# Internalizing the impacts of air pollution: a global integrated Cost-Benefit Analysis

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## Extended Abstract

*Introduction*

Air pollution (AP) is considered the main environmental problem by the World Health Organization (WHO) [1, 2, 3]. Outdoor AP is responsible for 3.3 million premature deaths yearly worldwide [4]. With the continuous burning of fossil fuels and the increasing number of population living in cities, where polluting intense activities are very concentrated, this number is bound to increase if no oriented or integrated policy is in place.

The increasing public awareness towards the effects of air pollution [5, 6] is urging local and national governments to act on air pollution reduction. At the same time, in the context of the United Nations Framework Convention on Climate Change (UNFCCC), nations worldwide have committed to reduce their Greenhouse Gas (GHG) emissions. Policymakers are then facing two major environmental problems that have the same origin: fuel burning. However, their temporal and regional scales do not totally coincide, nor their impacts are the same. While CC is a global problem at the planetary scale, air pollution is generally a short-term local-to-regional problem, which is more easily perceived by the population than the mid-to-long term impacts of climate change. Climate targets are typically formulated over a long time frame such as a century, while policy-makers have shorter governance cycles and are mainly concerned with short-term impacts on the population. Air pollution represents a stronger and more appealing argument than climate in the political agendas [7].

The connection between climate and air pollution is significant enough to interfere with the safe achievement of the intended climate target [8], and the changes that are require to decarbonize the energy system reduce exposure to air pollution [9, 7]. To this end, both problems should be taken into account by policy makers when facing the decision even in the short term. While climate change mitigation mainly generates benefits to air pollution reduction (with the exception of biomass and bio-fuels), the inverse might not be true. The reason is two fold: i) the reduction of particulate matter PM (aerosols) concentration might lead to a increase in the radiative forcing due to the reflecting properties of some particles; ii) air pollution emissions can be significantly reduced applying End-Of-Pipe (EOP) measures, which implement technology at the end of the process line before the release. They do not imply any change in energy demand or energy mix, allowing to reduce pollution of very carbon intensive activities.

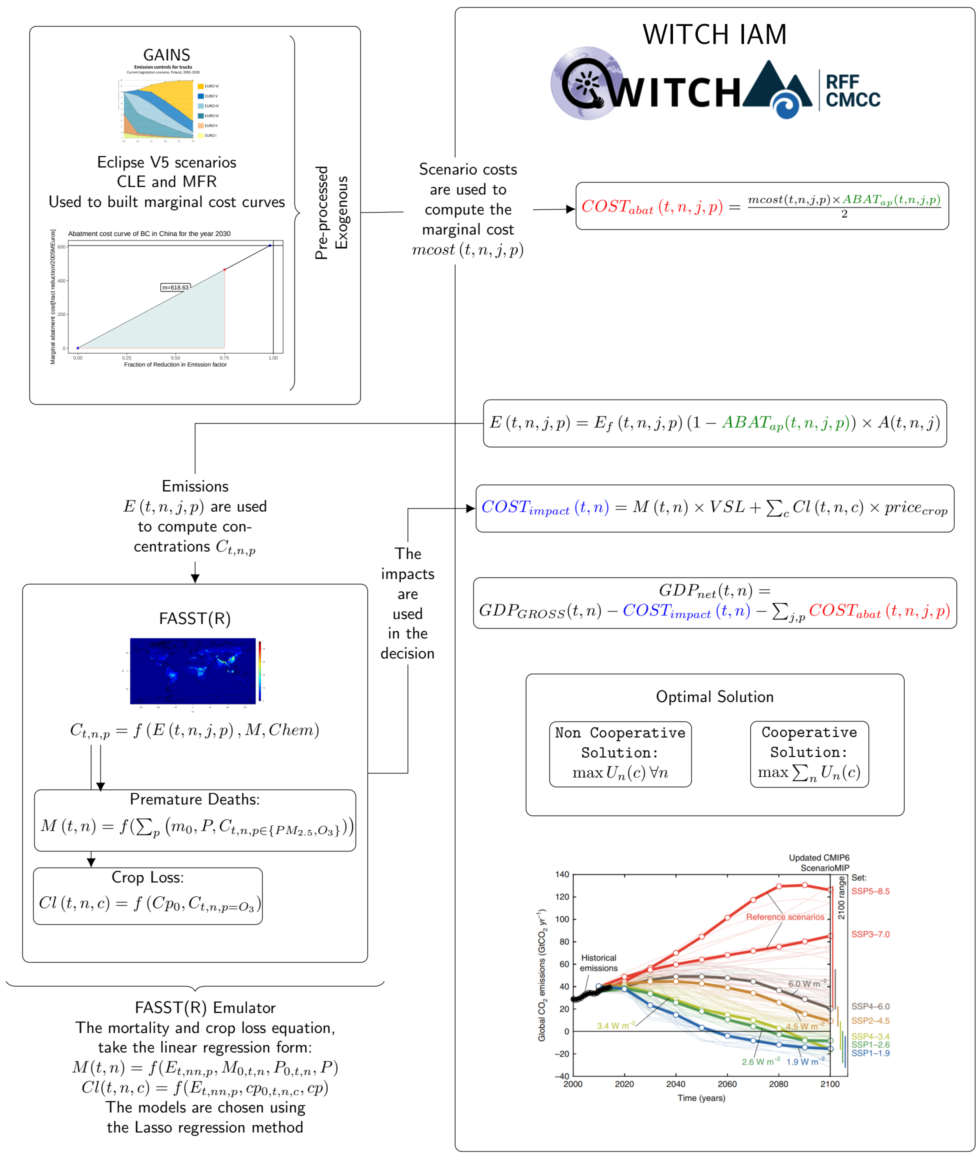
In the recent years, many studies have focus on the co-benefits of climate change mitigation for air pollution (e.g. [9, 10, 11]) or simply assessing the impacts of inaction towards climate change (e.g. [12]), as an attempt to urge policy makers to act on climate. However, this type of analysis does not deliver optimal solutions taking into account the costs of inaction, both on local air pollution and on climate change.

