Including Bottom-Up Emission Abatement Technologies in a Large-Scale Global Model for Policy Assessments

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Including bottom-up emission abatement technologies in a large-scale global model for policy assessments

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Highlights:

- Enhanced integration of bottom-up abatement curves into large-scale numerical models
- Framework captures non-linearities of bottom-up abatement cost curves
- Framework extendible to process emissions, local air pollution, or CCS modelling
- Illustration for non-CO_2 emission abatement under 2°C climate policy

Abstract: Economic models with global and economy-wide coverage can be useful tools to assess the impact of energy and environmental policies, but often disregard finer technological details of emission abatement measures. We present a framework for integrating and preserving detailed bottom-up information for end-of-pipe abatement technologies into a large-scale numerical model. Using an activity analysis approach, we capture non-linearities that typically characterise bottom-up abatement cost curves derived from discrete technology options. The model framework is flexible and can accommodate greenhouse gas and air pollution abatement, as well as modelling carbon capture and storage (CCS). Here, we illustrate this approach for non-CO_2 greenhouse gases in a large-scale Computable General Equilibrium (CGE) model and compare results with a fitted marginal abatement curve and with completely excluding non-CO_2 greenhouse gases. Results show that excluding non-CO_2 abatement options leads to an overestimation of the total abatement cost. When the detailed bottom-up technology implementation is replaced by an estimated smooth marginal abatement cost curve, significant over- or underestimations of abatement levels and costs can emerge for particular pollutant-sector-region combinations.

Keywords: marginal abatement costs; climate policy; bottom-up technology detail; CGE model; hybrid modelling; non-CO_2 greenhouse gases

JEL classification: C68, Q52, Q54

Declarations of interest: none

1. Introduction

Limiting climate change to the targets mentioned in the Paris Agreement will require profound cuts in carbon dioxide (CO_2) emissions. In addition, reaching ambitious temperature targets of well below 2°C or even 1.5°C will require substantial reductions across all greenhouse gases (GHGs), including those other than CO_2 (Montzka et al., 2011; Myhre et al., 2013; Rogelj et al., 2018). Studies show that the inclusion of abatement options for non-CO_2 emissions can significantly reduce not only the abatement cost (Weyant et al., 2006), but also the reliance on technologies for which sustainable upscaling is not guaranteed (van Vuuren et al., 2018). Further motivation to reduce non-CO_2 greenhouse gases such as methane are the potential benefits for air pollution and human health, as CH_4 is a precursor for ground-level ozone (Anenberg et al., 2012).

Abatement measures of non-CO_2 emissions have distinct characteristics that need to be captured in modelling studies and when assessing policy options. Unlike combustion CO_2, non-CO_2 pollutants are not associated with specific energy inputs to the production process, and are therefore often modelled with fixed proportions to sector-specific output levels. Abatement of these emissions can therefore mainly be achieved by reducing output, or by deploying additional end-of-pipe abatement options. Modelling efforts to capture these additional abatement payments are commonly informed by bottom-up studies that provide marginal abatement costs for emission reductions (e.g. Hyman et al., 2003). Since this type of abatement equipment adds costs (typically at the end of the production process) without changing the underlying production input structure itself, end-of-pipe emission reduction measures require an explicit modelling framework that accounts for the corresponding technology characteristics.

The traditional approach to (marginal) abatement cost functions is to fit an aggregate curve to point estimates from bottom-up data (Golub et al., 2009, Kiuila and Rutherford 2013a, 2013b, Bollen 2015, Faehn and Isaksen, 2016). The resulting curve is commonly assumed to be monotonically increasing and has a continuous derivative. Available abatement options, however, can be quite heterogenous across different pollutants and sectors, with very cheap abatement potential (such as chemicals with high global warming potential that can be easily substituted) or very expensive abatement options (e.g. production processes that cannot be easily changed or substituted). For example, the chemical sector is usually a single industrial sector in large-scale CGE models, however, some chemicals or chemical processes can be more easily replaced by others – while their abatement potential can greatly differ. This discrete technology behaviour can lead to very non-linear curves that would be better represented with e.g. piecewise linear functions.

