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Summary

This paper presents estimates of the economic benefit of air quality improvements in Europe that occur as a side effect of GHG emission reductions. We consider three climate policy scenarios that reach radiative forcing levels in 2100 of three Representative Concentration Pathways (RCPs). These targets are achieved by introducing a global uniform tax on all GHG emissions in the Integrated Assessment Model WITCH, assuming both full as well as limited technological flexibility. The resulting consumption patterns of fossil fuels are used to estimate the physical impacts and the economic benefits of pollution reductions on human health and on key assets by implementing the most advanced version of the ExternE methodology with its Impact Pathway Analysis. We find that the mitigation scenario compatible with +2°C reduces total pollution costs in Europe by 76%. Discounted ancillary benefits are more than €2.5 trillion between 2015 and 2100. The monetary value of reduced pollution is equal to €22 per abated ton of CO2 in Europe. Less strict climate policy scenarios generate overall smaller, but still considerable, local benefits (14 € or 18 € per abated ton of CO2). Without discounting, the ancillary benefits are in a range of €36 to €50 per ton of CO2 abated. Cumulative ancillary benefits exceed the cumulative additional cost of electricity generation in Europe. Each European country alone would be better off if the mitigation policy was implemented, although the local benefits in absolute terms vary significantly across the countries. We can identify the relative losers and winners of ancillary benefits in Europe. In particular, we find that large European countries contribute to as much as they benefit from ancillary benefits. The scenarios with limited technology flexibility do deliver results that are similar to the full technology flexibility scenario.

Keywords: Ancillary benefits, External costs, Climate change mitigation, Integrated Assessment Models, ExternE, Impact Pathway Analysis

JEL Classification: Q47, Q51, Q53, Q54

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Quantifying the ancillary benefits of the Representative Concentration Pathways on air quality in Europe

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Abstract

This paper presents estimates of the economic benefit of air quality improvements in Europe that occur as a side effect of GHG emission reductions. We consider three climate policy scenarios that reach radiative forcing levels in 2100 of three Representative Concentration Pathways (RCPs). These targets are achieved by introducing a global uniform tax on all GHG emissions in the Integrated Assessment Model WITCH, assuming both full as well as limited technological flexibility. The resulting consumption patterns of fossil fuels are used to estimate the physical impacts and the economic benefits of pollution reductions on human health and on key assets by implementing the most advanced version of the ExternE methodology with its Impact Pathway Analysis. We find that the mitigation scenario compatible with +2°C reduces total pollution costs in Europe by 76%. Discounted ancillary benefits are more than €2.5 trillion between 2015 and 2100. The monetary value of reduced pollution is equal to €22 per abated ton of CO_2 in Europe. Less strict climate policy scenarios generate overall smaller, but still considerable, local benefits (14 € or 18 € per abated ton of CO_2). Without discounting, the ancillary benefits are in a range of €36 to €50 per ton of CO_2 abated. Cumulative ancillary benefits exceed the cumulative additional cost of electricity generation in Europe. Each European country alone would be better off if the mitigation policy was implemented, although the local benefits in absolute terms vary significantly across the countries. We can identify the relative losers and winners of ancillary benefits in Europe. In particular, we find that large European countries contribute to as much as they benefit from ancillary benefits. The scenarios with limited technology flexibility do deliver results that are similar to the full technology flexibility scenario.

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1 Introduction

There is wide consensus on the need to regulate Greenhouse gases emissions (GHG) to limit the adverse impact of climate change. Hardly any country in the world disputes that the current pattern of GHG emissions is unsustainable. However, there is wide disagreement on the magnitude of the optimal emission reductions, on the distribution of effort across countries, and on the timing of the emission reductions. This is hardly a surprise: the climate problem is a perfect example of intra-generational and inter-generational externality. Emission abatement costs are local, while the benefits of controlling the increase of GHG concentrations are global and will be experienced only far in the future.

Current carbon taxes and permit trading programs cover only around 12 percent of global emissions (Parry 2014) and current policies are still far from being effective and optimal (see, for instance, Máca et al. 2012; Somanathan et al. 2014). It is unclear if future negotiations will be able to change this dismal state of climate policy. The chances are that if any agreement can be reached, it will entail a low level of commitment (Barret and Stavins 2003).

Some authors suggest that one way to kick-start climate policy is to think locally instead of globally.[1] They notice that climate mitigation policy may have immediate and local co-benefits that could partially or totally offset the cost of reducing GHG emissions. The question then becomes: "what scale of CO_2 pricing is in countries' own interest" (Parry et al. 2014).

For example, investment in low-emission technologies may spur innovation and growth in markets with unemployment and knowledge externalities (Bauer et al. 2009; Acemoglu et al. 2012; OECD 2012a). Carbon taxes or revenues from auctioning emission allowances may reduce distortions in the tax system if appropriately managed (Pearce 1991; Goulder 1995; Carraro et al. 1996; Bovenberg 1999).

As a large fraction of GHG emissions comes from the combustion of fossil fuels, the use of oil, natural gas and coal must be substantially reduced to meet any long-term climate mitigation goal. Fossil fuels also cause local and present environmental damage because, if burnt, they release pollutants that negatively affect human health, ecosystems and other assets. Climate mitigation policies would thus reduce the burden of ground-level air pollution. The reduction of fossil fuels consumption and the shift of the energy mix away from coal – the most polluting among the fossil fuels – to natural gas is expected to reduce the concentrations of particulate matters, sulphur dioxide, nitrogen oxides, ozone precursors (NO_X and VOC) and other toxic pollutants. Climate change mitigation can thus generate immediate ancillary benefits[2] by reducing the negative impacts of pollution on human health, crop yields, building materials or ecosystems.

The aim of this paper is to provide estimates of local air quality ancillary benefits of carbon taxes in Europe. We assume that the carbon price is exogenously set to achieve the most recent set of

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[1] For a survey see Chapter 15 of the Fifth Assessment Report of Working Group III to the IPCC (Somanathan et al. 2014).

[2] The Intergovernmental Panel on Climate Change (Third Assessment Report) distinguishes between ancillary benefits and co-benefits (IPCC 2001). Ancillary benefits are related to policies or measures that are targeted entirely on climate change mitigation, while co-benefits are referred to when policies or measures are designed for more than one target (Dudek et al. 2003). We consider aggregated ancillary benefits in this report.

climate mitigation targets used in the literature[3] and we estimate the air-quality benefits of such climate policies. We argue that these benefits should be kept logically distinct from the benefits of climate mitigation. Our goal is to estimate the size of local air quality externalities compared to the global carbon price. We also estimate the value of ancillary benefits per ton of GHG emission abated and per Euro of abatement costs in the power sector in Europe.

In order to assess the local environmental benefits of climate policy we use the integrated assessment model WITCH to provide fossil fuel use in the power sector under alternative carbon tax scenarios and an impact pathway analysis embedded in the ExternE method (EC 2005) to estimate the economic damage of emissions of particulate matters or various fractions (PM10, PM2.5), sulphur dioxide (SO_2), nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOCs), and heavy metals (As, Cd, Cr, Hg, Ni, Pb). Although our economic model is global, we consider the ancillary benefits for Europe and the abatement costs involved for the electricity sector in Europe. Despite recent efforts to increase the level of renewable electricity generation, coal fired power plants still provide about 25% of total electricity generation in Europe. Coal is the fossil fuel that causes the largest local and global environmental damage. Any effort to reduce GHGs emissions will also yield large local environmental benefits in Europe.

Overall the strengths of our approach are: (1) cost effective energy and emissions scenarios that deliver the most recent climate mitigation targets; (2) the use of atmospheric circulation models to track the impact of air pollution using; (3) the ability to estimate EU-wide and country-level ancillary benefits; (4) the inclusion of Eastern European countries, typically not considered by European studies; (5) the possibility to separate the ancillary benefits between those caused by reduction in local energy use and those due to emissions reductions elsewhere.

In the RCP2.6 mitigation scenario – a +2°C compatible scenario – we find that discounted total ancillary benefits for Europe are greater than €2.5T, or about €21.6 per abated ton of CO_2. Less strict climate policy scenarios generate overall smaller local benefits, but the magnitude of ancillary benefits per abated ton of CO_2 is still considerable (€14.4, or €18.3, respectively) than under stricter mitigation. Without discounting, the ancillary benefits are in a range of €36 to €50 per ton of CO_2 abated. Over the whole century ancillary benefits per abated ton of CO_2 are 7-times larger than the carbon price in the less aggressive climate scenario and only 0.06 of the carbon price that has quite large value in the RCP2.6 mitigation scenario. Ancillary benefits cumulated over the century exceed cumulative additional cost of electricity generation in Europe in both strict mitigation scenarios. About 73% of total ancillary benefits attributable to the RCP4.5 mitigation scenario have domestic origin, while the rest of benefits is enjoyed in other countries than in a country where the emissions are abated. There are relative losers and winners with respect to produced and received ancillary benefits. However, there is no country in Europe that will be worse-off if the mitigation policy was implemented. Scenarios with technological constraints do not lead to qualitatively different results.

The rest of this paper is structured as follows: Section 2 reviews the literature on the ancillary benefits, while Section 3 describes the integrated assessment model, the impact pathway analysis, and the linkages between the two approaches. Section 4 describes climate policy scenarios and energy use in Europe. Section 5 presents estimates of the side benefits of climate policy. Conclusions follow.

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[3] We conduct cost-effectiveness analysis in our study rather than cost-benefit analysis in order to provide information on the efficient level of regulation and hence the optimal level of carbon tax.

2 Literature Review

The ancillary benefits of GHG mitigation policies have been investigated in a variety of empirical studies. The literature has used a wide range of techniques and models, it has covered different geographic areas, pollutants and pollution-related impacts. Some studies rely on air quality modelling while others use default damage factors per pollutant.[4] Due to these differences, results from these studies are difficult to compare.

Among the studies that analyze the effect of a policy on multiple pollutants, a first distinction can be made between studies that focus on physical impacts (e.g. Meyer et al. 1998) and studies that emphasize the monetization of the impacts (e.g. Burtraw et al. 2003). Several studies investigated the links between regional air pollution and climate policy in Europe (Syri et al. 2001; Alcamo et al. 2002; van Harmelen et al. 2002). Most, if not all, studies on ancillary benefits either utilize a damage factor for each pollutant or connect emissions to changes in concentrations, human exposures, physical effects and monetary damages using an integrated assessment model, such as the US APEEP (Muller and Mendelsohn 2007) or the EU ExternE's impact pathway analysis (Holland et al. 2011).

Regarding the economic modelling, the ancillary benefits are quantified (a) relying on a linear programming partial equilibrium energy model (e.g., Burtraw et al. 2003; Van Vuuren et al. 2006; Riekkola et al. 2011; Holland et al. 2011; Rečka and Ščasný 2013) that can be further enriched, for instance, by econometric estimates of abatement costs (Burtraw et al. 2014), or (b) using a computable general equilibrium model (e.g., Glomsrød et al. 1992; Scheraga and Leary 1993; Paltsev et al. 2005; Grossman et al. 2011; Nam et al. 2013; Kiuila et al. forthcoming). Bollen et al. (2009) use the MERGE model, a top-down optimization model with a good energy sector detail. MERGE is the model used in the ancillary benefits literature that is most similar to WITCH. There are however several differences between our study and Bollen at al. (2009). First, we are concerned with the estimation of ancillary benefits rather than the joint optimal determination of local pollution abatement and global GHG emissions reduction. Second we consider the most recent scenarios in the climate change literature and we provide information on ancillary benefits associated to each scenario. Third, while Bollen et al. (2009) only consider PM pollution, we include a much larger set of pollutants in our analysis. Fourth, we do not have a hard-linked air pollution impact module, which is a weakness, but the flexibility of a soft-link approach allows us to use a more complicated modelling approach that takes into account the atmospheric circulation of local pollutants. Finally, Bollen et al. (2009) deal with global costs and benefits while we provide EU-level and country-level analysis.

