013). With China as one of the large countries in ‘Non Annex-1 Energy Importers’ region, it is assumed that this region has a renewable target equal to 15% (although never binding). The 13% target of the USA is not binding when they reduce GHG emissions 7% below their 1990 emission level.

analysis in this paper- is determined by a linearly increasing percentage change over time from the ‘RefPol’ scenario that matches the global CO2 cumulative budget. The time profile for the global CO2 emissions is imposed as a constraint, and the model simulation yields an endogenously determined uniform CO2 emissions price for all sectors and regions in the world. This CO2 emissions price is transformed to an emissions price of the non-CO2 gases (based on the Greenhouse Warming Potential - GWP - of that particular GHG), and therefore is labeled above as a ‘consistent’ emissions price. Although there is no constraint on the total GHG emissions, the non-CO2 gases are also subject to the same CO2 emissions price, so there are also non-CO2 emission reductions. This means that the CO2 budget (thus simulating a comparable restriction on energy markets to models only modeling CO2 in Kriegler et al, 2013) also yields a reduction in emissions of non-CO2 gases, and it is assumed that this is in line with the true 450/550 CO2 eq. ppmv scenarios. It should be noted that this linearly increasing percentage change of emissions over time will probably deviate from an economically non-optimal GHG price pathway. Also there is a subsidy on renewable energy (technology target if applicable in a scenario).

The GHG emissions price yields structural changes through energy savings and reallocation of resources of capital and labour to emission-extensive activities, and through input changes at the sectoral level to lower the pollution per unit of production. Simultaneously, the GHG emissions price generates EOP abatement. The structural changes in turn result into the indirect benefits of lower emissions of air pollutant gases, which are explored further in this paper. The emission prices of greenhouse gases are fixed in the ‘450P-CE’ and ‘RefP-CEback’ scenarios (and global emissions of greenhouse gases are consequently endogenous). Table 2 highlights to what level the emission prices are fixed, i.e. the scenarios start with ambitious emission prices in the EU27 and ‘Non Annex -1 Energy Importers’ region, and from 2030 either move to ‘450’ (‘450P-CE’) or fall back to ‘RefPol’ (‘RefP-CEback’).

Related to each climate policy scenario, there are four additional air pollution scenarios. These four air pollution scenarios are one for each region (EU27, ‘Rest of Annex-1’, ‘Non Annex-1 Energy Importers’, and ‘Non Annex-1 Energy Exporters’). The air pollution scenarios have no climate policies, but instead assume that one particular region unilaterally reaches the simultaneous reduction of emissions of all air pollutant gases as achieved in the climate policy scenario. For the purpose of this paper on the evaluation of avoided costs (at the macro-level) of the co-benefit of climate policy, the policy shock of all regions simultaneously achieving the co-benefit of the climate policy is not analyzed. The reason is that this paper tries to highlight and explain the first-order impacts at the macro-level of sectors confronted with air pollution policies in an international context. The paper refrains from the possibility of other regions also simultaneously imposing an air pollution policy (and thus changing the trade pattern as well). This will produce other (and often higher) costs for the different regions than the costs for the different regions of the four separate air pollution scenarios. The (avoided) costs - only including the first-order region-specific responses from changing trade patterns from air pollution policies - involved with these air pollution scenarios indicate the economic value of the co-benefits of the related climate policy scenario.

4 Results

WorldScan is used to assess the impact of the policy simulations described in the previous section 3. This section presents results for 2030 and 2040, with a particular focus on region-specific emissions, decomposition of emissions to activities and sectors, and on prices and welfare. Welfare changes are measured by the Hicksian Equivalent Variation (HEV), i.e. the additional income required to compensate for any losses of utility compared to the BAU, see also Boeters and Kornneef (2011), and Bollen et al. (2011).[19]

First, the importance of structural changes induced by the climate policy will be illustrated, which result in co-benefits of reduced emissions of air pollutant gases.[20] Next, it will be shown how air policies can also directly generate these co-benefits, and how large the estimated economic value of the climate policy co-benefit is for different regions. Finally, the discussion will be broadened again to compute the region-specific values of the co-benefit for all climate policy scenarios as to assess the benefits in the context of the climate mitigation costs.

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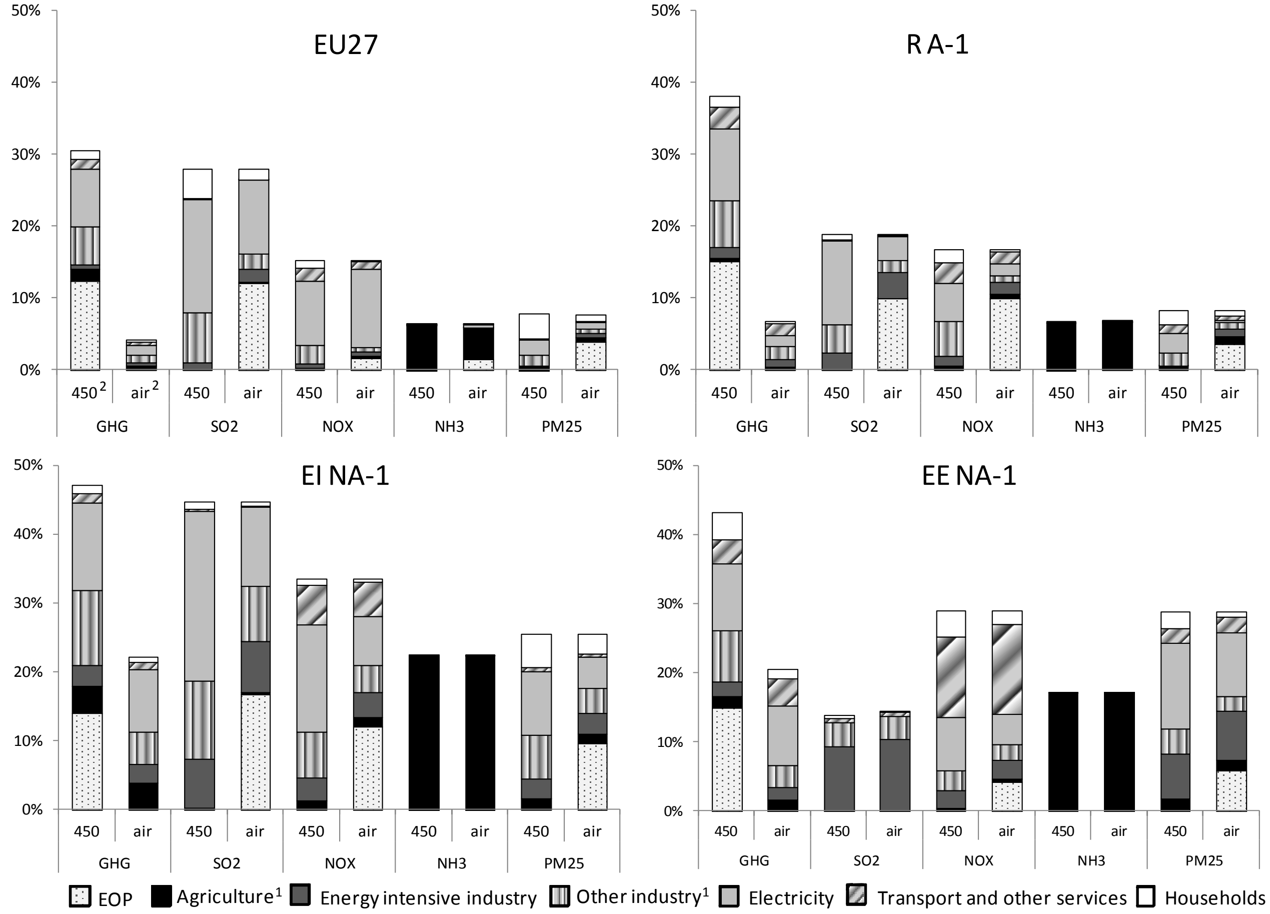
[19] Besides emissions, any change in environmental quality is not included in this indicator.