Here, we present and apply a methodology to embed a high degree of technological detail in a global model, which (1) facilitates the dialogue across disciplines by bridging the gap with engineering, (2) enhances transparency to avoid a black box-critique, (3) enables a translation of model results to practical measures that can be communicated and implemented, (4) allows for a consistent assessment across bottom-up and top-down models, and (5) fosters credibility and strengthens reputation vis-à-vis policymakers. In addition, our approach is able to take general equilibrium effects into account in two ways. First, shocks to the model are able to influence the abatement cost of individual technologies and, consequently, affect the shape of the abatement curve endogenously. Second, our analysis covers the effects on other upstream and downstream sectors and trade flows, including the intermediate goods and services required for particular abatement equipment.

This paper extends the work of Kiuila and Rutherford (2013b) to produce results that include bottom-up data for all sectors in a global model under various climate scenarios. We use the "activity analysis" approach to model discrete abatement technologies that are inactive (or "slack") in the baseline, but can become active with sufficiently high pollution charges. The "activity analysis" approach has been used for general equilibrium models mainly in the realm of modelling different energy technologies (e.g. different electricity generation technologies or power plants; Böhringer, 1998). This allows adding additional detail typically present in bottom-up models inside a general equilibrium model (coined "hybrid modelling"; Hourcade et al., 2006, Böhringer and Rutherford, 2008). Rive (2010) uses the activity analysis approach for modelling air pollution abatement for SO_2, NO_X, and $PM_{2.5}$ to assess the cost of air pollution control and its interaction with climate policy in Western Europe.

We apply this approach to study a climate policy pathway that limits global warming to 2°C with technology-specific end-of-pipe abatement options for several non-fossil fuel originating greenhouse gas pollutants in a large-scale, global CGE model. Rather than merely using bottom-up estimates to fit a marginal abatement cost curve, the bottom-up information is preserved and integrated into the CGE model. The mixed complementarity structure of the model allows specifying conditional inequalities, such that a technology is only active when the pollution charge is sufficiently high. Hence, we extend the existing literature, which has a strong pedagogical nature, by integrating roughly 3000 specific abatement technologies in a global economy-wide model and by quantifying how this affects climate policy assessments. To compare the choice of modelling smooth approximations of abatement cost curves with bottom-up information, we compare the outcome from both modelling approaches. Aggregating bottom-up data into a (smooth) abatement cost curve leads to over- or underestimation of costs, loss of information, and implies that the modeller cannot pinpoint the specific abatement technology that is adopted in a scenario. While this paper's illustration focuses on non-CO_2 abatement options, the methodology of integrating bottom-up abatement technologies to model end-of-pipe technologies can be readily applied to other areas. Clear examples where the approach could be used include abatement of air pollutant emissions and CO_2 emission reduction through carbon capture and storage (CCS).

The remainder of the paper is structured as follows. Section 2 describes the implementation strategy, presenting intuition and modelling advantages, followed by mathematically representation and an account of how it was implemented into a large-scale CGE model. Section 3 illustrates the framework's impact with three variants of a 2°C climate policy scenario. Section 4 sketches out possible extensions and section 5 concludes.

2. Implementation

In this section, we present how we implement the integration of bottom-up, end-of-pipe abatement cost information into a CGE model. In section 2.1, we first start with providing some intuition, using a simple example illustrated with a set of figures before providing a mathematical formulation in section 2.2. Section 2.3 then briefly describes how the framework was implemented in a large scale CGE model and the input data used.