The range of estimates of air-quality ancillary benefits is large and depends on many factors, including climate policy scenario, modelling assumptions and the time period over which the benefits are calculated. In their review of the literature Davis et al. (2000) report a range from €0.6 to €78 (Dessus and O'Connor 1999) and €148 (Aunan et al. 2000) per ton of reduced CO_2 emissions.[5] A review of 48 peer reviewed studies by Nemet et al. (2010) provides a range of the air quality co-benefits of climate change mitigation from €1.6 to €152 per ton of abated CO_2 with a mean of €38/tCO_2. Focusing on the co-benefits from mitigation in the US electricity sector, Nemet et al. provide a range of estimates ranging from €3 to €90, and found larger ancillary benefit estimates for

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[4] See, for instance, Bell et al. (2008) that discusses the methodological aspects in quantification of ancillary benefits.

[5] Davis et al. (2000) and then OECD (2002) report the ancillary benefits per ton of carbon in 1996 US$. We use OECD CPI and purchasing power parity and express the benefits in 2005 Euro per ton of CO_2. Following same approach, we recalculated the 2008 USD from Nemet et al. (2010) and the 2010 USD from Parry et al. (2014) in 2005 Euro.

developing countries (with a mean of €62) than for the developed countries (mean €33). Parry et al. (2014) derive 'nationally efficient carbon prices' that reflect domestic non-internalized environmental benefits for top 20 emitters of GHG emissions. The efficient prices reflect primarily health co-benefits from reduced air pollution at coal plants and reductions in automobile externalities, which are net of fuel taxes or subsidies. They find that the cross-country average of nationally efficient prices is equal to €44 per ton of CO_2 in 2010 (with a range between €22 to €66 per ton as the damage values are reduced and increased by 50 percent). These prices substantially vary, however, across countries; the nationally efficient CO_2 price is as high as €224 per ton in Saudi Arabia, €48 per ton in China, or €28 in the United States. Brazil on average overcorrects for co-benefits through pre-existing policies that results in the negative efficient price of -€18. Coal air pollution damage is estimated for the top twenty emitters at €66 per ton. It is important to note that Parry et al. (2014) do not consider any benefit from reduced global warming when they calculate the 'nationally efficient carbon price'. They calculate the value of the ancillary benefit of a carbon tax and find the level at which the tax is equal to the local benefits.

For the EU, Holland et al. (2011) estimate that the 2˚C stabilization scenario would reduce SO_2 emissions by 60%, NOx emissions by 46% and particulate matters by 19% using the partial equilibrium energy model GAINS. These emission reductions would lead to large health improvements and important co-benefits in ecosystems. The air quality co-benefits are estimated at €43B per year by 2050 in the EU27, which corresponds to about €24 per ton of CO_2. Markandya et al. (2009) obtained similar results for the EU, but much greater co-benefits in fast growing countries such as China and India. Barker and Rosendhal (2000) estimate the co-benefits from SO_2, NOx and PM10 reduction as an effect of carbon tax for Western Europe at €41 per ton of CO_2 abated.

While the literature on ancillary benefits has considerably grown during the past twenty years, studies aiming at developing countries or transforming economies in Eastern Europe are relatively few (Morgenstern 2000). Aaheim et al. (1997) and Aunan et al. (2000) investigated the ancillary benefits of several policies, covering energy efficiency or public transport, in Hungary. They estimated annual health benefits in a range of $370 to $1,168m. Dudek et al. (2003) provide an analysis of ancillary benefits of energy market reforms and emission trading for Russia and observe 30,000 to 40,000 lives saved that are then monetized using the Value of Statistical Life (VSL). Using a linear optimization energy model linked to ExternE's impact pathway analysis, Rečka and Ščasný (2013) estimated the ancillary benefits of the EU Emission Trading Scheme (EU-ETS) in the Czech power sector at €3,100B during 2006-2030, or €4,100B if no new nuclear plant is allowed. These results imply the ancillary benefits of €15 per ton of CO_2 in both scenarios. Using same approach, Ščasný and Rečka (*forthcoming*) obtained the ancillary benefits for tightening CO_2 target in Slovakia at €11 per ton of CO_2. Kiuilia et al. (*forthcoming*) estimated co-benefits of full internalization of external costs attributable to local pollutants in the Czech Republic by CGE model in a range of €32 to €72, depending on the scenario and taxed sectors. The ancillary benefit estimates are summarized in Table A - 2 in the Appendix.

3 Modelling framework

3.1 The WITCH model

WITCH (World Induced Technical Change Hybrid) is an Integrated Assessment Model (IAM) designed to study the socioeconomic impacts of climate change and the implications of mitigation policies on the energy sector, the economy and climate. WITCH is a global model where countries of the world are grouped into thirteen regions: USA (United States of America), WEURO (Western EU and EFTA countries), EEURO (Eastern EU countries), KOSAU (South Korea, South Africa and Australia), CAJAZ

(Canada, Japan and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states and non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa except South Africa), SASIA (South Asian countries except India), EASIA (South-East Asian countries), CHINA (People's Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India).[6] These regions strategically interact following the rules of an open-loop Nash game: each region maximizes its own welfare given the behaviour of all other regions. A cooperative solution, where one global social planner jointly maximizes a social welfare function can also be implemented but was not used to generate the scenarios used in this study.

The model is defined as hybrid because it features an aggregated top-down Ramsey-type optimal growth model combined with a detailed description of the energy sector. The aggregated economic model is structured according to a Constant Elasticity of Substitution (CES) framework where the two macro-inputs, capital and labour, are combined with energy to produce the final output. The energy node is then disaggregated in a detailed, fully integrated, bottom-up section that features all major power technologies and non-electric energy demand aggregated by fuel. The model is able to study the evolution of the energy sector in relationship with major economic and climate variables.

Technical change is endogenous in WITCH and is modelled via Learning-by-Researching (LbR) and Learning-by-Doing (LbD) effects. LbR determines technology cost reduction by means of dedicated investments in R&D capital. International R&D spillovers are also taken into account. LbD reduces the investment cost of renewable and backstop energy technologies as a consequence of progressive deployment of the technology. A more detailed description of the model can be found in Bosetti et al. (2006 2007 and 2009).

3.2 The ExternE method

We estimate the impact of climate change mitigation on air quality using a method based on the most recent ExternE (Externalities of Energy)[7] Impact Pathway Analysis (IPA).[8] The IPA is an analytical procedure examining the sequence of processes through which polluting emissions result into external damages. The method allows to estimate the marginal physical impact and the marginal cost of pollution from each power plant (in general from any emission source), as a function of the technology and of the location of the plant.

The IPA comprises four basic steps: (i) selection of the reference power plant, determination of the technology used and of the harmful emissions released, (ii) calculation of changes in pollutant concentration for all affected regions using atmospheric dispersion models, (iii) estimation of

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[6] For the purposes of this work, the European Union is given by the sum of WEURO (Western Europe) and EEURO (Eastern Europe), although this is not rigorously correct due to the presence of the EFTA countries in the EU.

[7] The European Commission in collaboration with the US Department of Energy launched a joint research projects to assess the energy-related externalities in 1991 (European Commission 1995; ORNL and RFF 1995). Following a detailed bottom-up methodology relying on impact pathway approach, the EU/US studies provided estimates of marginal external costs of electricity production from a wide range of energy technologies at various locations. The EC provided additional funding over the years to improve the ExternE accounting framework and to expand it to new EU member states and to other non-EU countries. The ExternE IPA framework that we use has been recently updated within the NEEDS project (http://www.needs-project.org/). For more information on ExternE see http://www.externe.info. Weinzettell et al. (2012) apply the ExternE method to quantify production and consumption related externalities of power sector in Europe.

[8] An internet accessible version of EcoSense (EcoSenseWeb1.3) was developed within the NEEDS project (Preiss and Klotz 2008).

physical impacts from exposure using concentration-response functions (CFRs), and (iv) economic valuation of impacts using direct costs (effect on crop yield, damage on building materials or biodiversity) or compensating/equivalent surplus measured through the willingness-to-pay approach. The ExternE's IPA method is very similar to an integrated assessment model used in the American studies to connect emissions to changes in concentrations, human exposures, physical effects and monetary damages by the Air Pollution Emission Experiments and Policy model (APEEP, see Muller and Mendelsohn 2007, 2009; Muller et al. 2011; Grossman et al. 2011).

The IPA procedure has been incorporated into EcoSense, the integrated atmospheric dispersion and exposure assessment model that we use for our analysis.[9] EcoSense uses air transport models to control changes in the atmospheric concentration of pollutants at local, regional and global level.[10] The model then determines a range of impacts on human health, buildings, biodiversity, and crop yields using concentration-response functions. We evaluate the economic impact of micro-pollutants using generic estimates of marginal costs – i.e. the same damage value regardless which country releases the micro-pollutant – as estimated in the ExternE project series. The loss of ecosystems is assessed using a measure of Potential Disappeared Fraction of species (Frischnecht and Steiner 2006) linked to acidification and eutrophication. We use appropriate concentration-response functions to estimate the economic loss from mortality and morbidity, from agricultural productivity losses and for damages to building materials. Valuation methods of welfare economics are used to translate the physical impacts into monetary impacts.

Impacts on human health, mainly on mortality, are the most important among all impacts. In order to establish a causal relationship between pollution and human morbidity and mortality, ExternE uses concentration-response functions calibrated using a large number of epidemiological and toxicological studies. At the beginning of the ExternE project the CRFs of all European countries were calibrated using studies for the United States. The European functions have now been re-calibrated using epidemiological and toxicological studies for Europe. The economic loss due to increased mortality is estimated using the Value of Life Year (VOLY) (Desaigues' et al. 2011), reflecting recent changes in the ExternE methodology. Previously, ExternE used a uniform Value of Statistical Life (VSL) to value excess mortality. Several studies have argued that the VSL is appropriate to value large losses of life expectancy from fatal accidents but it should not be used to estimate the usually smaller impact of pollution on life expectancy, especially of elderlies (Rabl et al. 2014). Regardless which one of the two metrics is used, they should be both based on the willingness to pay for a small reduction in risk of dying (Hammitt 2007).

In this study, following the ExternE method, the VOLY for chronic mortality is set at €40,000, the recommended value of ExternE for cost–benefit analyses of EU-level policies.[11]

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[9] http://ecosenseweb.ier.uni-stuttgart.de/

[10] EcoSense uses three models of air quality: (i) the Industrial Source Complex Model for transport of primary air pollutants on a local scale delaminated by 100 x 100 km around the power plant, (ii) the EMEP/MSC-West Eulerian dispersion model for modelling transport and chemical transformation of primary pollutants on a regional scale covering all Europe, and (iii) the N-Hemispheric Model which served for estimation of the intercontinental influence primary and secondary pollutants (secondary inorganic aerosols, tropospheric ozone).

[11] The recommended value of so called chronic VOLY is based on the mean estimate of the willingness to pay for changing life expectancy by two months using data from a pooled sample of nine European countries. Data is adjusted using a simple benefit transfer technique to correct for the differences in income and population in EU Member States. Monetary values for work loss day, medical costs, or the willingness to pay to avoid illnesses also reflect EU-wide averages.

The valuation of morbidity is by no means trivial. Morbidity increases medical costs and causes a loss of productivity, but it also causes large, harder to measure, disutility from pain and suffering. There has been recent interest in assessing the value of utility losses from illness, but more research is needed, especially to value the damages from chronic illness (e.g. chronic bronchitis or asthma symptoms). We follow here the valuation of additional morbidity proposed in the NEEDS update of ExternE. Their values range from €1 for each use of bronchodilator to €200,000 per new case of chronic bronchitis.

Crop losses are valued at the international market prices. The impacts on building materials are assessed using replacement and maintenance costs, the assessment of biodiversity impacts is based on restoration costs.