[20] Europe is extensively discussed in Bollen and Brink (2012), which focuses on air pollution policy in 2020. Although emission data for 'Non Annex 1 Energy exporters' region is limited, this section does present the results for this region for completeness. Probably, structural change for this region will be overestimated.

Figure 2 **Decomposition across Sectors of Emission Reduction through Structural Changes for the Climate Policy Scenario (450) and the Air Policy Scenario (AIR, one for each region) in the different world regions**



		EU27	Rest A-1	EI NA-1	EE NA-1
Costs '450'	HEV (%NI)[3]	-0.16	-0.56	-0.82	-6.05
Costs 'air'	HEV (%NI)[3]	-0.04	0.00	-0.47	-0.66
SO_2	2004 US$/kg	2.3	1.6	3.1	-
NO_x	2004 US$/kg	1.3	3.3	4.7	19.2
NH_3	2004 US$/kg	3.2	2.7	7.4	12.3
PM_{25}	2004 US$/kg	1	0.8	2.5	9.9

Note: [1] The sector 'Agriculture' is the aggregate of 'Animal products' and 'Other Agriculture'. The sector 'Other Industry' comprises the following sectors: 'Services', 'Minerals NEC', 'Consumer Goods', 'Capital Goods and Durables', and the primary energy sectors 'Oil', 'Coal', 'Petroleum Coal Products', 'Natural Gas (incl. distribution)'.

[2] '450' is the climate policy scenario aiming for stabilization of greenhouse gases at 450 ppmv and 'air' is the air policy scenario achieving the same emission reduction of a specific air pollutant as achieved in the '450' climate policy scenario.

[3] HEV (%NI) expresses the costs as compensating Hicksian Equivalent Variation (HEV) as % of National Income (NI).

In Figure 2, the sectoral contributions to the emission reduction and the EOP abatement for the entire economy for all four regions are illustrated for the year 2030 for the ‘450’ climate policy scenario and for the different regional ‘air’ pollution scenarios. For example, the left bar in the EU27 panel shows the ‘450’ climate policy scenario. The right bar illustrates the air pollution scenario with the emission levels of the air pollutant gases of the ‘450’ climate policy scenario for EU27 imposed as a ceiling. Likewise, the right bar in the ‘Rest of Annex-1’ panel shows the results of another air pollution policy scenario with ceilings for air pollutant gases in ‘Rest of Annex-1’ equal to their emission levels of the ‘450’ climate policy scenario. So, a regional panel consists of two scenarios, and all four panels consist of one simultaneous climate policy scenario and four separate air policy scenarios. Below the four panels, the region-specific costs of the climate policy scenario and of the four separate air pollution scenarios are presented. The costs are measured as welfare losses as a percentage of National Income (NI). Finally, also the emission prices of the air pollutant gases are presented (uniform over sectors in a region but substance-specific).

The global GHG emission reductions result from a constraint on CO2 emissions (a 45% and 55% reduction of emissions of the BAU in 2030 and 2040, respectively) and a non-CO2 emissions price. The CO2 constraint yields a worldwide CO2 emissions price, which in turn is also used for non-CO2 gases (by multiplying it with the relative GWP of that particular non-CO2 gas compared to CO2). The uniform carbon price in the ‘450’ climate policy scenario is equal to 74 and 160 2004US$/t$CO_2$ eq. in 2030 and 2040, respectively.[21] The level of the carbon price for 2030 seems to be low when considering the range reported in Kriegler et al. (2013) for all models. The main reason is that for the ‘Non Annex-1 Energy Importers’ region the model simulates large emission reductions. In that particular region the energy prices are low, and therefore a global uniform carbon price will have a large impact anyhow. But WorldScan seems to simulate relatively large structural changes in the economy, large energy savings, and the

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[21] Appendix D presents in Table A3 the carbon prices and renewable subsidies of all climate policy scenarios.

phase-out of cheap coal in favour of renewable energy.[22] However, for 2040, emissions prices catch-up with other models.[23] The GHG emission reduction can be seen to be the largest by the 'Non Annex-1 Energy Importers' region (almost 50%), followed by the 'Non Annex-1 Energy Exporters' region, and the EU27 reduces emissions with the smallest percentage around 30%.

Weyant et al. (2006) pioneered with a multi-gas mitigation model comparison. For a climate target of 650 ppmv in the atmosphere, they showed that the average ratio of CO2 to non-CO2 abatement (of all models) increased from 3 to 5, and even 9 in 2025, 2050, and 2100, respectively. In the '450' climate policy case this ratio here is equal to 4 and 3 in 2030 and 2040, respectively. So, the increase of this ratio over time contrasts to Weyant et al. (2006), and there are three reasons. Firstly, the climate policy targets in this paper concern the more stringent '450' and '550' climate policy cases compared to the '650' climate policy case in Weyant et al. (2006). The less stringent climate policies lead to early reliance of non-CO2 abatement in GHG emission reductions, and an indication is given by the '550' climate policy case where this ratio does increase over time (3.9 to 4 in 2030 and 2040, respectively). Secondly, in the BAU the ratio of CO2 to non-CO2 emissions decreases after 2030, which also differs from Weyant et al. (2006). There are more non-CO2 abatement options in the BAU here, and hence may increase the importance of non-CO2 reductions for GHG mitigation. And thirdly, it should be noted that the time horizon of the analysis in this paper is only 2040, which shows much less pronounced changes in this ratio than the enormous increase beyond 2050 in Weyant et al. (2006).

Now returning to Figure 2, it can be seen that the ranking of sectors contributing to GHG reductions is similar for EU27 and 'Rest of Annex-1': EOP with CCS, followed by the electricity sector, and the 'Other industry'. Although the GHG emission reduction is slightly larger in 'Rest of Annex-1' compared to EU27, the co-benefit of emission reductions of SO2 are larger in EU27 (30%) than in the 'Rest of Annex-1' region (20%). The main reason is the simulated subsidy in

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[22] See Brink et al. (2013) when they compare WorldScan with TIMER on emission reductions in China.

[23] The range of WorldScan' carbon prices in 2040 of climate policy scenarios is as large as those of similar recursive dynamic multi-sector models (GEM-E3 and the partial model GCAM), see Kriegler et al. 2013).

the EU27 of 45% of renewable energy price to stimulate the share of renewable energy to 20%. This subsidy reduces the demand for coal-fired power plants in EU27 - originally the contributing source within the power sector to SO2 emissions. And this subsidy is zero in 'Rest of Annex-1', so in this region only the carbon price yields the switch away from coal.