2.1. Intuition

In order to provide intuition for our approach, assume that there are three abatement options available that are characterized by different marginal abatement costs (MAC). Ordering the abatement options by their MAC provides a typical step function present in many bottom-up estimations for abatement costs (Figure 1 (a)). Under an (exogenous) carbon price, indicated by the dashed red line in Figure 1, the cheapest of the three options would be economically viable and used to the full extent. The more expensive options would not be used. Modelling the distinct abatement technologies can therefore be meaningfully interpreted and abatement through different abatement options can be reported in a detailed fashion.

For the economic model, flat costs could pose a numerical problem as in different sectors there might be abatement options with identical cost. Further, when the carbon price is equal to the abatement cost of one option, very small changes in the carbon price will lead to a corner solution with either full use or no use at all of a technology, which might not be realistic. We therefore implement a slope into each step of the marginal abatement curve. This means that technologies might only be used partially, as indicated for one of the abatement technologies in Figure 1 (b).

In addition, we allow for the cost of the abatement options to be endogenous. If the technology is dependent on particular inputs which are more expensive in a scenario, use of this abatement option will also be more expensive. This is important when abatement activities require different inputs whose costs are changed under a policy scenario. For example, some abatement technology might come with an energy penalty, i.e. requires higher energy input, while others are more intensive in labour use. In Figure 1(c), one abatement option is assumed to become more expensive while another one becomes less expensive. This endogenizes the marginal abatement curve not only by shifting costs up and down, but also by re-ordering the choice of abatement options that are used.

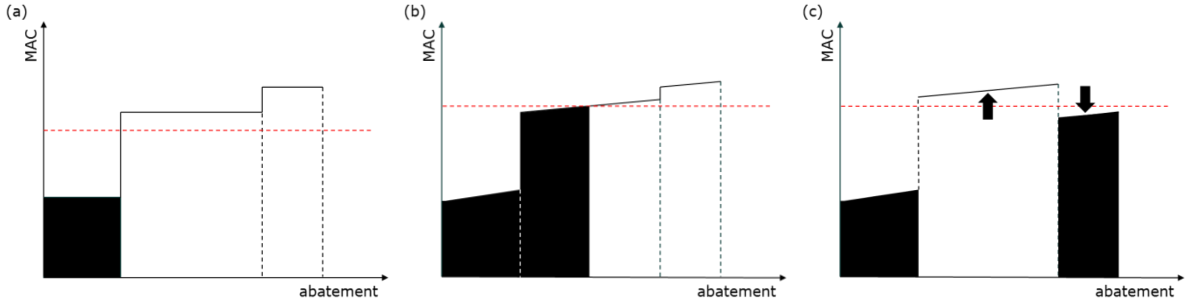

Figure 1: Example of marginal abatement curves from bottom-up data (a), with adding a positive slope (b), and with endogenous costs (c). The red dashed line represents a carbon price; solid blocks indicate technologies that are actively used to abate emissions.

Modelling discrete technologies can better capture non-linearities as the bottom-up abatement cost structure is better preserved. Therefore, this approach can avoid over- or underestimation that could occur with fitted curves, depending on the realized level of abatement and the prevailing emission price. Figure 2 shows how the bottom-up representation relates to simple fitted curve that either overestimate or underestimate the abatement cost relative to the bottom-up representation with discrete technologies. In addition, fitted curves often pass the origin which further complicates tracking the bottom-up abatement cost curve.