We use country-specific impacts valued by EU-wide social damage costs to express them in €2005 per ton of emission of pollutant as estimated by the project NEEDS. We include the most common air pollutants (SO_2, NOx, $PM_{2.5}$, PM_{10}, NMVOC) and heavy metals (As, Cd, Cr, Hg, Ni, Pb). NEEDS provides the average value of external costs per ton of emission for a total of 39 European and non-European countries.[12]

The marginal social cost of emissions of heavy metals is developed in NEEDS using data from the EU-funded project ESPREME (2007) and from two studies (Fantke 2008; Spadaro and Rabl 2007). Since the background concentration of NO_X, SO_2, NMVOC and NH_3 influences the generation of secondary pollutants – e.g. ozone, sulphates, nitrates – the NEEDS project provides two sets of impact estimates for non-metals: one in 2010 and the other in 2020 (see, Preiss and Klotz 2008). The EU-wide average external cost of pollution is reported in Table 1.

Pollutant	*$PM_{2.5}$*	*PM_{coarse}*	*NO_X*	*SO_2*	*NMVOC*	*Cd*	*As*	*Ni*	*Pb*	*Hg*	*Cr*
Emission scenario 2010	12.08	0.52	5.84	6.54	1.01	84.69	536	1.67	284	8371	9.90
Emission scenario 2020	11.10	0.43	6.00	6.55	0.52	74.59	472	1.47	251	7372	8.72

Note: Monetary values in €2005 per ton of emitted pollutant. PM_{coarse} indicates particulate matters with an aerodynamic diameter between 2.5 and 10 µm. Source: Preiss and Klotz (2008).

Table 1. Average damage factors for air quality pollutants and heavy metals for the 2010 and 2020 background emission scenarios (thousands €2005 per ton).

As an example, Figure 1 presents the EU-wide impacts of one additional unit of $PM_{2.5}$ released in any EU country, in 2010 and in 2020. The figure also displays the EU average marginal cost of $PM_{2.5}$. The marginal cost of pollution in Figure 1 is the EU-wide social cost of pollution. The social cost differs across countries because of different environmental conditions, different density of receptors, and different characteristics of the receptors. For instance, the unit damage cost of $PM_{2.5}$ is much smaller (about 4,000 € per ton) in countries with lower population density in their neighbouring countries (Finland, Norway, or Sweden) than in countries (Benelux, Germany) at the centre of a heavily populated region (about 20,000 € per ton).

The cost of pollution for Europe is equal to the sum of the cost attributable to fuel use and hence emissions released from their burning in each of the 28 European countries. The released emissions

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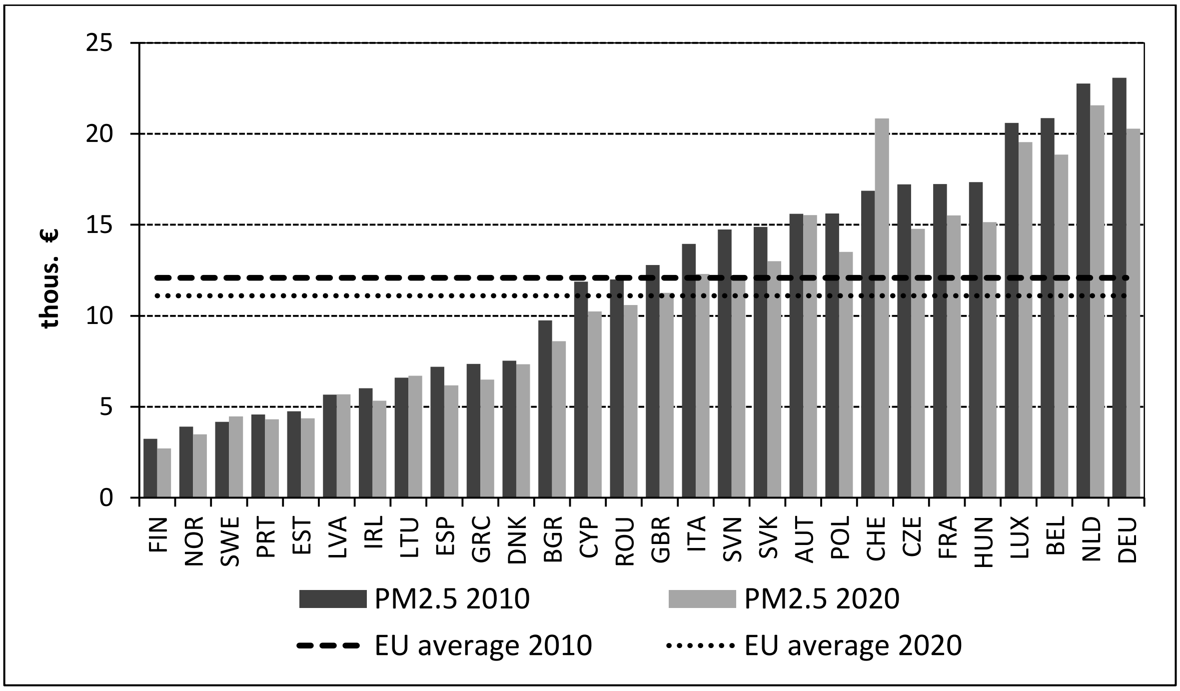
[12] The costs were estimated using several runs of the EcoSenseWeb tool with the EMEP/MSC-West Eulerian pollution dispersion model.

have an effect on receptors (humans, species, assets) in the 28 European countries but they also affect emission receptors in the rest of the world. Using the EcoSenseWeb tool, we derive the cost of one additional unit of pollution released in country *i* that is inflicted to each of the remaining European countries *j* and to the rest of the world (*j+1*). In our case, this procedure generates 28 x 29 pollution costs. We assume that the distribution of impacts due to emissions releases from country *i,* i.e. regional increase in ambient concentrations, remains same over the whole period 2015-2100 as in the reference year. In other words, we do not model meteorological conditions and transport of pollutants over time.



Source: Preiss and Klotz (2008).

Figure 1. Damage factors per ton of $PM_{2.5}$ for 2010 and 2020 background emission scenario (thousands €2005 per ton).

3.3 Linking the WITCH model and the ExternE approach

The ancillary benefits of reducing GHG emissions are derived using data on fossil fuels consumption for power generation (*EN*) from WITCH. WITCH provides energy scenarios for Eastern and Western Europe until 2100. In order to provide country-level scenarios of fossil fuels combustion for power generation ($EN_{f,j}$) we assume that the current distribution of power generation across countries remains unchanged.[13] Emission factors (*EF*) from fossil fuels used for power generation are from the EMEP EEA air pollutant emission inventory guidebook (EMEP/EEA, 2013) and are listed in Table A - 1 in the Appendix. The damage factors (*DF*) for each pollutant are from the Impact Pathway Analysis of

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[13] Primary energy use in country *j* equals to ($EN_f\ sh_j$), where EN_f denotes primary energy use for electricity generation in one of the two European regions from WITCH and sh_j indicates the share of country *j* on use of fuel *f*, as it was in the base year 2005.

ExternE. We assume that damage factors change after 2015, following the assumptions in the EcoSenseweb software.

There are five channels through which both GHG and air quality emissions can be reduced: (1) reducing total economic output (scale effect), (2) restructuring the economy towards less emission-intensive sectors (composition effect), (3) reducing the fuel intensity of production (fuel intensity effect), (4) using fuels with reduced or no carbon emissions (fuel mix effect), and (5) utilizing more efficient end-of-pipe technologies (emission-fuel intensity effect).[14] By linking WITCH and IPA we are able to take into account channel (1); channel (2) is also accounted for, but it cannot be separated from (3) because WITCH has only one aggregate final good sector; the mix of the capital-labour aggregate with energy is instead optimally determined in WITCH; channels (4) and (5) are also accounted for.

The change of the fuel mix responds to changes in the cost of fuels and of power generation capital and to the carbon tax penalty. However, WITCH does not track non-GHG emissions.[15] As the non-GHG emission factors for fuels (EF_f) remain constant over the entire period, it implies time invariant efficacy of the end-of-pipe abatement technologies and hence constant emissions per unit of fuel over time.

As noted above, in ExternE the willingness to pay used to derive the damage factors reflects EU average values, implicitly assuming that all Europeans share the same preference for avoiding adverse health and other negative impacts.

The real value of pollution costs (PC) attributable to air polluting emissions released by country *i* in year *t* is derived as follows:

$$PC_{t,i} = \sum_j \sum_f \sum_p \left(EN_{j,f} \cdot EF_{f,p} \cdot DF_{j,p}\right) \cdot \left(\frac{Y_j}{Y_{EU}}\right)^{\varepsilon_y^{wtp}} \cdot \prod_{s=2005}^{t} \left(1 + g_s \cdot \varepsilon_y^{wtp}\right) \tag{1}$$

where *f* denotes the fuel type (coal, gas, oil, biomass, nuclear, renewable energy), *p* denotes the pollutant (SO_2, NOx, PM, NMVOC, heavy metals). For each country *i*, the cost of air pollution is determined summing damages in each own country and on all other *'victim'* countries *j*. We sum the damage of emissions on each other and 28 European countries plus the rest of Europe[16], including *i*th country, in that airborne concentrations are changed due to emissions released from the emitting country *i*. Thus, the first term in equation (1) $\left(EN_{f,j} \cdot EF_{f,\mathrm{p}} \cdot DF_{p,j}\right)$ quantifies the external cost of non-GHG emissions released by country *i*. Our impact assessment follows a static approach: neither of the parameters on emission-fuel factors ($EF_{f,p}$), damage factors ($DF_{p,j}$), country's share on fuel use (sh_j), or ε_y^{wtp} are time invariant. Then, the second and the third terms adjust for the differences in income levels across 28 European countries, and over time, respectively. These adjustments are based on a simple benefit transfer that assumes that richer people are willing to pay more – not necessarily strictly proportionally – than poor people. The second term translates the EU average value into the values that are more relevant to a *'victim'* country *j*, where Y_j and Y_{EU} are real per

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[14] Carbon capture and sequestration is an end-of-pipe technology for GHG emission reductions.

[15] A new version of the model with local pollutants and other non-GHG emissions was under preparation while this article was written.

[16] To analyse the distribution of the impacts, country-specific damage factors and external costs are derived for 28 countries. We have data on the EU28 countries, with the exceptions of Malta and Croatia. We include also Norway and Switzerland. The impacts on the rest of the world are valued as if they were born in the emitting country.

capita GDP in purchasing power standards in country *j,* or in the EU, respectively, in the year 2005. As a result we monetize physical impacts by country-specific values, instead of using an EU-average value (e.g. Holland et al. 2011). The third term adjusts for possible changes in income over time in the 'victim' country. ε_y^{wtp} denotes the income elasticity of willingness to pay, for which we use a value equal to 0.8, similarly (OECD 2012b, 2014; WHO and OECD 2015).[17] The parameter g_p is real growth in per capita GDP, as endogenously determined by WITCH for the two European regions. No equity weighting is assumed in our calculation of pollution costs.

Several adjustments are made to ensure the comparability of monetary values and to guarantee consistency between the two modelling approaches. The WITCH model provides results in 2005 USD, while the pollution costs in the ExternE are expressed in 2000 €. All values are converted to 2005 € by using the GDP deflator and the market exchange rate for 2005. In order to compare the ancillary benefits with economic impacts expressed in present value, the ancillary benefits are discounted using the interest rate endogenously determined in WITCH.[18]

We repeat this exercise for a set of climate mitigation scenarios recently developed. We follow Riekkola et al. (2011) and express the ancillary benefits as the difference between the air pollution damages in the baseline scenario and in the policy scenario. For each policy scenario we calculate the absolute benefit of pollution reduction, the benefit per ton of CO_2 emissions abated in the European electricity sector, the ratio between air pollution ancillary benefits and total CO_2 abatement cost in the electricity sector, and the benefit as a ratio of the global carbon price.