With respect to substances, the order of percentage emission reductions compared to the BAU of air pollutant gases is SO2, NOx, PM25, and NH3, and it is the same in all regions. Only in 'Non Annex-1 Energy Exporters' the percentage emission reduction of SO2 is much smaller than of NOx. The decoupling from the growth of SO2 emissions to the growth of GHG emissions in 'Non Annex-1 Energy Exporters' in the BAU is much higher than in the other part of the Non Annex-1 region.[24] Overall, if we compare the energy importers and the energy exporters in 'Non Annex-1', then we can see that the co-benefit is larger in the former region for all substances, except for PM25 (it is of similar magnitude). Thus, the co-benefit of declining emissions of air pollutant gases is larger in the energy importers' region than in the energy exporters' region of Non Annex-1. The reason is that 'Non Annex-1 Energy Importers' region expands on coal compared to the base-year as to sustain high economic growth (China) in the BAU. The co-benefits are much smaller in Annex-1, because they have achieved much lower emission intensities from existing air pollution policies.[25]

The co-benefits are very comparable to the results in Rafaj et al. (2012). For EU27, the levels in 2030 and the percentage emission reductions compared to the BAU are very similar for SO2, NOx, and PM2.5. Even the order of sectors contributing to emission reductions of the air pollutant gases is the same. For example, in Rafaj et al. (2012) the GAINS/POLES analysis shows that the emission reductions in SO2 come from the electric sector and the 'other industry,

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[24] Figure A2 in Appendix D presents region-sector-specific emissions of the BAU for GHG and air pollutant gases.

[25] Only in the '450P_CE' scenario in the 'Non Annex -1 Energy Importers' region there are no co-benefits in 2040, because the climate policy breaks down in this region.

whereas for NOx it will be mainly the electric sector.[26] But also adding the results for China and India, and then comparing the percentage emission reductions and the relative importance of sectors contributing to those reductions with WorldScan suggest similar results. The percentage emission reduction of GAINS/POLES is 45% for SO2, 35% for NOx, and 15% for PM25. Only for PM25, WorldScan shows more co-benefits. The first reason for this is probably that in WorldScan 'the other energy importing African countries' are included in 'Non Annex-1 Energy Importers' with large PM25 emissions. And the second reason could be that in this analysis more flexibility is assumed with respect to the possibilities of households to switch their consumption pattern thereby lowering their emissions (although the domestic sector in GAINS/POLES is also a significant contributor to the co-benefits). It is more difficult to compare results with McCollum et al. (2013) as they mainly report global results, although they also conclude that stringent climate policies have significant impacts on the (worldwide) emissions of air pollutant gases.

But with WorldScan in hand, including all the EOP options available to a region to reduce emissions of air pollutant gases, direct air pollution policies can also be investigated. Carbon prices can be simulated to keep emissions below a chosen ceiling for greenhouse gases, and air pollution prices can be simulated to limit emissions of air pollutant gases. The air pollution prices are region-pollutant-specific to yield a government income that is returned lump-sum to the consumers. The production cost to a sector increases from the introduction of the emissions price on air pollutant gases. The simulated level of the price of emissions also depends on the marginal cost of employing EOP abatement measures. But the increasing production cost – in a sectoral CGE asWorldScan – leads to reallocation of inputs (labour, capital) across sectors, keeping in mind that production can also be used for trade. So compared to, for example, the

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[26] This is not a surprise, because GAINS was used to calculate emissions of air pollutant gases, and the emission inventories of GAINS and WorldScan are the same. The POLES model (Russ et al, 2007) was used to account for the structural changes of the climate policies in energy markets. Although the POLES is a recursive dynamic energy systems model, it can be expected that the structural changes in EU27 till 2030 will not be much different from those simulated with WorldScan.

GAINS model simulations – almost entirely relying on EOP abatement and to some extent on fuel-switches – WorldScan simulates a much wider structural response to abatement of emissions of air pollutant gases.[27] In Appendix E more details are given on the structural changes in the electric sector induced by the air policy in ‘Non Annex-1 Energy Importers’ region, focusing especially on coal-fired power plants. For this particular sector, it can be seen that the air pollution policy yields an emission price of SO2 and NOx. The substance specific mark-up of the demand price of coal in the electricity sector is equal to the emission price multiplied with the emission factor (including any EOP abatement if applicable) of coal-fired power stations and divided by the demand price of coal in the BAU scenario. The total mark-up is equal to the sum of all substance specific mark-ups (here SO2 and NOx). In the air policy scenario, 40% of the emission reduction of air pollutant gases comes from EOP abatement (maximum EOP potential is 66%, 83% and 77% for NOx, SOx, and PM25, respectively). In the air policy scenario, the total mark-up of the coal price to coal-fired power stations is equal to 50% of the level of the price in the BAU (driven by SO2 and NOx emission prices), which is about one-third of the mark-up (driven by the carbon emissions price) in the ‘450’ climate policy scenario. Instead of the 80% reduction of GHG emissions by coal-fired power stations in ‘450’ climate policy scenario, we can still see a 40% reduction in the ‘AIR’ scenario. McCollum et al. (2013) seem to conclude that there hardly any impacts from air pollution policies to worldwide GHG emissions, but they also don’t account for the mechanisms to analyze all structural responses to a restriction of APG emissions, because they do not optimize energy decisions of MESSAGE under any air pollution gas emission constraint.

The next step is to economically valuate the co-benefits of climate policy. If the costs of the air policy are lower than the climate policy costs, then these costs can be interpreted as the avoided costs of more stringent air pollution policies provided the lower emission levels can be

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[27] This does not necessarily mean that WorldScan outcomes are cheaper than GAINS, because of potential deadweight losses of emissions prices interacting with existing energy taxes.

part of a welfare improving target. In Bollen et al. (2009b) and Bollen et al. (2010) it is argued from a cost-benefit perspective that the welfare-optimal level of emissions of air pollutant gases lie well below the current existing levels. So for the sake of argument in this paper, the lower costs of emission prices of air pollutant gases indeed can be interpreted as avoided costs, and thus as the value of the co-benefit. These co-benefits could provide an extra incentive to pursue climate policy. In Bollen et al. (2009a) the value of the co-benefits was based on the valuation of premature deaths with MERGE. Instead of the simple macro-economic mechanisms (one-sector + detailed electricity generation, and only trade in gas and oil) employed, here WorldScan (multi-sector multi-region model with trade in all commodities) is used. As can be seen the climate policy costs in 2030 are equal to 0.16% of National Income (NI), and the direct air policy that attains the same improvement of air pollutant gases only costs 0.04% of NI in 2030. Thus the value of the co-benefit is 25% of the mitigation costs in EU27.

Surprisingly, the value of the co-benefit of ‘Rest of Annex-1’ is zero. If we, however, look closer at the air pollution policies of ‘Rest of Annex-1’ and EU27, and compare losses in General Domestic Product (GDP) versus NI, then the losses in NI turn out to be about 50% smaller.[28] The difference between changes of the two indicators is often dominated by terms-of trade changes, which is the change of average export price divided by the average import price. A gain implies that when production remains constant, income generated from net exports will be increasing. The terms-of-trade gain of energy related policies in net energy importing countries is a common result of multi-region multi-sector CGE models with trade.[29] The costs of the air policy can be passed onto foreign consumers. Larger economies have more market power (the variety produced is important to foreign consumers), and hence the producers can absorb environmental policy costs by having other countries pay for it. It turns out that the costs of the

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[28] The losses in 2030 are equal to 0.14 and 0.10 % of GDP in the ‘Rest of Annex-1’ and the EU27, respectively. The losses are equal to 0.07 and 0.06% of NI in the ‘Rest of Annex-1’ and in the EU27, respectively. It can be said that GDP is the value produced within a country’s borders, whereas the NI is the value produced by all the citizens.

[29] See for example Boehringer et al. (2011).

air policy of the ‘Rest of Annex-1’ region are zero, and hence they will hardly experience the economic benefit of lower emissions of air pollutant gases. This is not the same result as in Bollen et al (2009a), which estimated large values of co-benefits for e.g. the USA based on damage valuation (0.4% GDP). The trade perspective from the analysis in this paper provides an argument to lower the value of the co-benefit for this particular region because of terms-of trade gains.