Cost-Benefit Analysis (CBA) has often been used in integrated assessment modeling in the context of climate policy including adaptation [13, 14, 15]. The CBA method allows for the economical quantification of inaction, uncoordinated policies or non-optimal decisions.

The development of CBA in Integrated Assessment Models (IAMs) results in policies that are optimized internalizing not only mitigation costs but also the impact costs. This approach is not new, CBA has been addressed in previous studies and the literature is continuing to grow, but only few studies have looked so far at both the damages from AP and CC in a cost-benefit framework [16].

Global scale IAMs typically minimize the cost of climate policies, or national/regional energy strategies. Often this framework neglects the benefits that leak from the climate goals to other environmental issues. In this paper we propose a framework that internalizes the air pollution and the climate change impacts in order to inform on optimal cost-benefit multi-objective strategies.

We set out to quantify the AP and CC impacts that can be avoided using optimal CBA policy. We investigate the regional heterogeneity of the impacts and provide insights about the robustness of CBA.




**E**: Emissions
**Ef**: Emission factor
**A**: Activity (PJ)
**c**: Consumption
**VSL**: Value of a Statistical Life
**n**: region
**j**: sector
**p**: pollutant
**t**: time
**mcost**: marginal abatement cost
**ABAT**: End Of Pipe (EOP) abatement
**U**:Utility
**CLE**: Current Legislation Scenario
**MFR**: Maximum Feasible Reduction
**Cl**: Crop loss
**C**: concentration
**M**: mortality
**P**: Population

Figure 1: CBA framework implemented in the WITCH IAM.

*Methodology*

For global IAMs, CBA approaches involves not only the typical uncertainties inherent to cost, but also requires methodological engineering in order to be able to solve the problem from a computational point of view. We have developed a CBA framework for the WITCH IAM [17], which includes the air pollution impacts from ozone on crops (maize, wheat, soybean and rice) and from both ozone and PM2.5 on mortality. The framework implemented in WITCH is showed in Figure 1. The model can provide two different types of optimal solution: non-cooperative and in Equation 1 and cooperative as in Equation 2.

$$\max U_n(c) \, \forall n \tag{1}$$

$$\max \sum_n U_n(c) \tag{2}$$

The air pollution reduction in WITCH can occur via two means:

- **End-Of-Pipe measures:** In order to balance the impact cost the policy maker can choose to invest in the EOP measures that are available in the model.

- **Energy structure changes:** The other possible choice for the model is via the structural measures changing the energy technologies in order to balance the cost and benefits of reducing air pollution and ultimately (hopefully) reducing GHG thus limiting the temperature increase by the end of the century.