4 Scenarios

In this study we use four climate mitigation policy scenarios developed using WITCH for the EU-funded project GLOBAL-IQ (Massetti et al. 2014). The Reference scenario assumes the continuation of observed trends. We assume that there is no policy to reduce GHG emissions in the Reference scenario. We then use three climate policy scenarios in which emissions decline over time to achieve three levels of radiative forcing in 2100: 6.0, 4.5 and 2.6 watts/m^2 (they correspond to concentrations equal to 850, 650, and 490 ppm CO_2eq). These scenarios are named RCP6.0, RCP4.5 and RCP2.6 because the radiative forcing levels are those used in the Representative Concentration Pathways (RCP) (Van Vuuren et al. 2011).

The RCPs have been recently developed to provide greenhouse gases emissions scenarios to the climate models that have been used to generate the most recent set of climate change scenarios (Stocker et al. 2013). The RCPs are the new standard in the climate change literature and are now being complemented by a set of socio-economic scenarios, the Shared Socioeconomic Pathways (SSP) (Ebi et al. 2014, Van Vuuren et al. 2014).

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[17] The OECD (2012b) review finds that the income elasticity of the VSL is in the range of 0.7 and 0.9 in most of the regressions that use screening criteria. In other studies this range is substantially lower – about 0.3 to 0.4. Viscusi (2000) finds studies that use a value greater than unity. In most studies the income elasticity of the VSL ranges between 0 and 1 and the income elasticity of WTP around unity may be justified for the transfers between countries with heterogeneous income (Czajkowski and Ščasný 2010).

[18] In WITCH the pure rate of time preference declines over time. It starts at 3 % p.a. in 2005 and declines to about 2 % p.a. in 2100. The interest rate of the economy declines over time following the Euler equation. The model is calibrated so that developed regions have an interest rate equal to about 5% per year in 2005 while developing regions have an interest rate equal to 7% per year in 2005.

Each RCP scenario may be the outcome of different socioeconomic pathways. For example, a high emission scenario may be the outcome of both a fast-growing but highly efficient global economy and of a sluggish and inefficient global economy. Analogously, the same emission trajectory (RCP) may be consistent with both high and low global economic inequalities.

The Reference scenario used in this study reproduces population and economic growth of the SSP2 scenario. The SSP2 is a central-case scenario because current trends are assumed to continue indefinitely in the future. The SSP2 is commonly identified as the "Middle of the road" scenario.[19]

In our Reference scenario population and economic growth follow the trends observed in the past. There are considerable energy efficiency improvements in the Reference scenario, but global energy demand substantially increases as a result of economic and population growth. Without any global agreement to reduce greenhouse gases emissions this incremental energy demand is mainly covered using fossil fuels. The carbon dioxide emissions from the use of fossil fuels are the main source of additional GHGs that are released in the atmosphere in the Reference scenario. The power sector is one of the largest contributors to CO_2 emissions. In 2010 about 10 Gt CO_2 are released from power plants at global level, of which 1.4 Gt originate from Europe. This is equivalent to about 30% of total CO_2 emissions. The carbon intensity of the European power sector declines up to 2030 and then it climbs again as coal re-gains a share of the power mix. In 2050 emissions are equal to 1.1 Gt CO_2 per year (24% of European CO_2 emissions) and in 2100 emissions from the power sector total 1.7 Gt CO_2 per year (35% of European CO_2 emissions) (see Figure 2).

The climate module used by WITCH indicates that radiative forcing achieves 6.6 W/m^2 in 2100 in the Reference scenario. The global mean temperature increases by 4.1 °C in 2100, with respect to the pre-industrial level.

Emissions sharply decline in the RCP scenarios. While the RCP6.0 is only marginally different from the SSP2 scenario, the RCP4.5, and especially the RPC2.6 scenarios indicate that it is optimal to drastically cut emissions from power generation. Coal and natural gas power plants are retrofitted with carbon capture and storage equipment while investments in wind and solar power increase. Investments in end-use energy efficiency R&D reduce the demand of energy and of electricity in particular. As early as in 2040 emissions in the RCP2.6 scenario become negative because biomass (carbon neutral) is burnt in power plants with carbon capture and storage. Thus the power sector quickly shifts from being a major source of emissions to being a net sink.

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[19] The Reference scenario is thus characterized by: (1) slowly decreasing fossil fuel dependency, (2) reductions of resource and energy intensity, (3) uneven development of low-income countries, (4) weak global institutions, (5) slow continuation of globalization, with some barriers remaining, (6) well regulated information flow, (7) medium economic growth, slow convergence, (8) high intra-regional disparities, (9) medium population growth related to medium educational investments, (10) delay of achievement of the Millennium Development Goals (MDGs).

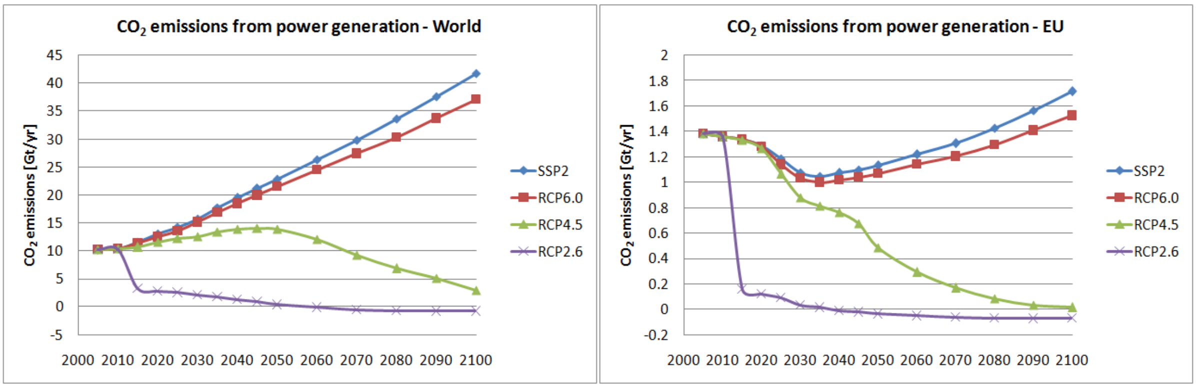

Figure 2. Global and European carbon dioxide emissions from fossil fuels used in the power sector.

All the RCP scenarios assume full technological flexibility. For example carbon capture and sequestration is deployed on a large scale starting from 2020. Biomass is assumed to be widely available. Energy efficiency gains, although costly, greatly contribute to the reduction of electricity demand. The energy system as a whole is assumed to quickly adapt to the new regulatory regime. In order to test the effect of a less flexible technological setup on local pollution we also use three scenarios in which technological adaptation is limited (see Massetti et al. 2014, Leimbach et al. 2014). These are limited adaptation scenarios (LA). We calculate the new carbon price that is consistent with the RCP4.5 scenario and we assess how the technology mix and the distribution of emissions changes across technologies and across sectors (total emissions are unchanged because we still impose the long-term climate target to be achieved). Specifically, we consider three additional scenarios: with limited energy efficiency (LA-EE), limited renewable energy (LA-REN) and limited supply and trade of biomass (LA-BIO). For the limited adaptation scenarios we calculate emissions reductions and climate mitigation policy costs using a ‘limited adaptation’ Reference scenario with the same technology constraint as in the policy scenario. We are particularly interested in whether there is any meaningful difference in local pollution as a consequence of constraints to key mitigation technologies.

5 Results

5.1 Economic impacts

In all climate mitigation scenarios our policy tool is a uniform – over countries, sectors and GHG emissions – carbon tax. The time path of the carbon taxes is shown in Figure 3.[20] The policy starts in 2015 and with the RCP6.0, RCP4.5 and RCP2.6 scenarios the global mean temperature increases by 3.7°C, 3.0 °C and 2.0°C, respectively. In the RCP6.0 case, the carbon tax starts at 3 USD/tCO_2eq and achieves 14 USD/tCO_2eq in 2100. The level of the tax is very low because the RCP6.0 target is not far from the Reference scenario. The carbon tax for the RCP4.5 reaches 335/tCO_2eq USD in 2100. Due to limited technology adaptation, the level of the carbon tax is 10% higher in LA-BIO and by 31% higher in LA-EE in 2100, but it is almost identical in LA-REN. The variations of the carbon tax reflect the relative importance of alternative mitigation channels. The tax escalates in RCP2.6 and reaches more than 3,500 USD/tCO_2eq in 2100. The tax is recycled lump-sum in each region. Nothing but the price of carbon is changed with respect to the corresponding reference scenarios.

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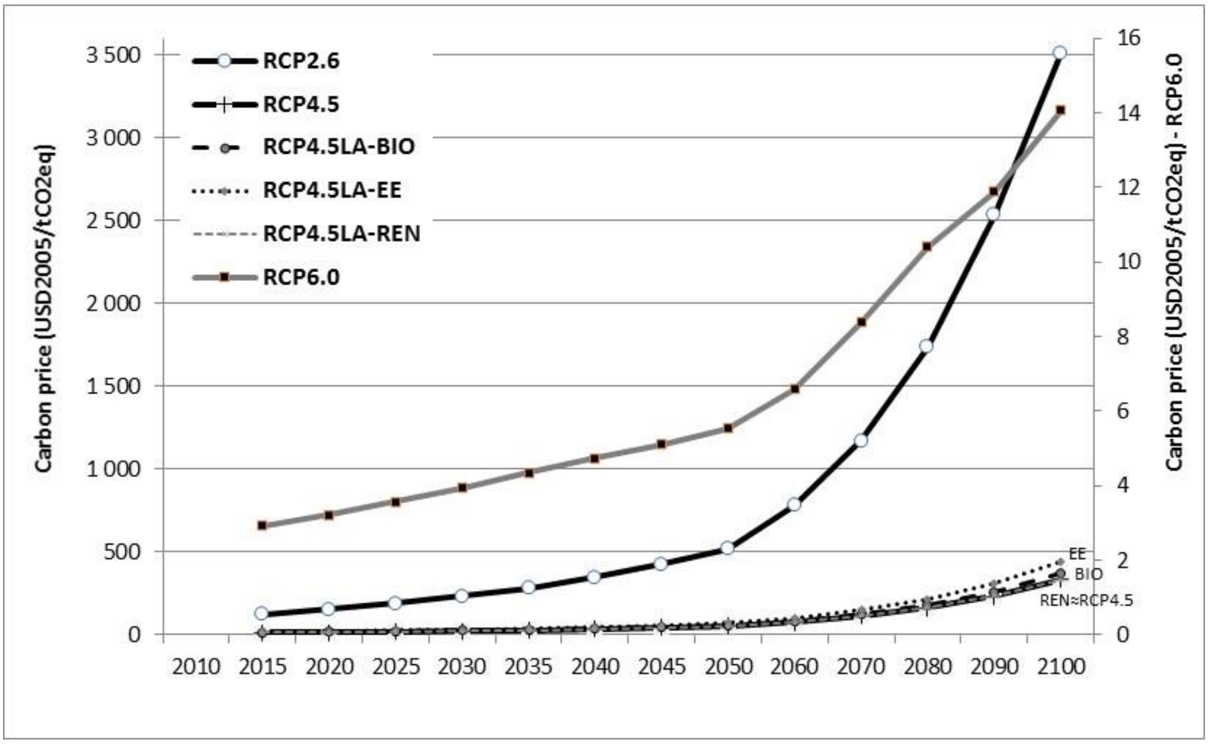
[20] The three carbon tax trajectories are consistent with the radiative forcing targets. They are not socially optimal taxes because they are obtained solving the model in the cost-effectiveness mode.



Notes: RCP6.0 on the secondary vertical axis.

Figure 3. The carbon tax – policy scenario.