In the Non Annex-1 region, EOP absorbs part of the necessary emission reduction in the air policy simulation. In case of SO2 emissions in the ‘Non Annex-1 Energy Importers’ region, the structural changes account for a large part for abatement in the air pollution scenario, even larger than in e.g. the EU27. The somewhat larger role of structural changes for APG abatement compared to the Annex-1 region may lead to the suspicion that the value of the co-benefit might be relatively high. Moreover, the terms-of-trade gains for ‘Non Annex-1 Energy Importers’ are relatively less pronounced, because their market power in foreign markets is less (calibration of preferences of varieties is based on 2004 data).[30] The value of the co-benefits for ’Non Annex-1 Energy Importers’ can accrue to 0.47% of NI, which is 60% of the ‘450’ climate policy cost (0.82%). Finally, for the ‘Non-Annex-1 Energy Exporters’ the value of the co-benefit is larger, but is small compared to the costs that they will likely experience from declining revenues of the export of fossil fuels.

Figure 3 then takes the broader perspective of showing impacts on the costs in 2030 and 2040 for all climate and air policy scenarios. Concerning the overall costs of the climate policy scenarios, the following can be said. First, the costs of the policy scenarios especially hurt the countries of the Non-Annex 1 region relatively to the rich North (Annex-1), see also the ranges on the lower panels of Figure 3. The assumption of the uniformity of the carbon prices accounts

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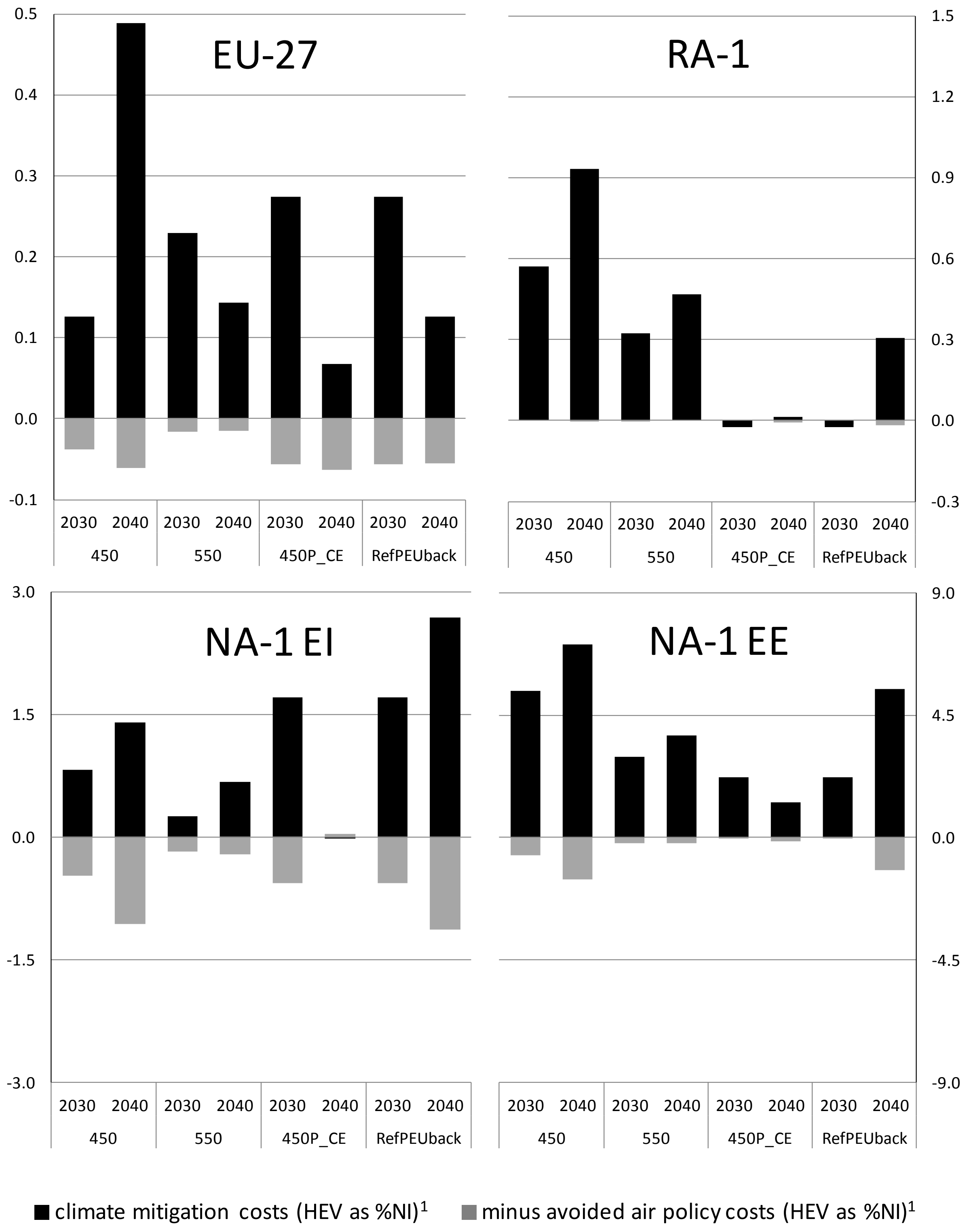
[30] The losses in GDP in 2030 in ‘Non Annex-1 Energy Importers’ region are 1.1% and 0.9% in BBP and NI, respectively. So the difference between losses in GDP of ‘Annex-1’ and NI is 50%, and in Non Annex-1 Energy Importers’ region only 20%.

for this phenomenon, because carbon prices distort low-income economies (low energy prices) much more than high-income economies (higher energy prices from existing energy taxes). Second, within Non Annex-1, the energy exporting economies will lose the most (their costs may be equal to 6%, see the range of the right y-axis on the lower panel) due to declining revenues from fossil energy exports. Third, within Annex-1 the losses in ‘Rest Annex-1’ are generally larger than in EU27. And also here the reason is that fixed uniform carbon prices have a larger impact on low energy price economies (such as the USA as part of ‘Rest of Annex-1’) than high energy price economies (EU27). Also in high energy price economies - such as EU27 - terms-trade-gains can be achieved that lower the costs of a climate policy. These findings confirm insights from earlier WorldScan analyses, see Bollen et al. (2011). Fourth, the costs of the policy scenarios tend to increase for all regions, except in ‘refP-CEback’, because of the setup of that particular policy scenario (lower ambition beyond 2030). But within EU27, the ‘550’ climate policy scenario will show lower economic impacts in 2040 compared to 2030 (losses decline from 0.22% in 2030 to 0.12% of NI). The increase of the uniform worldwide carbon price is limited in the ‘550’ climate policy scenario (from 34 to 47 2004US$/tCO2 eq. in 2030 and 2040, respectively) compared to ‘450’ climate policy scenario (from 74 to 162 2004US$/tCO2 eq. in 2030 and 2040, respectively), and then the terms-of-trade gains become more apparent and increasingly dominate the overall costs of the climate policy, thus lowering the costs for EU27.

Figure 3 Costs and co-benefits of different Policy Scenarios



Note: [1] HEV as %NI expresses the costs as compensating Hicksian Equivalent Variation (HEV) as % of National Income (NI).