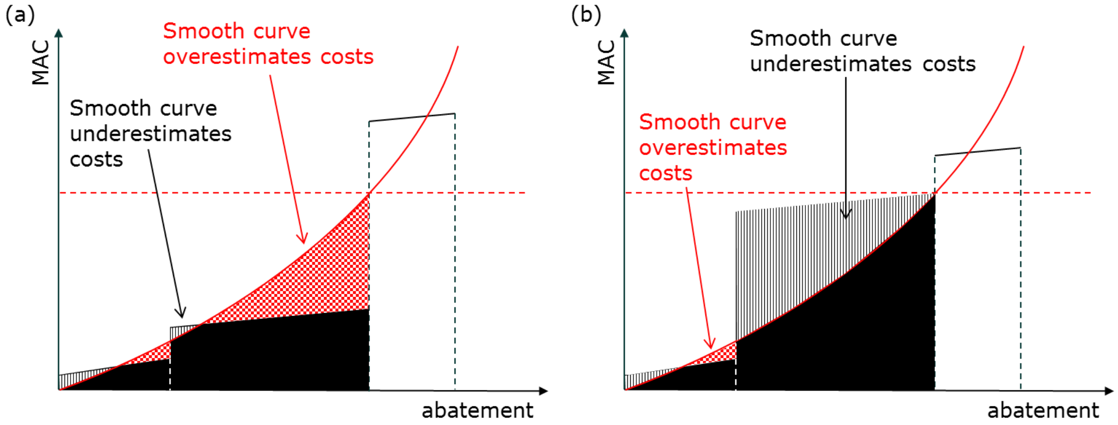

Figure 2: Comparison of bottom-up approach with discrete technologies to a fitted curve. Part (a) shows a situation in which a fitted curve (solid red line) overestimates abatement costs; part (b) shows a situation in which a fitted curve underestimates abatement costs. Examples are chosen such that a given emission price (dotted line) leads to the same level of abatement for the fitted curve and the bottom-up approach.

2.2. Mathematical formulation

The use of bottom-up abatement technology *i* is expressed in activity level $a_i \in [0,1]$, where 0 refers to a slack activity (i.e. not used) and 1 refers to full use (up to the technological maximum). Each technology can abate a share $\phi_i \in [0,1]$ emissions when used at maximum capacity. Total end-of-pipe emission reductions $A_j \in [0,1]$ per unit of output x_j in a sector are the sum of emission reductions from all bottom-up technologies in this sector

$$A_j = \sum_i \phi_i a_i. \tag{1}$$

Using θ_j as the emission factor[1] per unit of output without abatement, emissions E_j can thus be calculated as

$$\mathrm{E_j} = \sum_{\mathrm{i}} (1 - \mathrm{A_j})\theta_j \mathrm{x_j}. \tag{2}$$

We assume a quadratic cost function[2] c_i for each abatement technology *i* that is dependent on two parameters c_{1i} and c_{2i}, the level of abatement a_i as well as the value of the inputs required to

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[1] For the sake of simplifying notation, we defer from differentiating between emissions from different pollutants. In our model implementation, several non-CO_2 GHGs can be emitted in the production of one sector.

[2] This is motivated by the goal to depict marginal abatement functions aggregated over all technologies to be (piecewise) linear. In principle, this includes step functions with a choice of $c_{2i} = 0$. In the actual implementation in the model, however, this can lead to solving issues because a flat marginal abatement curve

produce the abatement service. We allow for using inputs from several sectors, using λ_{ik} to indicate the input share from sector *k*, with $\sum_k \lambda_{ik} = 1$. Indicating prices p_k and assuming a Leontief production function for the production of abatement services, the cost function is

$$\mathrm{c_i} = \sum_{\mathrm{k}} \mathrm{p_k}\lambda_{\mathrm{ik}}\left(\mathrm{c_{1i}a_i} + \frac{1}{2}\,\mathrm{c}_{2i}a_i^2\right). \tag{3}$$

The economic decision of firms to use a certain abatement technology depends on the cost of abatement activity and the cost associated with the emissions of a given pollutant. On the margin, an additional unit of abatement would cost exactly as much as the price τ to be paid under a tax or emission trading scheme, i.e. producers are indifferent between abating and polluting. The equation determining the activity level of a_i (within a range of 0 and 1) is therefore $\tau = c'(a_i)$, or in our case

$$\sum_k \mathrm{p_k}\lambda_{\mathrm{ik}}(\mathrm{c_{1i}} + \mathrm{c_{2i}a_i}) = \tau. \tag{4}$$

In this equation, the term in parenthesis refers to the marginal cost of abatement that can be directly obtained from bottom-up studies. The summation term $\sum_k \mathrm{p_k}\lambda_{\mathrm{ik}}$ should be normalized to 1, so that marginal cost as obtained from bottom-up estimation equal τ. The summation term is however included to reflect potential general equilibrium effects which can influence prices of goods used to produce abatement services and hence the (marginal) cost of abatement.