As it becomes more and more expensive to emit GHG emissions, the model scenario projects investment in carbon-free technologies for the energy sector, in energy efficiency R&D, in R&D to develop carbon-free backstop technologies, it substitutes the energy input with capital and labour and it invests in a series of activities to reduce CO_2 emissions from deforestation and other non-CO_2 gases. The resulting emissions trajectories are the optimal (efficient) solution of a complex inter-temporal and strategic optimization problem. Feedback from technology spillovers and from global energy markets are internalized in the solution of each regional social planner.

Emissions reductions in the power sector are the result of reduced demand due to higher efficiency and factor substitution in end uses and of decarbonization of the fuel mix. Fossils fuels without carbon capture and sequestration (CCS) are progressively phased out by nuclear, renewables, and fossil fuel power plants with CCS. When the carbon tax is high, bioenergy with CCS plays an important role. Coal power plants without CCS disappear by the end of the century in both the RCP4.5 and the RCP2.6 scenarios. The RCP2.6 scenario is so stringent that coal with CCS is also progressively phased-out because the penalty on the uncaptured emissions is very expensive. Thus climate policy also delivers local environmental benefits by greatly reducing harmful emissions released during coal combustion. Figure 4 illustrates how the power generation mix evolves over the century in the Reference and in the climate policy scenarios.

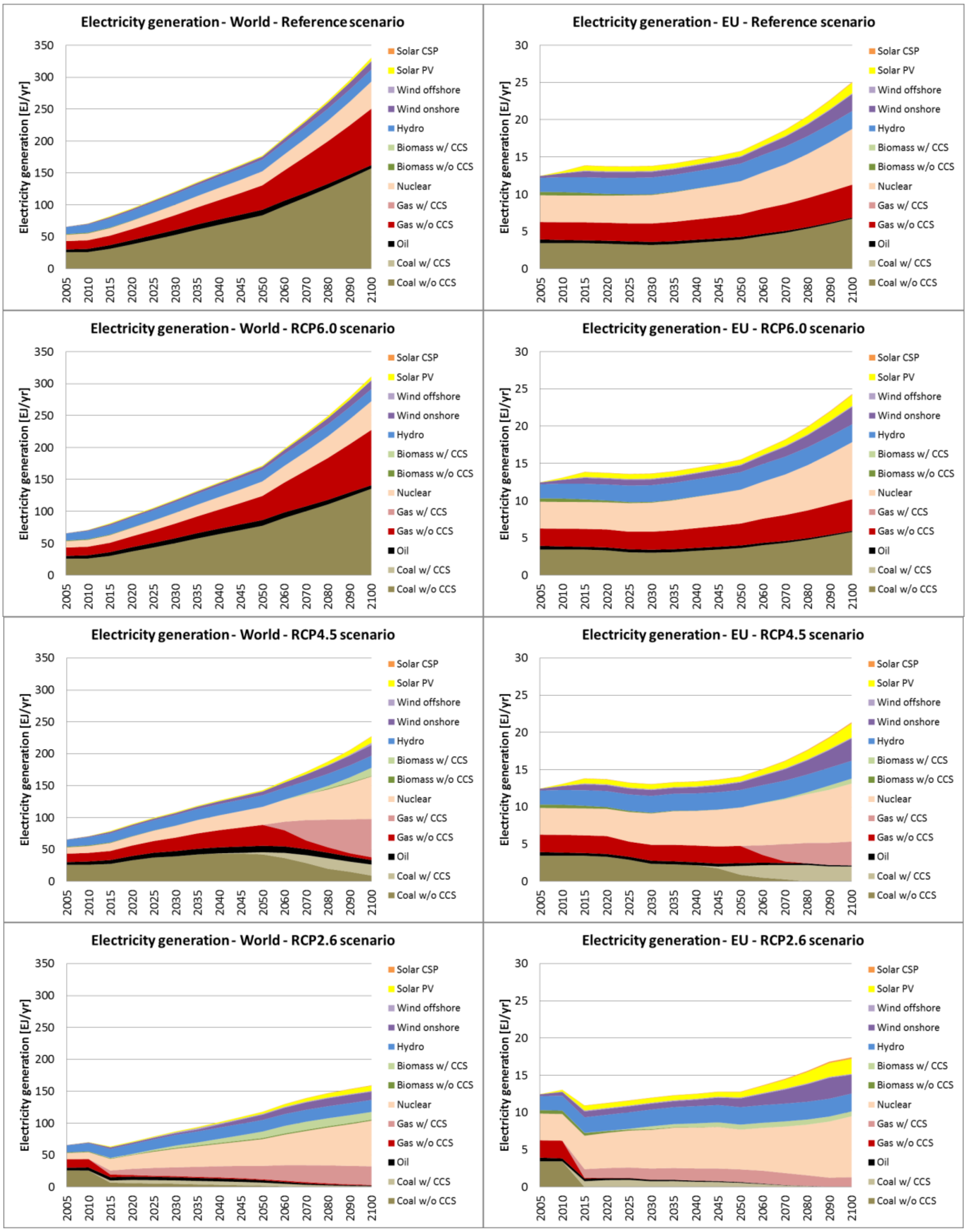
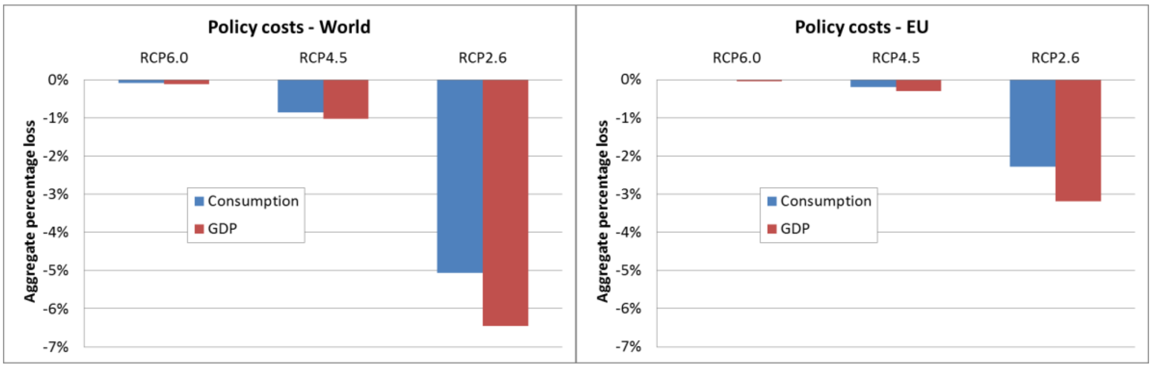


Figure 4. The electricity generation mix at global level (left column) and in the EU (right column).



Notes: costs discounted using the endogenous interest rate of the model.

Figure 5. Consumption and GDP losses in the tax scenarios.

We note that in the limited technology scenarios we still achieve the same target for overall radiative forcing and hence for carbon concentrations of the full flexibility scenarios. The only differences between the full flexibility scenario and scenario with limited adaptation are the technology mix and the cost of the policy. Emissions from the power sector are also different, as we document below.

All the mitigation measures implemented in the tax scenarios are costly because they reduce the overall efficiency of the economy. As a result economic growth is slower in the tax scenarios and aggregated consumption and GDP decline with respect to the Reference scenario. Figure 5 shows the aggregated consumption and GDP losses from 2010 to 2100, evaluated using the endogenous interest rate calculated in WITCH. These costs are not net of the economic benefit of reduced global warming and of reduced local pollution.

Consumption and GDP losses at global level range from almost zero in the RCP6.0 scenario to about 5% and 6% in the RCP2.6 scenario, respectively. In Europe the cost of the RCP2.6 scenario is lower than at global level, and it is equal to about 2% in terms of consumption and about 3% in terms of GDP.

5.2 Impact on emissions

Each climate mitigation scenario results in a remarkable decrease in the total volume of polluting emissions, with the exception of $PM_{2.5}$ and nickel emissions (Table 2). The increase in these two pollutants is a consequence of substituting fossil fuels with biomass, for which the EMEP/EEA inventory reports the highest emission factors among all fuels. As biomass is carbon neutral, it becomes a viable alternative to fossil fuels in all mitigation scenarios. In particular, the RCP2.6 scenario has a very large use of biomass with carbon capture and sequestration to compensate for emissions in other sectors. As a consequence, the RCP2.6 scenario displays the largest increase in $PM_{2.5}$ pollutants.

In the RCP4.5 scenarios with limited technological adaptation, emissions of air pollutants change, although not dramatically. The only exception is $PM_{2.5}$ when supply and trade of biomass is limited (RCP4.5-BIO). The fully flexible scenario (RCP4.5) leads to an increase of $PM_{2.5}$ emissions equal to 3,056 kt (with respect to the Reference scenario), while the constrained scenario leads to a reduction of 9 kt of $PM_{2.5}$ (with respect to the constrained Reference scenario). Annual changes in emissions of $PM_{2.5}$ and SO_2 for each climate mitigation scenarios are displayed in Figure 6.

Scenario	NMVOC (kt)	NOx (Mt)	PM2.5 (kt)	SOx (Mt)	Cd (t)	As (t)	Ni (t)	Pb (t)	Hg (t)	Cr (t)	CO_2 (Gt)
RCP2.6	-724	-182	13,686	-640	-494	-4,376	-7,904	-3,078	-923	-2,362	-120
RCP4.5	-574	-91	3,056	-306	-268	-2,385	3,775	-2,083	-504	-1,403	-74
RCP6.0	-345	-33	-144	-97	-94	-861	4,516	-864	-186	-538	-17
RCP4.5-EFFIC	-365	-86	3,890	-314	-273	-2,370	253	-1,997	-492	-1,376	-80
RCP4.5-REN	-323	-72	2,989	-261	-232	-1,981	-837	-1,687	-409	-1,154	-65
RCP4.5-BIO	-481	-71	-9	-247	-257	-2,078	-1,018	-2,037	-420	-1,285	-65

Table 2. Cumulative difference in emission volumes in Europe for each climate mitigation scenario compared to the corresponding reference scenario for the period 2015 – 2100.

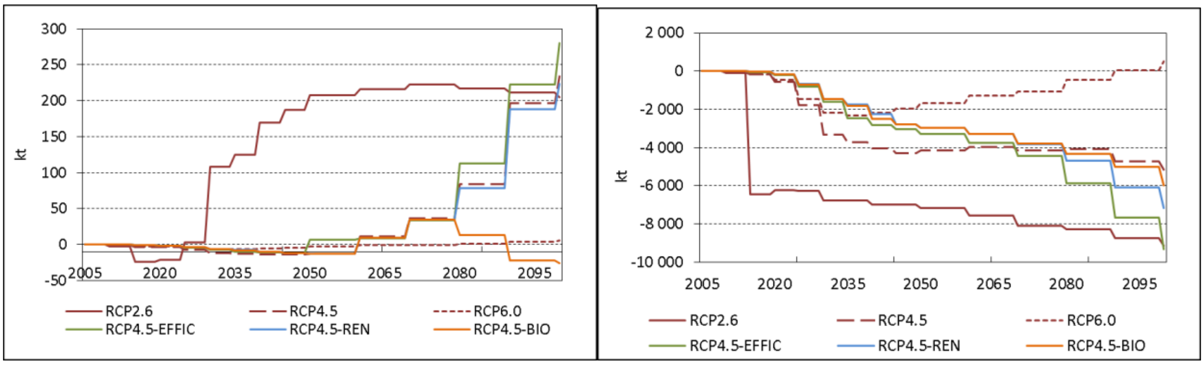


Figure 6. Annual change in emission volumes of PM2.5 (left) and SO2 (right) for Europe for each climate mitigation scenario.