The value of the climate co-benefit in the EU27 is significant and can accrue in the period 2030-2040 up to 10-20% of the costs in the '450' climate policy scenario. The value of the climate co-benefit in 'Non Annex-1 Energy Importers' is significant, only in 'RefPCEback' it is small. In terms of emissions, the co-benefits are significant - although smaller than in EU27. EOP measures are more important in 'Rest of Annex-1' than in EU27, because in that region the abatement potential larger (see also Amman et al, 2009). Secondly, the air pollutant emission prices can be passed on to foreign consumers. Hence, any production losses are compensated by terms-of-trade gains. If climate policy cost assessments consider that cheap EOP abatement options are available, and that indirect trade impacts of avoided air pollution abatement could be important, then 'Rest of Annex-1' will give little value to co-benefits.

The value of the climate co-benefit in 'Non Annex-1 Energy Importers' is the largest and can in the '450' climate policy scenario will be equal to 60 and 80% of the costs in 2030 and 2040, respectively. In the '550' climate policy scenario the co-benefits will be equal to 70% and 30% in 2030 and 2040, respectively. The opposing trend in the share of the co-benefits is due to the lower carbon price. Therefore, fossil fuel prices will be higher in the '550' climate policy scenario, and hence will lower the emission prices of the air pollution policy. This region is faced with term-of trade losses that decline as the policy shock increasingly becomes a marginal one.

The value of the co-benefits is significant in the 'Non Annex-1 Energy Exporters' region, but cannot sufficiently compensate for the large losses of the climate policies. They lose by far the most - the costs of the climate policy range from 3% to 8% of NI. The main reason is that energy exporters will also be faced with falling revenues of their fossil energy exports (gas and oil). Hence, co-benefits - although significant - only to some extent offset the climate policy losses (10% of the total costs). In 2030, the value of the co-benefits ranges between 0 and 0.7% of NI ('450' climate policy scenario). In 2040 in the '450' and '450_CE' climate policy scenarios, it can still accrue up to 20% of the total costs of the climate policy. Nevertheless, it can be seen that the co-benefits become much smaller in the milder ‘550’ or ‘RefP-CEback’ climate policy scenarios. The emission reduction from structural changes decline significantly, because the overall reduction of GHG emissions is lower. Also, EOP abatement becomes more dominant in the non-stringent cases. For example, in the ‘450’ climate policy scenario, EOP accounts for 25% of the total abatement (see Figure 2, panel on the bottom and the right-side). In the ‘550’ climate policy scenario, this percentage grows to 35%. So, then also the co-benefit of lower emissions of air pollutant gases will be lower. But also the ratio of the value of the co-benefit to the costs of the climate policy declines, see for example in the ‘Non Annex-1 Energy Importers’ region this ratio from 20% to 5%. The main reason is that the difference between the air emissions prices is larger than the differences in the carbon prices. For the air policy cases, EOP is more important than for GHG abatement. And it seems that the convex shape of the marginal abatement cost curves (see the two examples of coal-fired power plants in the ‘Non Annex-1 Energy Importers’ region in Figure A.1 of the supplementary material), thus allows the air emission prices to fall much sharper than the GHG emission prices, and hence also lowers the ratio of the value of the co-benefits to the climate policy costs.

5 Conclusion

This paper describes the extension of WorldScan, a CGE model originally designed to be able to analyze GHG policy, although the model approach was limited to taxation of energy related CO2 emissions. The extension of the model involves equations to calculate emissions and abatement of emissions of four major air pollutants (SO2, NOx, PM2.5, and NH3) and the non-CO2 greenhouse gases (CH4 and N2O). The model can now analyze climate and/or air policies. Further, this paper estimates the structural changes induced by climate policy, and shows the indirect consequences of this type of policy on the emissions of air pollutants. The air policy achieving the emission reductions of the air pollutants induced by the climate policy (co-benefit) can be seen as the policy than can be avoided. And the macro-economic costs of such an air policy can be seen as the economic value estimate of this co-benefit. This value can be compared with the overall macro-economic cost of the climate policy. The larger the value of the co-benefit, the more willing a region might be to undertake a costly climate policy. The analysis presented in this paper argues the value of the co-benefit - based on measuring costs as GDP losses induced by the air policy – needs to be adjusted with terms of trade gains or losses at the macro-level. It is shown that for net-energy importing countries that the amount of money to compensate for any utility loss divided by the NI of the BAU - is significantly lower than the percentage GDP loss of the air policy. It is shown that climate policies with uniform carbon prices over the world (or something alike in fragmented strategies) generally produces a large co-benefit in the poor South (or China), because these regions currently lack air pollution policies or expand economically so rapidly that air pollution is growing much faster than in developed countries. This implies that the aforementioned climate strategies may yield large structural changes (and also large GHG emission reductions) in low-energy-price economies and thus also large emission reductions of air pollutant gases. The value of the co-benefits can accrue up to 75% of the climate policy costs in the ‘Non Annex-1 Energy Importers’ region.

One other important issue concerns the uncertainty of the term-of-trade gains in perspective of multilateral environmental policies. In the current setup of the analyses of this paper, the air policy is a unilateral action of one net energy importing region, thus generating a terms-of-trade gain that ultimately lowers the value of the co-benefits. But what happens if air policies occur simultaneously in different net energy-importing countries? It is not clear at forehand what might be the impact on the co-benefits. The composition of bilateral trade flows between countries of different goods with different energy intensities may lead to asymmetric responses from multilateral air policies by several countries on the export price to the import price of a particular net energy-importing country. Nevertheless, as with the assessment of climate policy costs based on multi-sector multi-regional CGE models with trade, terms-of-trade matters and can be very substantial. This argument clearly extends also to the value of co-benefits of climate policies if they are based on avoided costs.

Another important issue is to be aware that the conclusion - of high values of co-benefits relative to climate policy costs – is conditional upon planned air pollution policies in the BAU. For example, if the air policies are assumed to become more stringent in the BAU, then the (value of the) co-benefits of climate policy will also be estimated to be lower. The emissions of developing countries in the BAU may be too pessimistic, as we may expect these countries to respond to serious air pollution problems. This argument is used in the assumption of the BAU that the gap in emission coefficients between developing countries and the OECD declines at the same rate as the gap closes in regional income levels per capita (OECD, 2012). The analysis in this paper is a first educated guess on this issue, and more assumptions need to be investigated in future research.

Also, this analysis is based on large regions, and deepening of the analysis by moving from regions to countries and a disaggregation of sectors (for example, the energy-intensive sector or transport sector) may give different and probably better indications of terms-of-trade consequences of the level of direct costs of air pollution abatement for different countries or the level of abatement costs to specific countries. This needs to be investigated further.

Finally, the GHG co-benefit from air policies also deserves more attention. The interesting aspect of air policies is that stringent air pollution targets will create a benefit of lower emissions of air pollutants that accrues in the short term to the region that pursues the air policy. Figure 2 showed that the ‘AIR’ scenarios yield a GHG emission reductions in the developing countries. And although this is beyond the scope of the analysis of this paper, the GHG emission reduction may reduce the long term impacts of climate change, which can be considered as a benefit to the rest-of-the-world . The political economy related to air policy and climate policy seems to be completely different as the former is a much more local issue than the latter. The co-benefits of a

GHG emission reduction induced by locally driven air pollution policies therefore need to be studied further.

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Appendix A: Calibrating the BAU Scenario

The effects of climate and air policy depend strongly on the underlying BAU. The policy scenarios developed in this paper are based on variations current policy baseline of the AMPERE project ‘refpol’ scenario (see Kriegler et al, 2013).