The cost of producing one unit of output in sector *j* is thus affected by the price of the input composite (i.e., all inputs before purchases of abatement services) $\widetilde{p_j}$, emission fees paid on unabated emissions, and the cost for abatement from all abatement technologies *i* used in this sector

$$p_j = \widetilde{p_j} + \theta_j\left[(1 - A_j)\tau + \sum_i \phi_i c_i(a_i)\right]. \tag{5}$$

In contrast to Rive et al. (2010), we do not assume that rents arise from scarcity of end-of-pipe abatement options. Instead, we assume that firms in a sector will implement abatement options when this reduces their production costs and are only able to pass on the cost of purchasing abatement equipment.

We make use of the mixed complementarity formulation such that equations are linked with the bounds imposed on variables (see e.g. Böhringer, 1998, for a more detailed description in a similar application of introducing bottom-up information into a CGE model). Using the ⊥ symbol to denote complementarity, we will have additional equation-variable pairs that will be added to the CGE model

$$\begin{aligned} Eq(1) &\perp 0 \le A_i \le 1, \\ Eq(4) &\perp\ 0 \le a_i \le 1. \end{aligned} \tag{6}$$

Note that in particular the activity level a_i is linked eq. (4) which resembles a zero profit condition. In other words, the technology a_i will be slack (unused) when $c_{1i} \ge \tau / \sum_k p_k \lambda_{ik}$ and will be fully used when $\tau / \sum_k p_k \lambda_{ik} \ge c_{1i} + c_{2i}$. The advantage of introducing slack abatement activities to the CGE

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implies indifference between abatement and paying emission charges. For the implementation in JRC-GEM-E3, we ensure positive values for c_{2i}. Other functional forms could be implemented if needed by the modeller.

model is that this modification does not require adjustments such as re-balancing to the underlying input output structure. Further, the linking of abatement activities to existing sectors allows for rapid expansion of abatement potential without changing the underlying input structure. Nonetheless, additional inputs and related costs are taken into account when deploying end-of-pipe abatement technologies.

Finally, when implementing this in a CGE model, we also need to make sure that the market clearance conditions are adjusted to account for the additional demand for inputs used to produce abatement services.

2.3. Implementation in JRC-GEM-E3

To show the feasibility of using this framework for practical policy assessment, we implement it into the global, multi-region, multi-sector CGE model JRC-GEM-E3 (Capros et al., 2013), which was designed to analyse energy, climate and environmental policies.[3] The model version used in this paper is based on cost-minimizing firms disaggregated into 31 sectors, including crude oil, refined oil, gas, coal and electricity generation, the latter further disaggregated into 10 generation technologies. An overview of the 40 regions and all sectors is provided in Appendix Table A1. International trade flows are captured by an Armington specification and intermediate input and supply chain linkages between sectors are included based on the GTAP9 data, described in Aguiar et al. (2016). Household behaviour is described by maximizing a Stone-Geary utility function, including the purchase of two types of durables – transport and residential – which are linked to the consumption of different fuel types and corresponding greenhouse gas emissions. All greenhouse gases other than CO_2 from land use (change) and forestry are covered. Besides CO_2 emitted from fossil fuel combustion and industrial processes, all non-CO_2 Kyoto greenhouse gases are modelled explicitly in JRC-GEM-E3: methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF_6). Emission data for non-CO_2 emissions comes from GAINS model (IIASA 2016) for EU countries and from POLES-JRC (Keramidas et al., 2017) for non-EU regions. Abatement cost information for non-CO_2 abatement costs likewise comes from GAINS for EU countries and from POLES-JRC for non-EU regions[4] and from GLOBIOM for non-EU agricultural sectors (Havlík, 2014). In total, we have up to 3148 different abatement technologies used, with the number varying between model years. For a small share of non-CO_2 emissions (less than 2%), we do not have bottom-up data and use the functional form described eq (7) below, taking parameters from POLES-JRC. This functional form is also used for CO_2 emissions originating from industrialized processes, which can also be abated with end-of-pipe technologies in JRC-GEM-E3. In addition to the pre-processing done by POLES-JRC, some additional data processing has to be carried out due to different sectoral aggregation between POLES-JRC and JRC-GEM-E3 models.