5.3 Ancillary benefits in total and per ton of abated CO_2

The ancillary benefits of climate mitigation are displayed in Table 3. The first two columns display total CO_2 emissions (CO_2) and total local pollution costs (PC). The third and the fourth column present the change of CO_2 emissions (ΔCO_2) and the ancillary benefits ($AB=\Delta PC$). The fifth column displays ancillary benefits per reduced ton of CO_2 ($AB/\Delta CO_2$). All results are relevant to Europe only and all nominal values are expressed in present value of 2005 Euro, discounted using the endogenous interest rate from the WITCH model.

In the RCP2.6 scenario the level of CO_2-eq concentrations is kept at 490 ppm thanks to a massive reduction of GHG emissions compared to the Reference scenario (120 Gt over the period 2015-2100). Due to this sharp reduction of GHG emissions also local pollution collapses and the discounted cost of pollution over the century drops from €3,394B to €816B (76% reduction). The ancillary benefits are higher than €2,500B, which implies an average benefit of about €21.6 per abated ton of CO_2-eq. in Europe. The RCP4.5 generates the second largest ancillary benefits, amounting to more than €1,061B. These benefits result from 31% cumulative reduction in the pollution cost in Europe. CO_2 emissions are reduced by 73 Gt in the RCP4.5 scenario, which implies 14.4€/tCO_2-eq of local benefits per abated. The RCP6.0 – with only 15% CO_2-eq reduction and 9% reduction of the pollution costs – leads to one order of magnitude smaller cumulative ancillary benefits than the RCP2.6. The magnitude of the ancillary benefits per ton of CO_2-eq avoided is, however, very similar. This result is explained by the strong similarity of the power generation mix across the three scenarios. The share of total emissions reductions from the power sector is also rather constant across scenarios. The RCP4.5 scenarios with limited adaptation have ancillary benefits that are similar to those found for the unconstrained RCP4.5 scenario. Our results are in line with other studies (see Section 2), but our study covers a longer time horizon, it considers more abatement options and more climate policy scenarios.

	(1) CO_2 Mt	(2) PC €bn.	(3) Δ CO_2 Mt	(4) AB €bn.	(5) AB/ΔCO_2 €
Full technological flexibility					
Reference scenario					
SSP2	118,396	3,394			
Climate policy scenarios					
RCP2.6	-1,144	816	-119,540	-2,578	21.56
RCP4.5	44,465	2,333	-73,931	-1,061	14.35
RCP6.0	101,807	3,090	-16,589	-304	18.33
Limited technologies					
Reference scenario					
SSP2-EFFIC	118,361	3,545			
SSP2-REN	109,371	3,321			
SSP2-BIO	108,453	3,299			
Climate policy scenario					
RCP4.5-EFFIC	38,614	2,397	-79,746	-1,148	14.40
RCP4.5-REN	44,532	2,352	-64,839	-969	14.94
RCP4.5-BIO	43,299	2,345	-65,155	-954	14.65

Notes: Cumulative and discounted over the period 2015-2100 (Euro 2005).

Table 3. Present value of ancillary benefits in Europe for climate mitigation scenarios.

Table 3 displays discounted ancillary benefits. Without discounting, climate mitigation yields in Europe, on average, ancillary benefits in the range of €36 (RCP4.5) to €50 (RCP6.0) per abated ton of CO_2eq for the whole period until 2100. Ancillary benefits of the stricter mitigation (RCP2.6) are about 44 €/tCO_2eq during 2015-2050 and after 2080 the benefits are over €50 per ton. Benefits for the RCP4.5 scenario follow an inverted U-shape form; the benefits are about 30 € per ton until 2025, then they are rising at €60 level around 2040-2044, and then they again go down reaching €27 per ton CO_2eq in the 2080's. Under mild climate mitigation (RCP6.0), the ancillary benefits start at around €30, then they reach €50. In absolute terms, total benefits, as cumulated over the period 2015-2100, are slightly over €5,600B (RCP2.6), €2,600B in RCP4.5, and only about €800B in RCP6.0.

We then compare ancillary benefits (AB) and the total cost of electricity generation (TC), both discounted and in present values. Table 4 displays both benefits and costs as cumulated over the period that always starts from 2015 and ends in the year at the end of given period. Both are derived as a difference with respect to the corresponding Reference scenario. For the whole period 2015-2100, the ancillary benefits exceed the additional cost of electricity generation in the RCP2.6 as well as in the RCP4.5; the RCP6.0 results in cost savings.

	RCP2.6		RCP4.5		RCP6.0		RCP4.5-EFFIC		RCP4.5-REN		RCP4.5-BIOM	
	AB	TC	AB	TC	AB	TC	AB	TC	AB	TC	AB	TC
2019	237	-59	8	19	7	18	1	2	1	2	1	2
2024	440	-70	20	67	17	51	5	34	4	27	4	28
2029	637	-20	81	128	69	77	28	82	24	68	25	70
2034	833	33	187	177	142	96	77	140	68	106	69	111
2039	1,009	104	291	232	207	104	145	191	115	160	119	172
2044	1,171	180	393	277	262	105	218	181	173	214	184	219
2049	1,316	268	489	258	301	95	290	204	240	215	250	222
2059	1,584	447	652	307	357	68	430	223	369	309	378	248
2069	1,830	660	773	259	378	18	568	305	491	335	502	302
2079	2,070	882	880	207	396	-71	702	431	605	403	619	374
2089	2,308	1,119	970	144	373	-205	884	624	757	522	761	459
2099	2,552	1,349	1,052	62	311	-360	1,121	786	947	683	935	547
2100	2,578	1,375	1,061	54	304	-379	1,148	817	969	703	954	564
ratio AB/TC	1.87		19.56		-0.80		1.41		1.38		1.69	

Note: Present value of cumulative benefits and costs up to the year indicated in the first column. AB – ancillary benefits, TC – total costs of electricity generation. All monetary values in Billion Euro 2005.

Table 4. Present value of cumulative ancillary benefits and total costs of electricity generation in Europe, 2015-2100.

Table 5 provides a comparison between the undiscounted (real) value of ancillary benefits and the carbon price per ton of CO_2 for each climate mitigation scenario and their progress until 2100. RCP6.0 implies the lowest carbon price, from €2 to €12 per ton of CO_2eq. We can also find that, on average for the whole period, ancillary benefits per ton of CO_2eq are 7-times larger than the carbon price. Due to higher carbon prices in stricter climate mitigation scenarios, this ratio is only 0.5 in RCP4.5 and 0.06 in RCP2.6. Our results are however still in line with other studies; for instance Grossman et al. (2011) found the ratio of ancillary benefits on permit price in a range between 40% and 250% in 2015 (with CO_2 price at $29), and between 18% and 125% in 2030 ($61).

	RCP2.6			RCP4.5			RCP6.0			RCP4.5-EFFIC			RCP4.5-REN			RCP4.5-BIOM		
	AB	AB/CO_2	p/CO_2	AB	AB/CO_2	p/CO_2	AB	AB/CO_2	p/CO_2	AB	AB/CO_2	p/CO_2	AB	AB/CO_2	p/CO_2	AB	AB/CO_2	p/CO_2
	bn. €	€	€	bn. €	€	€	bn. €	€	€	bn. €	€	€	bn. €	€	€	bn. €	€	€
2015-19	291	48	104	7	33	11	6	32	2	2	44	15	1	50	11	1	50	12
2020-24	568	44	129	22	29	13	18	26	3	7	45	18	6	45	13	6	45	14
2025-29	846	43	159	95	47	16	77	51	3	43	51	22	37	52	16	37	51	18
2030-34	1,140	44	194	243	60	20	170	54	3	122	69	27	108	72	20	109	71	21
2035-39	1,434	43	238	409	59	24	270	53	4	241	72	33	191	70	24	197	70	26
2040-44	1,733	43	292	593	60	30	364	53	4	377	60	40	299	71	30	318	72	32
2045-49	2,032	43	357	792	57	36	449	51	4	521	40	49	435	64	37	453	60	39
2050-59	2,644	44	436	1,171	43	44	591	49	5	827	34	59	718	44	44	734	42	48
2060-69	3,300	46	655	1,522	32	65	698	45	6	1,167	30	86	1,016	32	65	1,036	29	70
2070-79	4,010	48	982	1,872	28	95	785	43	7	1,559	29	125	1,354	29	96	1,373	28	103
2080-89	4,756	51	1,460	2,219	27	138	829	49	9	2,051	31	182	1,757	30	138	1,758	29	151
2090-99	5,555	55	2,128	2,598	28	198	829	-1*	10	2,674	34	261	2,259	32	199	2,202	31	218
2100	5,639	58	2,951	2,638	30	281	825	25*	12	2,749	36	370	2,317	34	283	2,255	33	311
average AB/CO_2		47.17			35.69			49.75			34.47			35.73			34.61	
ratio AB/price		0.06			0.52			7.11			0.41			0.59			0.53	

Note: AB – cumulative ancillary benefits over the period 2015 until the end of the year shown on the respective line (for instance, 2030-39 indicates the benefits over 2015 to 2039). AB/CO_2 – average ancillary benefits per ton reduced CO_2 in given period; p/CO_2 – carbon price per ton CO_2; all values in real undiscounted 2005 Euro. The indicators related to CO_2 emissions are expressing average annual value for given period shown in the first column. * Starting from 2090, CO_2 emissions are slightly higher than in the SSP2 reference scenario. In 2100, RCP6.0 generates ancillary damage, instead of benefits, but they are negligible in size.

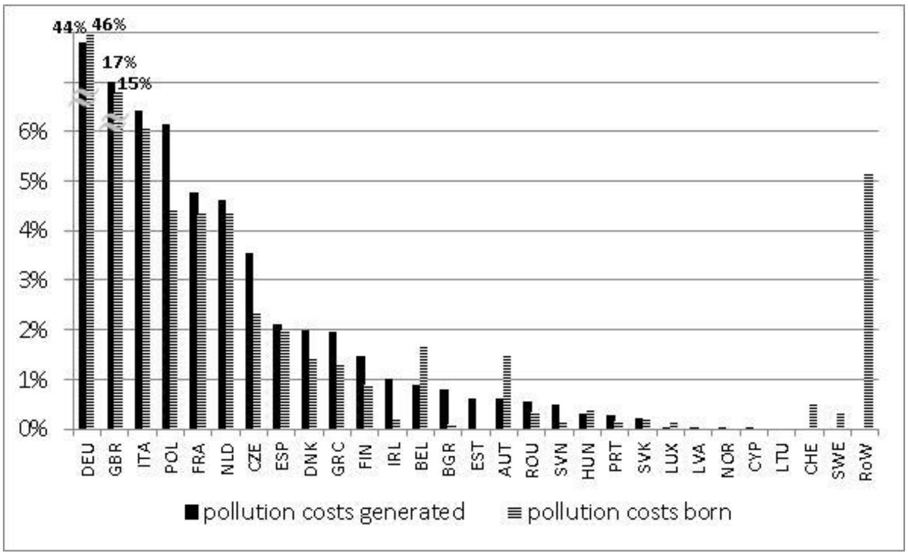
Table 5. Real values of (cumulative) ancillary benefits, average annual ancillary benefits and carbon price per ton of CO_2eq abated, 2015-2100 (values in Euro 2005).

5.4 Ancillary benefits for European countries: winners and losers

Lastly, we are interested in understanding the distribution of the ancillary benefits of climate change mitigation policy across European countries. Unfortunately we do not have country-by-country energy scenarios. WITCH separates Europe in two large blocs: Western and Eastern Europe. We build energy scenarios for 28 European countries assuming that each country's share of the total regional energy use remains constant over time and under alternative climate mitigation policies. Following equation 1, we compute pollution costs for each of the 28 countries that are born by each and every other European country and by people living outside of the 28 European countries. Having 28 x 29 pollution cost values, we can then derive total pollution costs that are associated with impacts on emission receptors in (1) country *i* due to emissions released by the same country, (2) other European countries *j* (*j≠i*) and 3) the rest of Europe that are due to emissions released by country *i*. It is then straightforward to derive the pollution costs – both due to domestic (1) or imported pollution (2) – for any country in Europe. Burden exported from Europe is measured by (3).