*WITCH IAM*

WITCH (World Induced Technical Change Hybrid) is an IAM designed to assess climate change mitigation and adaptation policies [18, 17]. It includes two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization. A top-down inter-temporal Ramsey-type optimal growth model is hard linked with a representation of the energy sector described in a bottom-up fashion. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activities of a set of representative regions. A climate model (MAGICC) is used to compute climate variables from GHG emission levels and an air pollution model (FASST(R)) is linked to compute air pollutant concentrations. WITCH-GLOBIOM represents the world in a set of a varying number of macro regions for each, it generates the optimal mitigation strategy for the long-term (from 2005 to 2100) as a response to external constraints on emissions. A model description is available in [17], and a full documentation can be found at `http://doc.witchmodel.org`. The climate damages are modelled in WITCH using a set of regional reduced-form damage functions that link the global average temperature increase above pre-industrial levels to changes in regional gross domestic product. The damage functions consist of two components accounting for both negative and positive impacts as in [17].

*EOP costs*

Air pollution can be reduced implementing EOP measures, which reduce the emissions of pollutants at the end of the production line. These are generally very effective and less expensive then the structural measures. We have included in the WITCH IAM, the possibility of investing in EOP techniques in order to reduce pollutants. The EOP costs were derived from the GAINS model [19]. We use the Eclipse scenarios, Current Legislation (CLE) and Maximum Feasible Reduction (MFR), in order to draw the yearly, $t$, marginal costs of reducing the emission factor of the sector $j$ in region $n$ of pollutant $p$. The current version neglects the fact that implementing a given EOP technique might reduce more than one pollutant, and implements the measures assuming that the emission reduction of one pollutant is independent of the other pollutants.

*Air pollution Impacts*

We use a fast chemistry transport model, FASST(R), an R version of the reduced-form TM5-FASST model developed at JRC-Ispra [20], to compute the annual concentrations of several pollutants $p$, namely $SO_2$, $NO_x$, fine Particulate Matter ($PM_{2.5}$) and $O_3$. The fine $PM_{2.5}$ include Particulate Organic Matter (POM), secondary inorganic PM, dust and sea-salt. The FASST(R) model produces concentrations on a world spatial grid of resolution of $1^\circ \times 1^\circ$. The FASST model has already been previously used in other studies to assess premature death from air pollution exposure [9]. It includes an urban increment algorithm in order to account for the population distribution and the distribution PM concentrations. FASST(R) uses source-receptor matrices in order to calculate world annual concentrations. Ozone and $PM_{2.5}$ (including secondary and natural $PM_{2.5}$) concentrations are then used to calculate moralities and crop loss as in [20].

For higher precision FASST(R) would run inside the optimization of the WITCH model, however due to computational time and feasibility these types of models cannot be run inside and IAM in optimization mode. The solution to this technical problem is then to built an emulator that can approximate fairly well the response from the FASST(R) model. This is undertaken by solving 550 plausible emission scenarios based on the SSP-RCP scenario exercise, with FASST(R) and using the mortality and crop loss outcomes to train linear regression models. The models take the form:

$$M(t,n) = f(E_{t,nn,p}, M_{0,t,n}, P_{0,t,n}) \tag{3}$$

$$Cl(t,n,c) = f(E_{t,nn,p}, cp_{0,t,n,c}), \tag{4}$$

Where annual mortality $M(t,n)$, region $n$, time $t$, $f$ is a multiple linear model, emissions $E$ of pollutants $p \in \{CO, VOC, NO_x, SO_2, NH_3, OC, BC, CH_4\}$, and $nn$ are the countries who's emissions might contribute for mortality in country $n$, including $n$; and $P$ is population. $Cl(t,n,c)$ is the annual crop loss of crop $c \in \{maize, wheat, soybean, rice\}$, and $Cp$ is crop production. $f$ is a function that describes a multi-linear regression model that is chosen using the Lasso method allowing a reasonably trade-off between fitness and the number of the dependent variables. The validation of the emulator shows good agreement, as seen in the Taylor diagram in Figure 2, where the predictions of maize and soybean crop loss and premature deaths have good score of correlation, standard deviation and normalized standard deviation.

*Impacts costs*

The Value of a Statistical life (VSL) used in this study in taken from [16]. The VSL is adjusted using per-capita Gross Domestic Product (GDP) of each region with respect to the EU region. Regarding the crop prices the model current version is based on [21].

*Scenarios*

The set of scenarios that has been used is described in Table 1.