The additional variables and equations added to the model increase its complexity. While this increased required time to find a solution, we generally conclude that a solution is generally found reliably. However, it can help the solver to find a solution for the about 3000 distinct abatement options in the model when appropriate starting values are chosen. A strategy that proved helpful

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[3] See Vandyck et al., 2016; 2018, for a recent applications and https://ec.europa.eu/jrc/en/gem-e3/model for a list of policy contributions.

[4] POLES-JRC mainly draws on EPA (2013) and the GECS project (Criqui et al., 2002) for non-CO_2 abatement cost information differentiated by sector and region.

was to perform a first solve of the model with fixing the bottom-up abatement variables a_i, hence dropping the respective equations (eq (4) in section 2.2)) from the model; a second solve would then free up the a_i variables.

3. Illustration with a 2°C climate policy

To illustrate the importance of the modelling implementation of abatement cost technologies for a comprehensive policy assessment, we compare a set of climate change mitigation scenarios described in the following subsection. Stylized scenarios compare the inclusion of non-CO_2 with the absence and the modelling approach described in section 2 with a more conventional approach of a fitted marginal abatement cost curve. The main aim of this section is to demonstrate the feasibility of the framework and show the channels that can influence abatement levels and costs.

3.1. Scenario design

We compare three main scenarios to elicit the importance of including a bottom-up representation of end-of-pipe abatement technologies for non-CO_2 GHG emissions. The first scenario (**"top-down"**) is described in Kitous et al. (2017) and applied in Vandyck et al. (2018). This scenario serves as our default scenario to which we compare other scenario variants; the scenarios variants describes below thus also serve as a sensitivity analysis to this scenario.

We apply a climate policy that is aimed at implementing emission reductions to limit global warming to 2°C as agreed under the Paris Agreement (comparable to Vandyck et al., 2016). In this climate policy scenario, we levy economy-wide regional carbon prices on greenhouse gas emissions. For the transition of the power system, we rely on POLES-JRC. The shares of different electricity generation technologies are exogenously adjusted, whereas the agents in the CGE model react to endogenous price changes by adjusting demand for power. This exogenous adjustment of power shares also includes exogenous shares of CCS, which is modelled as described in section 4.1.[5] Since the share of CCS deployment per generation technology is assumed to be exogenous, we impose an exogenous value for a_i, dropping eq. (4) for this abatement option.

In the top-down scenario, we estimate a marginal abatement curve by sector and technology based on the bottom-up data used for the "bottom-up" scenario. The functional form that is used for the estimation describes abatement as a function of the emission price

$$A_j = \bar{A}_j\left(1 - e^{\beta_j \tau}\right), \tag{7}$$

where $\beta < 0$ is the form parameter, τ is the carbon price in dollars, and $\bar{A}_j$ is the maximum abatement potential in the sector. Although this functional form is quite simple by having only one free parameter to be estimated, it has some properties that are desirable for the analysis. For $\tau \geq 0$, the function is limited to $0 \leq A_j \leq \bar{A}_j$ with $\lim_{\tau\to\infty} = \bar{A}_j$. While some other functions also fulfil these properties and are used for similar studies (e.g., Faehn and Isaksen, 2016, use polynomials), ensuring that these properties hold and adjusting the functional form manually when needed can be cumbersome when including many regions and sectors.