The calibration of ‘refpol’ in WorldScan employs trends for population and GDP by region, energy use by region and energy carrier, technology targets if applicable, 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 (TFP, 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. Learning rates are fixed, and the long run costs of electricity technologies decline with each doubling of the cumulative production of these technologies, i.e. 20% for CCS, biomass, wind-offshore, and solar, 10% for wind onshore, and 0% for the other electricity technologies. The potential reduction of costs in the long-run (one minus long-term floor cost level divided by the 2004 cost level) is 80% for CCS, 65% for wind-offshore and biomass, 80% for solar, 33% for all other technologies. This calibration of learning for the ‘RefPol’ scenario reproduces the ordering of reductions of electricity technologies of the ‘reference’ scenario of IEA (2010), In policy variants, TFP, energy efficiency, and natural sources are fixed. GDP, energy use and prices are endogenous.

The ‘refpol’ assumes 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.

The last step – relevant for welfare analysis of climate policies in this paper – is to wipe-out all existing regional climate and energy policies (e.g. ETS and technology targets for 2020 in EU27 and technology targets outside EU27) from the ‘refpol’ scenario and derive no-policy baseline or BAU scenario, which keeps the same emission coefficients of APG’s of the ‘refpol’ scenario.

The emission coefficients of all input/sector combinations are based on emissions of APG’s of the BL-WEO 2009 scenario and WorldScan simulation of ‘refpol’ scenario.[31]

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[31] Emissions are based on GAINS model scenarios, and extracted from http://gains.iiasa.ac.at/models/. The BAU scenario is ‘BL_WEO_2009’, which is a Current Legislation (CLE) Scenario. For Europe, see Capros et al.(2010). For the regions and years (beyond 2030) not covered by GAINS, the emissions are in line with the OECD Environmental Outlook scenario to 2050 (OECD, 2012). More on this issue when discussing the calibration of emission factors. The abatement options are based on: for Europe (‘BL_WEO_2009’), for Annex-1 (‘PRIMES_BL2009_14jan10’), for China (‘Baseline08’) and for India (‘Baseline08 + no solid fuel in HH’).

Appendix B Mapping between GAINS activities and WordScan sectors

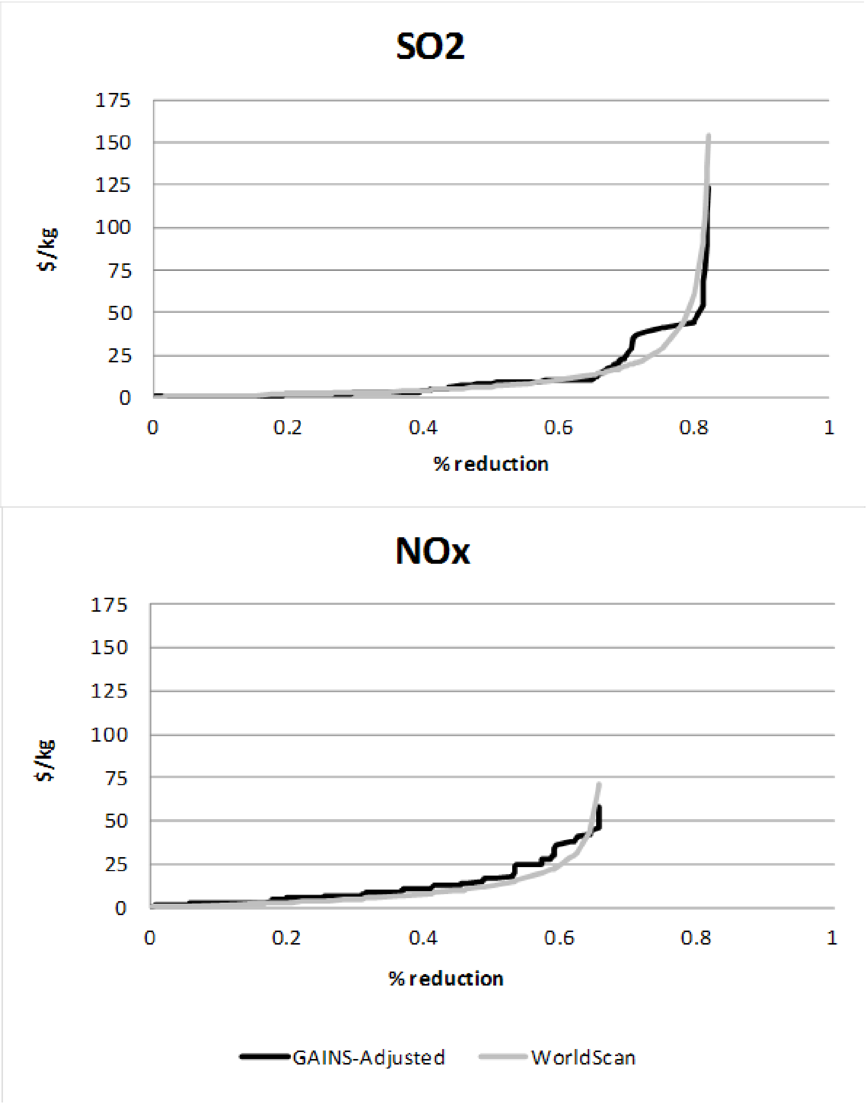
Table A.1 Mapping between GAINS activities and WordScan sectors

Worldscan sectors	**GAINS sectors**
Animal Products	Agriculture: Livestock
Other agriculture	Agriculture: Ploughing, tilling, harvesting
	Crops left on field
	Other transport: agriculture and forestry
	Domestic sector - other services, agriculture
	Domestic sector - forestry, fishing, and non-specified sub-sectors
	Storage and handling: Agricultural products (crops)
	Rice cultivation
	Agriculture: grassland and soils / organic soils / 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
Consumer Goods	Meat produced
	Food (incl. beverages and tobacco) manufacturing industry
	Fat, edible and non-edible oil extraction
	Textile industry
	Wood and wood products industry
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, Consumer Goods, Capital goods & durable	Other Industry
	Ind. Process: Agglomeration plant - pellets / Small industrial and business facilities
	Ind. Process: Carbon black production / Open hearth furnace
Energy intensive	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
	Ind. Process: Production of Bricks / Basic oxygen furnace / Cast iron / Coke oven
Transport	Road transport - Heavy duty vehicles / Light duty vehicles
	Road transport - Motorcycles / Motorcycles, mopeds and cars with 2-stroke engines
	Other transport: rail / offroad / other off-road
	Other transport: domestic air traffic - civil aviation / inland waterways / maritime activities
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

Appendix C EOP Abatement Cost Curves for 2030 of SO2 and NOx in the NA-1 EI region and Abatement Potential of EOP in 2030

Figure A.1 shows to what extent a MAC curve (WorldScan) relates to the GAINS data (the GAINS-adjusted line). The smooth curved line is the derivative (with respect to x) of equation 3, and the parameters β, κ are estimated by the statistical technique of Ordinary Least Squares (OLS), while the parameter x_{max} is directly taken from GAINS.

Figure A.1 Marginal abatement cost curves for 2030 in the NA-1 EI region of coal-fired power plants for SO2 and NOx: The bottom-up data of GAINS-models and WorldScan approximation



Note: The costs are corrected for price changes 2005-2030 of 'capital goods and durables'

From Figure A.1 it can be seen that the OLS estimated curve as implemented in WorldScan provides a reasonable fit to the GAINS data. Also, Figure A.1 shows that Maximum Feasible Reduction (MFR) percentage of coal-fired power plants in NA-1 EI regions is more than 80% for SO2 and almost 70% for NOx. These MFR percentages are much larger in the NA-1 region than in the economically more developed countries belonging to the Annex-1 group of countries (in WorldScan EU27 and RA-1), because in the past in especially the latter region more financial resources have been spent to mitigate acidification and air pollution.