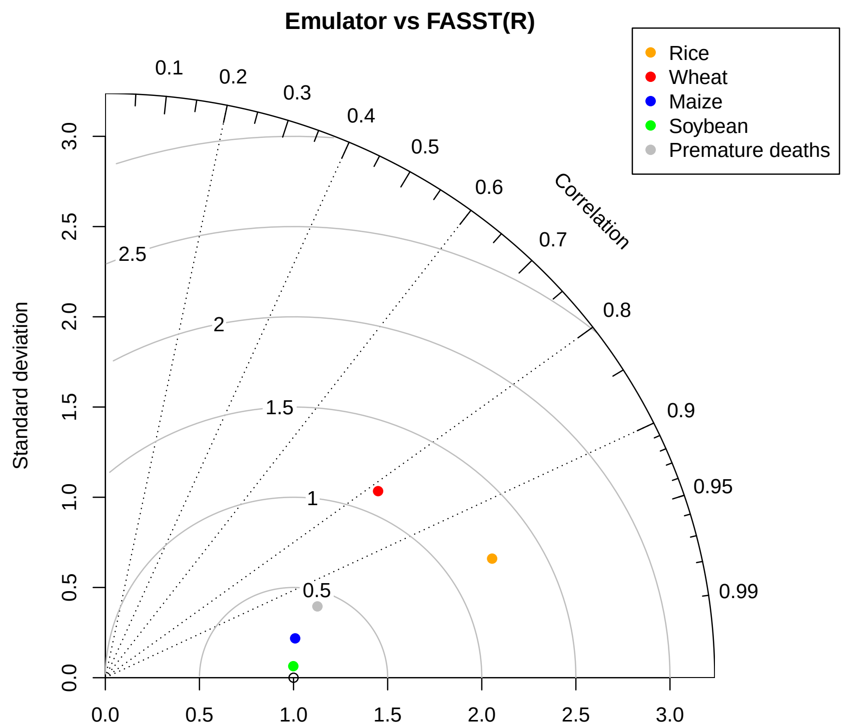



Figure 2: Taylor diagram of the emulator results versus the FASST(R) full run, for the different types of crops and for premature deaths. The horizontal axis represents the normalized standard deviation. The back dot represents the perfect fit.

The *Reference* scenario is the contractual scenario SSP2 [22] which is in line with a middle-of-the road baseline. It is important to note that SSP2 scenario already foresees a decrease in the emission factors throughout the century as in [23]. The other scenarios are CBA solutions where the marginal cost of abatement equals the marginal benefit of abatement. The *AP* and *AP_coop* scenarios are a non-cooperative and a cooperative solution, respectively, that include the economic impacts of air pollution. The difference between this two scenarios inform about the possible advantages of considering cooperation on air pollution emissions, since the framework include transboundary air pollution. The *AP_CD_coop* is a cooperative solution where a world policy makers optimizes the cost of decarbonizing and abating air pollution emissions against the economic benefits of avoid the damages caused by both climate change and air pollution. It differs from *AP_CT100*, from that fact that the latter imposes a global carbon tax of 100 USD2005/tCO2eq

Table 1: Scenario description.

| **Scenario name** | **Scenario Description** |
|---|---|
| **Reference** | Business as usual SSP2 scenario (no policy) |
| *AP* | Cost-Benefit Analysis taking into account the air pollution impacts |
| **CD_coop** | Cost-Benefit Analysis taking into account the climate damages in cooperative mode |
| **AP_CD_coop** | Same as CD_coop including the air pollution impacts |
| **AP_coop** | Same as AP but in a cooperative solution |
| **AP_CT100** | Same as AP but with a strong carbon tax |
| **AP_noEOP** | Same as AP but without allowing for investments in EOP measures |
| **AP_EQVSL** | Same as AP but the VSL is not adjusted wrt to the EU27 GDPcap |

in a non cooperative solution instead of internalizing the economic damages of climate changes. The *AP_noEOP* constrains the model to act on air pollution only by investing in structural measures. The difference between this scenario and *AP* is that in the latter the rationality that EOP is cheaper will act against climate change, while the changes in the energy system will drive the model to both reduce AP and GHG. Finally, the *AP_EQVSL* is a theoretical scenario where a life is economically equally independently of each region, i.e. on single VSL is used and is equal for every region.

*Results and Discussion*

Figure 3 shows the premature deaths associated with each of the scenarios described in Table 1.