The total value of ancillary benefits for the RCP2.6 scenario between 2015 and 2100 is estimated to be equal to €2,578B and about 73% of these benefits have a domestic origin, that is, the local benefits are enjoyed by residents of the European country in which the abatement in local air ambient pollution occurs. The remaining share of ancillary benefits is divided between beneficiaries from European countries (€570B, about 22%) and beneficiaries from rest of the world (€134B, about 5%).

Switching to a country-level analysis, we find that (1) each of the 28 European countries is better off in terms of air quality improvement if RCP2.6 mitigation policy is implemented. In absolute terms, European countries benefit between 2015 and 2100 from a modest 88m € (in Cyprus) to 1,192B € (in Germany). (2) Countries' shares of abatement effort and share of the benefits that are enjoyed by their residents vary significantly, as shown in Figure 7. Germany generates the largest share of the ancillary benefits, about 44%, followed by the United Kingdom with a contribution of 17%, Italy and Poland both with 6%. These countries also enjoy the largest shares of local benefits. Half of the 28 European countries do not contribute more that 5% to total ancillary benefits, but also do not enjoy more than 5% of the total ancillary benefits. (3) In three European countries – Switzerland, Lithuania and Sweden – the RCP2.6 mitigation scenario results in higher non-GHG emissions than in the Reference case and as a result the generated ancillary benefits are negative in these countries, i.e. RCP2.6 generates damage; thanks to reduced import of emission air quality would be overall also improved.



Notes: RCP2.6 scenario. Percentage of EU reduction of costs.

Figure 7. Countries' contribution to total ancillary benefits and to total effort of their generation in Europe.

From Figure 8 it is also possible to infer which countries are net externality producers and which countries are instead net beneficiaries. We define net producers of the ancillary benefits those countries whose share of total benefits generated in Europe is larger than their share of total benefits that are enjoyed by its residents. For example, Bulgaria's contribution to cumulative ancillary benefits due to its non-GHG emission reductions is 0.8% of the total benefits in Europe (€20.7B), while Bulgarians receive only 0.1% of total ancillary benefits in Europe (€2.5B). This implies that Bulgaria contributes more to overall ancillary benefits in Europe than it receives in the RCP2.6 scenario. Such a country can be considered to relatively lose out as a result of the GHG mitigation policy, although we highlight that each country is better off with respect to overall pollution costs in RCP4.5. Estonia, Ireland and Slovenia face the same situation as Bulgaria. Cyprus, Portugal, Finland, Romania, Czech Republic, Greece, Poland and Denmark belong among the net producers as well, but their relative contribution to the overall ancillary benefits is not as large compared to their share of benefits that their residents would enjoy as it is in the first group of net producing countries. The contribution of large countries, such as Germany, France, Italy, Spain, or the United Kingdom, but also of the Netherlands, Slovakia and Hungary is roughly equivalent to their benefits. Belgium, Austria, Latvia, Norway and Luxemburg are the relative winners in Europe since they all receive more ancillary benefits than they generate.

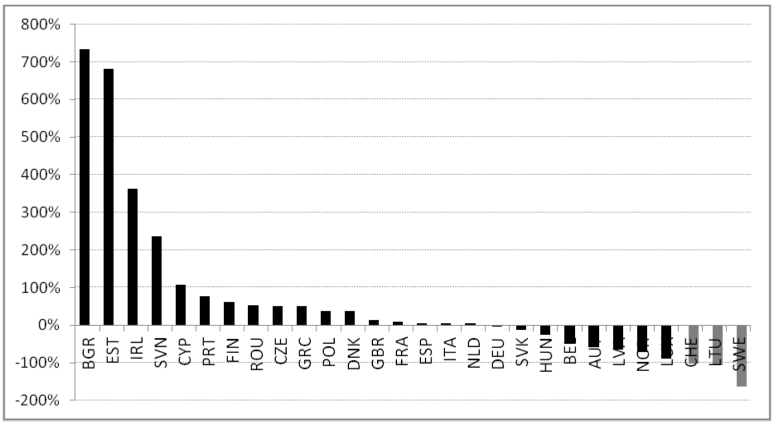


Figure 8. Contribution to ancillary benefits generated relative to the share of benefits that a country would enjoy in RCP2.6, 2015-2100.

The left panel of Figure 9 displays the percentage of ancillary benefits that result from emission reduction in one country which are ‘exported’ elsewhere. The rest of the benefits have a domestic origin, i.e. they happen due to emission abatement in the same country. The right panel shows ‘imported’ ancillary benefits as a fraction of total ancillary benefits. These benefits are enjoyed thanks to the emission reductions in other countries. For instance, emission reductions in Italy will mainly benefit the local population and local assets. Only 11% of ancillary benefits are ‘exported’ to other countries. Cyprus, Italy, Spain or Greece do not benefit much from emission reductions in other countries. Most of the benefits in Luxembourg, Latvia, Norway or Belgium are instead due to the external emissions reductions. In the case of Sweden, Lithuania and Switzerland the share exceeds 100% which describes a situation when ‘imported’ benefits exceed total benefits. This happens when ancillary benefits due to domestic abatement are negative, that is when the RCP2.6 climate mitigation policy increases local pollution.

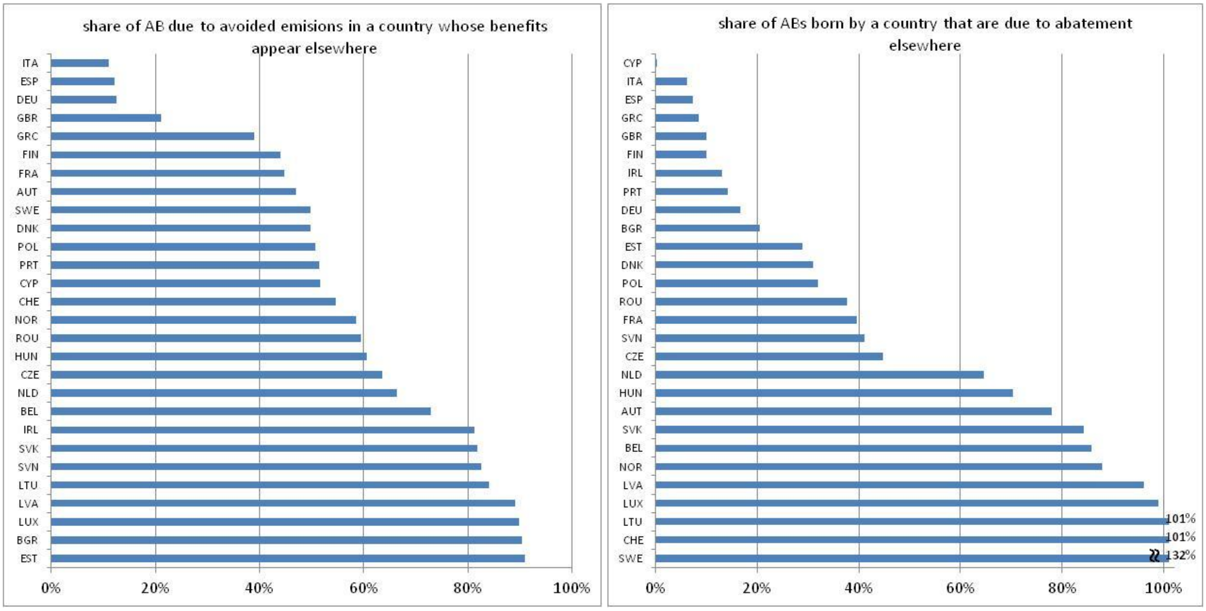


Figure 9. Exported (left panel) and imported (right panel) ancillary benefits from pollution reduction.

6 Conclusions and remarks

This paper presents estimates of the air quality ancillary benefits of GHG emission reductions. We consider three climate policy scenarios that achieve three standard radiative forcing levels in 2100: 6.0, 4.5 and 2.6 W/m^2. These three levels correspond to concentrations of GHG equal to 850, 650, and 490 ppm CO_2 equivalent, which result in global mean temperature increases of 3.7°C, 3.0°C and 2.0°C, respectively. These radiative forcing targets are achieved by introducing a uniform tax on all GHG emissions in the Integrated Assessment Model WITCH, assuming full as well as limited technological flexibility. Our scenarios cover the whole world for the period 2015-2100, however, we assess only ancillary benefits from emissions reductions in electricity generation in Europe.

As emitting GHG becomes more expensive, WITCH projects investment in carbon-free technologies for the energy sector, energy efficiency and R&D to develop carbon-free backstop technologies, substitutes the energy input with other factors and invests in a series of activities to reduce CO_2 emissions from deforestation and other non-CO_2 gases. As a result economic growth is slower in the tax scenarios. In Europe, mitigation policies are usually less costly than in other regions of the world, with cumulated consumption and GDP losses amounting to about 2% and 3% in the RCP2.6 scenario, respectively, if a discount rate based on the endogenous interest rate of WITCH is applied. Compared to the Reference scenario, until 2100 cumulative GHG emissions are reduced by 14% in the RCP6.0, but they are 62% smaller in the RCP4.5 and RCP2.6 leads even to negative cumulative GHG emissions due to the use of biomass with carbon capture and sequestration.

The resulting consumption patterns of fossil fuels in the European electricity sector are used to estimate the physical and economic benefits of pollution reductions on human health and on key assets by implementing the most advanced version of the ExternE methodology with its Impact Pathway Analysis. The ancillary benefits are derived as the difference between pollution costs for the mitigation and the reference scenario, when impacts on human health, crop yield, materials, and biodiversity associated with emissions of PM2.5, PM10, SO_2, NOx, and NMVOC are considered.

In sum, our estimates of the ancillary benefits of reducing non-GHG polluting emissions in the electricity sector in Europe are in line with estimates in the literature and very close to 33 € per ton of CO_2 abated, the mean value of the benefits reported in the review by Nemet et al. (2010) for developed countries. Specifically, in the RCP2.6 mitigation scenario, we quantify these benefits in Europe at more than €2.5T during 2015-2100, which implies average ancillary benefits of about 21.6 €/t CO_2eq abated in the European electricity sector. Less strict scenarios generate overall smaller local benefits, but the magnitude of ancillary benefits per ton of CO_2eq abated is only slightly smaller (€14.4, or €18.3, respectively) than under stricter mitigation. In real terms, without discounting, the ancillary benefits are in the range of €36 to €50 per ton of CO_2eq abated and the unit value of the benefits for most mitigation scenarios slightly increases over time.

On average, ancillary benefits per ton of CO_2eq abated in Europe are about 7-times larger than the projected carbon price by WITCH for the RCP6.0 mitigation scenario. As the carbon price increases in the RCP4.5, this ratio declines to 0.5, and it gets as low as 0.06 in the RCP2.6. A lower ratio for larger carbon prices has been frequently documented elsewhere (Grossman et al. 2011) and our results are in fact in line with general empirical evidence. For the whole period, cumulative ancillary benefits also exceed cumulative additional cost of electricity generation in Europe, with an exception in the RCP6.0 that actually results in overall cost savings in the power sector.

At country level we find that about 73% of total ancillary benefits attributable to the RCP2.6 mitigation scenario have a domestic origin, while the rest of the benefits are enjoyed in other countries than in the one where the damaging emissions were abated. There are several key findings worth mentioning: first, each of the 28 European countries is better off if RCP2.6 mitigation policy is implemented, although the absolute value of the benefits varies significantly across countries, reflecting their size, primary energy use, and fuel and technology mix to generate electricity. Second, Germany is the key player; it contributes to ancillary benefits by about 44% and receives approximately the same share of total ancillary benefits generated in Europe. Other large European countries such as the United Kingdom, Italy and Poland also considerably contribute to total ancillary benefits. Many other European countries are either small or have cleaner energy mixes and do not contribute much to European-wide ancillary benefits. 14 out of 28 countries generate (and enjoy) less than 5% of total European ancillary benefits. Third, there are relative winners and losers with respect to ancillary benefits in Europe. Large European countries are neutral – they contribute to ancillary benefits as much as they benefit. Hungary, Belgium, Austria, Latvia and Norway benefit more than they contribute to ancillary benefits. Although Switzerland, Lithuania and Sweden generate domestically ancillary damage rather than benefit, overall they win as well due to larger ancillary benefits imported from other European countries.