Table A.2 Maximum feasible reductions (%) in sectors for SO2, NOx, and PM25 based on GAINS

	NOX				SO2				PM25			
	EU27	RA-1	NA-1 EI	NA-1 EE	EU27	RA-1	NA-1 EI	NA-1 EE	EU27	RA-1	NA-1 EI	NA-1 EE
Electricity - Fossil	43	41	65	43	27	64	83	36	7	38	77	20
Biomass	12	25	0	0	8	71	0	42	0	0	0	0
Energy Intensive	21	11	3	0	41	43	38	2	55	69	84	59
Petroleum Coal Products	4	29	0	0	25	24	8	6	47	0	78	0
Coal	0	0	0	0	0	0	0	0	0	1	0	0
Oil	0	0	0	0	0	0	0	0	0	0	0	3
Gas	0	78	0	0	0	0	0	0	0	0	0	3
Other Agriculture	2	1	30	0	0	0	0	0	74	77	86	74
Animal Products	0	0	0	0	0	0	0	0	37	63	76	67
Minerals NEC	48	56	71	64	40	31	22	50	16	25	30	61
Consumer Goods	0	0	0	0	20	0	24	0	0	0	64	0
Capital Goods&Durables	0	0	0	0	0	0	13	0	29	0	0	0
Services	22	23	0	0	34	29	0	0	64	0	71	8
Gross Rent and Fuel	24	37	0	34	37	17	25	0	84	90	89	37
Other transport	0	0	0	0	20	23	53	36	0	0	0	0
Total	30	27	43	29	34	44	51	15	58	63	70	45

Note: GAINS data based on WEO2009 and sectoral mapping as in Table A.1

The MAC's exist for most air polluting inputs relevant for particular sectors. The inputs are Coal, Oil, Gas, Energy-Intensive Sector (producing fertilizers), Biomass, Biofuels, Bio-ethanol. Also, most sectors simulate process related emissions, i.e. emissions that are linked to production instead of the use of a particular input (for example, coal) to produce output (for example, electricity), Table A.2 shows the MFR percentages as estimated for WorldScan sectors (including process emissions if applicable).

Table A.2 shows the MFR percentages for all economic sectors and GRF by households. The MFR percentages of Figure A.2 are in the same range as for fossil-based electricity in the NA-1 EI region (83 versus 65%). Table A.2 shows these percentages for all sectors. It is important to realize that coal-fired power plants are part of fossil electricity, whereas the production of coal is handled by the coal sector. The main emission sources at the global level are energy-intensive, electricity (both in range 25-75%), oil refineries (P_C, SO2, 15%), other transport (NOX, 35%), and Households (GRF, PM2.5, 26%).

In principal there are 11 production sectors and 9 consumption categories. So in each region there are 20 times 6 number of possible MAC curves each substance. It can be seen – after conducting the mapping procedure - that only a small fraction of the number of sectors times the number of inputs are of importance and applicable to emission reductions by EOP. For example, in ‘Rest of Annex-1’ there are 18 MAC-curves, which is about 15% of all possible combinations of sectors, inputs, and substances for which theoretically a MAC curve might exist.

Appendix D: Taxes in All Scenarios and Emissions of All Gases in the Base

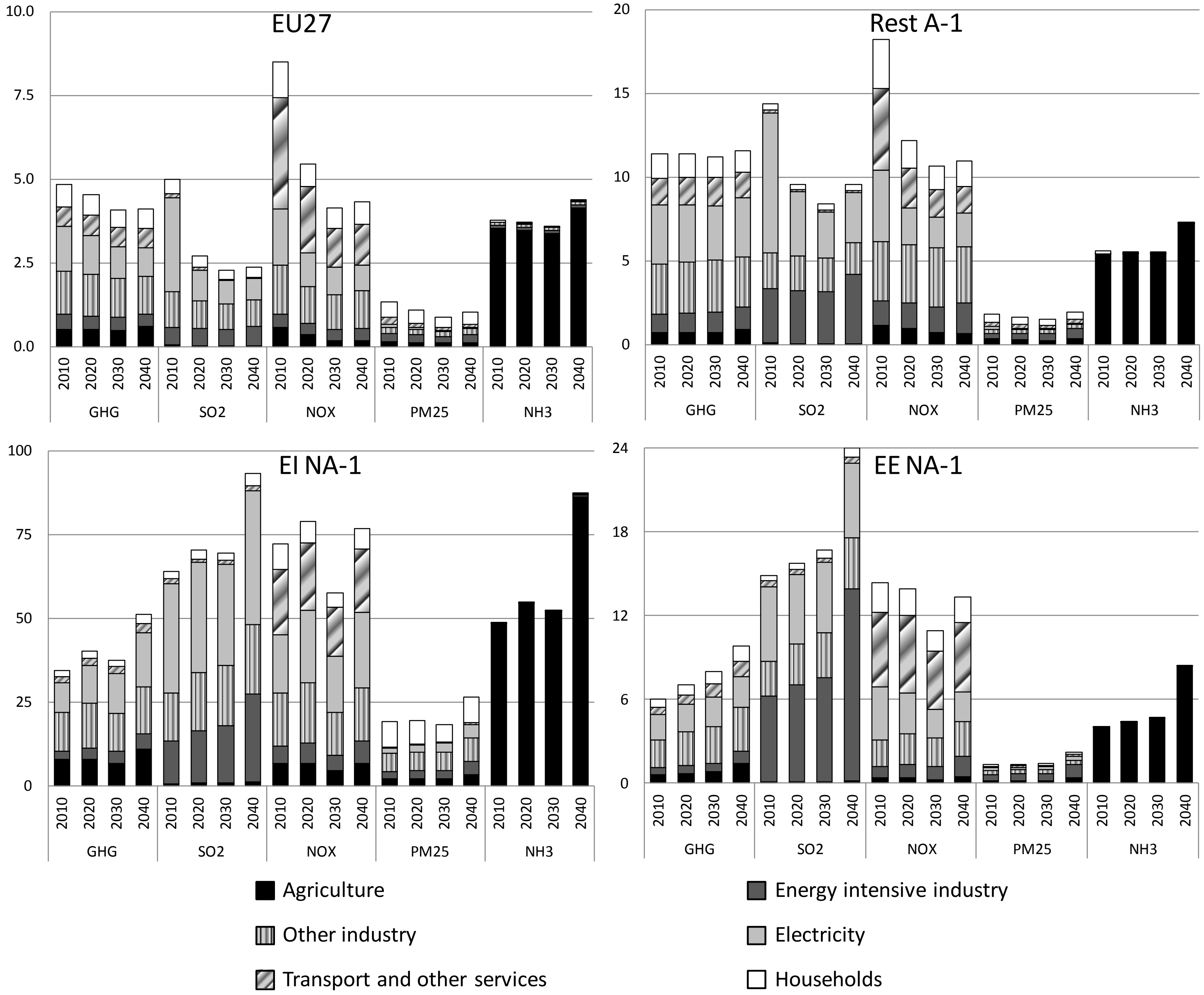
Here, carbon prices of the different climate policy scenarios are presented. It is not included in the main text of this paper, because it is part of Kriegler et al (2013). But the structural changes depend on these carbon prices. Below in Table A.3 the carbon prices ($ / 2004US$/tCO2 eq.) and renewables subsidy (% of the average electricity price) in 2030 of the climate policy scenarios are presented.