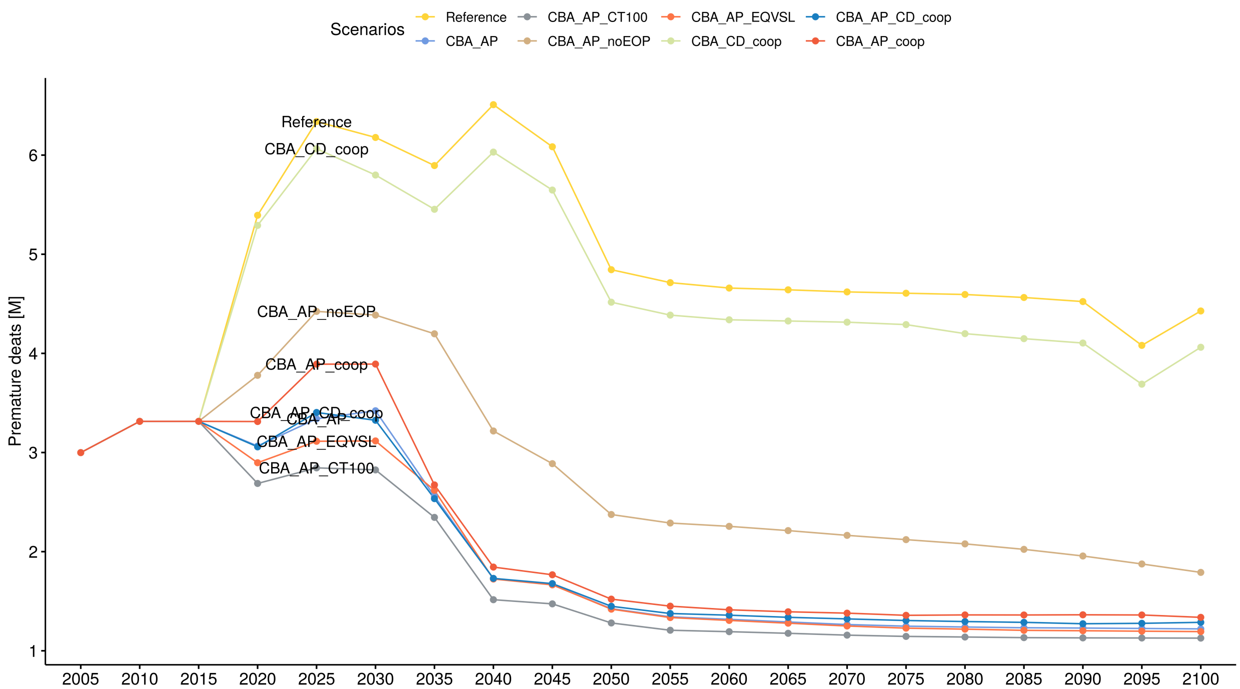



Figure 3: Premature deaths implied in each of the scenarios of Table 1.

The *Reference* SSP2 scenario foresees more than 6 million premature deaths from air pollution annually until 2045. Including the damages from climate change reduces mortality by approximately half million people annually and leads to an average increase of temperature by the end of the century of approximately 3.6°C. The internalization of climate damages alone contributes little to avoid premature mortality due to air pollution when compared with all the other policy designs considered. On the other hand, applying a carbon tax, compatible with a 2.2°C average temperature increase by 2100, together with the internalization the costs of air pollution impacts is the policy set up that results in the best outcome saving approximately 3.5 million lives annually. Considering a CBA solution accounting only for the impacts of air pollution, avoids approximately 3 million premature deaths annually. The internalization of both types of damages results in a very similar mortality pathway but with to a 0.01°C reduction in temperature. Another, relevant result is that considering the same VSL worldwide, without GDP per capita adjustment, saves more lives than considering an adjusted VSL. Finally, forcing the policymaker to invest into energy system changes results into one million less of avoided premature mortality, due to the higher marginal costs of abatement. Additionally, the net contribution of the AP induced decarbonization to temperature is somewhat marginal (approximately 0.04°C).

**Conclusions**

We have implemented a CBA framework, that takes into account the impacts of air pollution on human health and crops and climate damages. This framework allows the study of different types of solutions (cooperative and non-cooperative), and policy options, such as different types of damages, taxes and different considerations of the impact costs.

The results show that considering climate damages alone is less efficient in avoiding premature mortality than considering a stringent climate policy (*AP_CT100*). As expected, more lives are saved internalizing the costs of the air pollution impacts. It is worth noting that if one considers that a life has the same economic value all over the world the net cost-benefit solution saves more people that adjusting the VSL to the GDP per capita. This is because in certain regions the cost of a life becomes significantly important for that region to invest in less polluting technologies, reducing also the expected average global warming by the end of the century. The results indicate that the best outcome comes from the integration of both policies but considering a stringent climate target instead of internalizing the damages of climate change, which saves more lives and diminishes the average temperature increase. One of the reasons for this might be the low estimation of climate damages, a sensitivity analysis to the climate damages is an important subject of future research. Additionally, the results are highly dependent on the somehow subjective VSL, on how to discount it over time, on how to consider different ages groups and on how to better adjust it regionally.

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