Technologically constrained RCP4.5 scenarios lead to a higher price of carbon, but the price effect on all emissions is relatively small compared to the emission predictions for the scenario with full flexibility. Overall, limited flexibility in energy efficiency, biomass supply and renewable energy technologies does not yield substantially different results from the ones that we obtain for the mitigation scenario with full flexibility.

The literature suggests that the ancillary benefits of climate mitigation can be very large and are thus policy relevant. Our results confirm previous studies. As pointed out by Burtraw et al. (2003), not considering ancillary benefits could lead to an incorrect assessment of the net costs of mitigation policies and to an incorrect identification of 'no regrets' levels of GHG mitigation. For instance, Nam et al. (2013), by using the EPPA5 model, found that if China achieves its SO_2 and NOx emission reduction targets, as proposed in its 12th Five Year Plan, the corresponding carbon-mitigation potential exceeds China's official 17% CO_2 intensity reduction goal. Hence, if these ancillary benefits can be measured in monetary terms, they should be included in the cost calculation of climate policy (Davis et al. 2000). However some caveats apply.

First, in an ideal world each externality should be addressed using a specific tool. For example, most of the externalities from fossil fuels combustion are additive and should be corrected using taxes on fuel use that reflect the marginal cost of pollution (Heine et al. 2012).[21] Efficient regulation thus requires the imposition of a penalty on fuel use that is equal to the sum of the marginal cost of each pollutant. Climate policy cannot substitute local pollution policies and *vice versa*. Unfortunately, this efficient solution is rarely implemented. If local pollution effects are not internalized, a carbon tax calibrated to reflect the marginal cost of carbon emissions has positive spillovers. If climate policy is not implemented taxes aimed at reducing local pollution may have a positive global spillover if the fuel mix shifts towards cleaner fuels. If local pollution is reduced using end-of-pipe technologies carbon emissions may remain constant or may increase due to efficiency losses This externality should be included in the cost calculations of local pollution policies.

Second, the existence of ancillary benefits should not be a reason for increasing the carbon tax or to make climate regulation more stringent. The goal of carbon taxes is to reduce the climate externality and the carbon price should be set to reflect the social cost of carbon. If climate policy also improves air quality, then air quality policy can be less stringent than it would be if climate policy was not implemented. This benefit of GHG mitigation should not be neglected but the social cost of carbon does not change.

Finally, we appreciate Ian Parry's et al. (2014) suggestion to "understand how much carbon emissions reduction is in the self-interest of countries" and to derive nationally efficient carbon prices. We are however more cautious than to call for "an approach that builds on national self-interest and spurs a race to the top in low-carbon energy solutions" (Parry 2014.). It is true that policies regulating local damage are more acceptable by the public than policies which have local costs but global benefits far in the future. The focus on local benefits may increase the political acceptability of carbon taxes. However, it remains unclear what would happen if the carbon tax had to increase above the level that is deemed optimal to reduce local pollution. We find that the +2°C compatible scenario has a carbon price that is always much higher than what would be justified by local benefits alone. Although we do not account for all possible ancillary benefits, it seems plausible to assume that pursuing local benefits alone will not keep the increase of global mean temperature below +2°C.

There are several limitations in our modelling approach that may require further research.

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[21] In some cases climate and local pollution have a multiplicative effect. For example ozone formation depends on the joint combination of local pollutants and particular climatic conditions. However, these are special cases that require special treatment. It is safe to assume that short-term climatic conditions are not affected by the carbon tax and that long-term ozone formation is not affected by the present level concentrations of local pollutants. The same reasoning applies to environmental regulation that aims to curb local pollutants.

First, since the quantification of ancillary benefits is based on a soft-link of WITCH global model and ExternE's Impact Pathway Approach, there is no optimal joint management of local and global externalities. Within the very recent LIMITS project, air quality model has been made endogenous in WITCH model, which will allow later analysing the joint management of the two externalities.

Second, we use WITCH to determine the economic and technological impacts at global level, while the non-GHG impacts and ancillary benefits are quantified for Europe and only from non-GHG emission abatement in electricity sector. Our assessment is hence not complete.

Third, we are interested in finding out the distribution across European countries of the pollution costs and of the ancillary benefits of climate change mitigation policy. The WITCH model provides energy scenarios for two large blocs in Europe: Western and Eastern Europe. We therefore build energy scenarios for 28 European countries assuming that each country's share of total energy use in the European bloc remains constant over time and under alternative climate mitigation policies. In reality, fuel-mix may change differently across countries in the bloc. Assuming that each country will *mimic* others within the bloc is quite a reasonable assumption, especially in the long run.

Fourth, ancillary benefits are determined by emission-fuel coefficients that are derived from the EMEP EEA air pollutant emission inventory guidebook (EMEP/EEA 2013). More sources may provide a wide range of the emission-fuel coefficients that might be used in a sensitivity analysis to estimate uncertainty in our estimate of ancillary benefits. The emission factors of fuels also remain constant over the entire period that actually implies no improvement in the efficacy of the end-of-pipe non-GHG abatement technologies. Incorporating dynamic improvement in the abatement efficacy would significantly improve our calculations.

We leave all these possible extensions to future research.

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Appendix

Pollutant	Unit	Hard Coal			Gaseous fuels			Heavy Fuel Oil			Biomass		
		Value	Lower	Upper	Value	Lower	Upper	Value	Lower	Upper	Value	Lower	Upper
NMVOC	g/GJ	1	0.6	2.4	2.6	0.65	10.4	2.3	1.4	3.2	7.31	2.44	21.9
NOx	g/GJ	209	200	350	89	15	185	142	70	300	81	40	160
TSP	g/GJ	11.4	3	300	0.89	0.445	1.34	35.4	2	200	172	86	344
PM10	g/GJ	7.7	2	20	0.89	0.445	1.34	25.2	1.5	150	155	77	310
PM2.5	g/GJ	3.4	0.9	90	0.89	0.445	1.34	19.3	0.9	90	133	66	266
SOx	g/GJ	820	330	5000	0.281	0.169	0.393	495	146	1700	10.8	6.45	15.1
Cd	mg/GJ	0.9	0.627	1.46	0.25*	0.08*	0.75*	1.2	0.6	2.4	1.76	1.06	2.47
As	mg/GJ	7.1	5.04	11.8	120*	40*	360*	3.98	1.99	7.97	9.46	5.68	13.2
Ni	mg/GJ	4.9	3.44	8.03	0.51*	0.17*	1.53*	255	127	510	14.2	8.51	19.9
Pb	mg/GJ	7.3	5.16	12	1.5*	0.5*	4.5*	4.56	2.28	9.11	20.6	12.4	28.9
Hg	mg/GJ	1.4	1.02	2.38	100*	10*	1000*	0.341	0.17	0.682	1.51	0.903	2.11
Cr	mg/GJ	4.5	3.2	7.46	0.76*	0.25*	2.28*	2.55	1.27	5.1	9.03	5.42	12.6

Note: Lower and Upper values indicate the range of 95% confidence interval for given emission factor. Term * denotes factors expressed in g/GJ. Source: EMEP/EEA (2013).

Table A - 1. Emission factors for source category 1.A.1 - Public electricity and heat production.

Authors	Country	Scenarios	AB in 2005€/tCO_2	Pollutants	Impacts covered
Abt, 1999	USA	tax $30, $67 /tC*	2.3, 20	Criteria pollutants	Health – mortality and illness; Visibility and household soiling (materials damage)
Aunan, Aaheim, Seip, 2000	Hungary	Energy Conservation Program	148	TSP, SO_2, NOx, CO, VOC, CO_2, CH_4, N_2O, VOC	Health effects; damage on materials and vegetation. Annual health benefits $648m, with a range of $370 to $1168m (Aaheim et al. 1997).
Barker and Rosendahl, 2000	Western Europe (19 regions)	Tax $161/tC*	45	SO_2, NOx, PM10	Human and animal health and welfare, materials, buildings and other physical capital, vegetation
Boyd, Krutilla, Viscusi, 1995	USA	$9/tC*	12	Pb, PM, SOx, SO_4, O_3	Health, visibility
Brendemoen and Vennemo, 1994	Norway	Tax $840/tC*	72	SO_2, NOx, CO, VOC, CO_2, CH_4, N_2O, Particulates	Indirect: Health costs; lost recreational value from lakes and forests; corrosion Direct: Traffic noise, road maintenance, congestion, accidents
Burtraw et al., 1999	USA	tax $10, $25, $50 per ton C*	0.6 to 0.9	SO_2, NOx	Health
Burtraw et al., 2003	USA	$25 carbon tax in the energy sector	12.5 – 14.5	NOx, PM_{10}, TSP, SO_2, sulfates	Health effects
Burtraw, Linn, Palmer, Paul, 2014	USA	cap-and-trade & tradable performance standards that reach 17% goal for 2020	34 – 44	SO_2	Health effects based on damage factors in EPA (2011)
Cifuentes et al. 2000	Santiago, Chile	Energy efficiency	18	SO2, NOx, CO, NMHC, PM10, dust	Health
Dessus and O'Connor, 1999	Chile	Tax $67, $157, $284 (10%, 20%, 30% C reduction)*	73, 74, 78	7 air pollutants	Health (morbidity, mortality, IQ effect)
Garbaccio, Ho, Jorgenson, 2000	China	Tax $1/tC, $2/tC*	15	PM10, SO_2	Health
Grossman, Muller, O'Neill-Toy, 2011	USA	Warner-Lieberman bill (S.2191) of 2007	1 – 63	PM2.5, VOC, NOx, SO_2,NH3 and O_3	Health effects using APEEP model
Holland et al., 2011	EU27	2˚C stabilization scenario	24	PM2.5, PM_{coarse}, SO_2, NOx	Health effects, effects on crops, building materials and ecosystems (ExternE).
Kiuila, Markandya, Ščasný, Tsuchimoto, *forthcoming*	Czech Republic	Full internalization of local external costs	32 – 72	PM2.5, PM_{coarse}, SO_2, NOx	Health effects, effects on crops, building materials and ecosystems (ExternE).
Nemet, Holloway, Meier, 2010	review	NA	38 (1.6 – 152) 33 (developed)	NA	Health effects, various impact categories
Parry, Veung, Heine, 2014	20 top world-wide emitters	Nationally efficient carbon prices	44 (from -17 to 220) 65 (for coal)	PM2.5, SO_2, NOx	Health (intake fractions extrapolated from the average plant in China)
Rečka and Ščasný, 2013	Czech Republic	EU ETS till 2030	15	PM2.5, PM_{coarse}, SO_2, NOx	Health effects, effects on crops, building materials and ecosystems (ExternE).
Scheraga and Leary, 1993	USA	$144/tC*	12	TSP, PM10, SOx, NOx, CO, VOC, CO_2, Pb	Health – morbidity and mortality
Ščasný and Rečka, *forthcoming*	Slovakia	17€/tCO2, -20% & -25% CO2 target	11	PM2.5, PM_{coarse}, SO_2, NOx	Health effects, effects on crops, building materials and ecosystems (ExternE).
West et al. 2013	14 world regions	NA	43 – 326		Health impacts, air quality model used

Note: * This information is based on OECD (2002) and tax is expressed in 1996 US$. The ancillary benefits are recalculated in 2005 Euro by CPI and purchasing power standard rate.

Table A - 2. Review of ancillary benefits per ton of CO_2, in €2005.

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