Table A.3 Carbon Prices and Renewable Subsidies in the Different Policy Scenarios

Scenario	Region		Carbon price in 2004 US$/ tCO2 eq.	Renewables Subsidy (% of electricity price)	Scenario	Carbon price in 2004 US$/ tCO2 eq.	Renewables Subsidy (% of electricity price)
450	R A-1	2030	74	-	450P_CE	30	-
		2040	162	-		162	-
	NA-1 EI	2030	74	-		74	-
		2040	162	-		162	-
	NA-1 EE	2030	74	-		5	0.13
		2040	162	-		162	-
	EU27	2030	74	0.45		74	0.40
		2040	162	0.14		162	0.25
550	R A-1	2030	34	-	RefPEUback	30	-
		2040	47	-		40	-
	NA-1 EI	2030	34	-		74	-
		2040	47	-		12	-
	NA-1 EE	2030	34	-		5	0.13
		2040	47	-		22	-
	EU27	2030	34	0.42		74	0.40
		2040	47	0.35		77	0.30

Also the emissions of GHG’s and APG’s of the BAU is presented in Figure A.2 as it is relevant to understand to where and when the potential of co-benefits may occur. Figure A.2 presents the sectoral emissions of GHG’s and APG’s up to 2040 in the four regions . It is important to recognize that most of the emission reduction of APG’s in the Base scenario occurs up to 2030. Beyond 2030, the emission coefficients are slowly declining (see also OECD, 2012), and hence as activities grow again, we can see that emissions of APG’s are somewhat higher in 2040 compared to 2030.

Figure A.2 Sectoral Emissions of GHG's (Gt CO2 eq) and APG's (Mt) in the BAU



Appendix E: EOP measures versus structural changes as a response to emission prices: an example in coal-fired power plants in NA-1 EI in the year 2030

Below, Table A.4 shows the example of the 450 climate policy scenario and the air policy scenario of coal demand in the electricity sector. The table summarizes data for the year 2030 and the NA1-EI region.

Table A.4 Energy use, Emission Prices, Mark-up price of coal, Emissions, and the Change of Emissions (compared to BAU) through EOP abatement or structural effects in coal-fired power plants in NA-1 EI region in 2030 in the BAU, in the '450' climate policy scenario (450), and the 'air' policy scenario (AIR) in NA1- EI region.

		BAU	450	AIR
Energy use				
- Coal (EJ)		2376	912	1575
Prices				
- GHG ($/ton CO2-eq.)			74	0.0
- SO2 ($/kg SO2)			0.0	3.1
- NOx ($/kg NOx)			0.0	4.7
- PM2.5 ($/kgPM2.5)			0.0	2.5
Mark-up price of coal				
- related to price GHG			140%	0%
- related to price SO2			0%	28%
- related to price NOx			0%	21%
- related to price PM2.5			0%	4%
Emissions				
- GHG (Gton)		10	2	6
- SO2 (Mton)		28	11	13
- NOx (Mton)		15	6	7
- PM2.5 (Mton)		3	1	2
Change of emissions of GHG (Gton)			-8	-3
of which	- end-of-pipe		-2	0
	- structure effects		-6	-3
Change of emissions of SO2 (Mton)			-18	-16
of which	- end-of-pipe		0	-6
	- structure effects		-18	-10
Change of emissions of NOx (Mton)			-9	-8
of which	- end-of-pipe		0	-3
	- structure effects		-9	-5
Change of emissions of PM2.5 (Mton)			-2	-1
of which	- end-of-pipe		0	0
	- structure effects		-2	-1

Table A.4 shows the response on the demand for coal in the power sector, on emissions of GHG's and APG's (NH3 is omitted as coal-fired powerplants do not produce any NH3 emissions), on the mark-up or (implicit) tax on coal stemming from pollution prices (either on GHG's or air pollutants), and on the reduction through changes in EOP or structure effects.

First, it can be seen that indeed according to the assumptions of the '450' climate policy scenario there is a GHG emission price, which is zero in the air pollution scenario. The CO2 emission price is endogenous to meet the predefined CO2 budget to 2050, which has been used in the AMPERE project, and is described in Kriegler et. al (2013). The CO2 price is also used for the non-CO2 gases by using the appropriate factors of the greenhouse warming potential. The emission prices of the APG's in AIR are determined by the model with the regional benefit (a regional emission reduction) equal to the regional co-benefit of the '450' climate policy scenario.

Second, the carbon price of 74 US$/tCO2 eq. in the '450' scenario implies a mark-up for the coal price equal to 140%, i.e. the international coal price is increased with another 140% to comply with the carbon budget prescribed in the 450 scenario.

Third, the region-specific air emission prices are translate to 28% (from the SO2) and 21% (from NOx), and 4% (from PM2.5) of the mark-up for coal, which is in total 53%. We can see that the price increase of coal in 'AIR' is one third of the price increase of '450'.

It is important to realize that these emission prices are handled in WorldScan in the same way as the carbon prices in the climate policy scenarios. This means that these emission prices increase the costs of using the polluting input (here the burning of coal), and it is implemented as a tax that yields a government budget returned lump-sum to the consumers. The endogenous tax also depends on the extent to which EOP measures can be used to lower the emissions of using the polluting input, but also here there is marginal cost of abatement involved – directly paid by the power sector yielding a increase of production cost. So compared to the GAINS model analyses – allowing for EOP abatement and some fuel-switches – WorldScan allows for a much wider structural response to abatement of emissions of APG's. Not only changes within electricity sector to renewable sources are optional, also sectoral reallocations of inputs and trade are part of the optimal response as well. This does not necessarily mean that WorldScan outcomes are cheaper, because there are complexities at work because of the existence of second-best economies (deadweight losses from emissions prices interacting with existing taxes).

The substance specific mark-up of the demand price of coal in the electricity sector is equal to the emission price multiplied with the emission factor (including any EOP abatement if applicable) of coal-fired power stations and divided by the demand price of coal in the BAU scenario, and the total mark-up is equal to the sum of all substance specific mark-ups (here SO2 and NOx).The mark-ups for coal explain the incentive for electric power sector to switch away from coal. It can be seen the total emission reduction enables to lower emissions starting from 10 GtcO2 eq down to 2 Gt CO2 eq, and only 2 Gt CO2 eq is coming from EOP (for climate policy this is CCS). The CCS option is not rational or applicable in the AIR scenario, because it does not yield to emission reductions of any air pollutants. Nevertheless, although there are other EOP abatement options applicable to reduce the emissions of APG's, the price increase of coal is not insignificant in 'AIR'. And thus, we can see that instead of an 80% reduction of GHG emissions in '450' there will still be a 40% reduction of GHG's in 'AIR'. This is the same finding as explained in more detail in Bollen and Brink (2012) that focused on air pollution policies in Europe. EOP is important in AIR, and we can see it to contribute with 40% of the total emission reduction by coal-fired power plants (for both NOx and SO2). This EOP abatement is less than the maximum feasible reductions in the NA-1 EI region in coal-fired power plants, which is in all years equal to 66% for NOx (it is about 30% in the A-1 region) and 85% for SO2 (20% in EU27 and 65% in RA-1). These numbers are taken directly from a careful mapping of all abatement options to the WorldScan resolution (in this case all coal-fired power plants).

But WorldScan allows - next to EOP as explained above – simulating structural responses as well to price increases induced by emission prices or taxes of air pollutants. It turns out that these structural responses are important and sometimes cheaper. We need to be aware that poorer countries in the NA-1 EI region have higher emission coefficients, but costly air policies in economies with lower energy prices. This means that cheap abatement options as implemented in Europe in the past - may have a larger relative impact on the costs of production in these poorer countries, and hence structural responses may play a bigger role in abatement strategies than occurred in Europe in the past.