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[5] Note that we use this power sector structure to model CCS in all scenarios.

Solved for τ, the function from eq. (7) shows the typical pattern of increasing marginal abatement costs. Total cost of abatement is the integral over marginal abatement cost

$$\int_0^{A_j} \frac{\ln\left(1 - A_j/\bar{A}_j\right)}{\beta_j}\, dA_j = \frac{\left(\mathrm{A_j} - \bar{A}_j\right)\ln\left(1 - A_j/\bar{A}_j\right) - \mathrm{A_j}}{\beta_j}. \tag{8}$$

As in eq. (3), we assume that the abatement services for a sector are produced with a Leontief technology, hence this cost is multiplied with $p_k \lambda_k$. For the estimation of β_j, we impose an upper limit of $\bar{A}_j$ that would emerge from eq. (1) with all $a_i = 1$.[6]

In the second scenario ("**bottom-up**"), we implement bottom-up abatement technologies based on data as used in GAINS, GLOBIOM as well as from POLES-JRC, which in turn uses data from various studies and other models as described in section 2.3. This scenario includes bottom-up formulation for non-CO_2 emissions as well as for CCS. Again, the level of a_i for CCS is imposed exogenously.

In the third scenario ("**only CO_2**"), we completely disregard non-CO_2 GHG emissions as is still done in a number of large scale CGE models analysing climate policies. We can therefore infer the overall importance of including non-CO_2 emissions, as well as sectoral or regional economic consequences. In this scenario, we keep the same percentage reduction targets relative to 2015 baseline emissions. However, in this scenario the abatement has to come exclusively from a reduction in CO_2 emissions. As in the other scenarios above, we model CO_2 emissions from industrial processes with the functional form described in the "top-down" scenario, and model CCS with bottom-up technology based on exogenous power shares.

3.2. Scenario results and discussion

For a first glance of different scenario results, we compare a broad measure of cost from climate policy. The relative costs between regions depend on the respective climate policy ambition level in the baseline and 2°C policy scenario that is developed in Kitous et al. (2017). The regional distribution of costs is of lesser interest for this paper, we instead want to focus on differences between scenarios for a region. Figure 3 therefore plots GDP loss for aggregate regions relative to the top-down scenario for 2030[7]. In our particular application, the modelling choice on implementation (bottom-up vs. top-down) has little impact on the aggregate results in general. For the BRIC countries (Brazil, Russia, China, and India) and other industrialized countries (i.e. non-EU industrialized countries), the bottom-up approach leads to slightly higher costs than the top-down approach. For other developing countries (i.e. developing countries not included in BRIC), the bottom-up approach leads to lower abatement costs. We will explore the differences leading to these observations below, in order to identify mechanisms that are at play when a difference emerges between approaches. When non-CO_2 emissions are excluded, cost is significantly increased to reach the same percentage reduction in emissions little impact. Globally, GDP losses in 2030 would be overestimated by 24% when non-CO_2 emissions are not accounted for. When non-CO_2

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[6] Unlike Faehn and Isaksen (2016) we do not allow exceeding estimated bottom-up potentials at higher carbon prices. When estimating a the parameter based on least squares, we also include this limit in the function which improves the fit of the estimation. To summarize, we obtain two parameters from bottom-up data, β_j and $\bar{A}_j$, an upper limit on A_j.

[7] The year 2030 was chosen because it has the highest number of bottom-up technologies available. For the sake of clarity, we aggregate the model regions to five larger macro regions (see Appendix Table A2 details).

emissions are excluded, there is no "what flexibility" and abatement of non-CO_2 gases is on average less expensive than abatement of CO_2. This confirms earlier findings that including non-CO_2 abatement options can reduce the bill for emission reductions. Approximating reductions in all GHGs with reductions in CO_2 emissions only can thus lead to biased results.

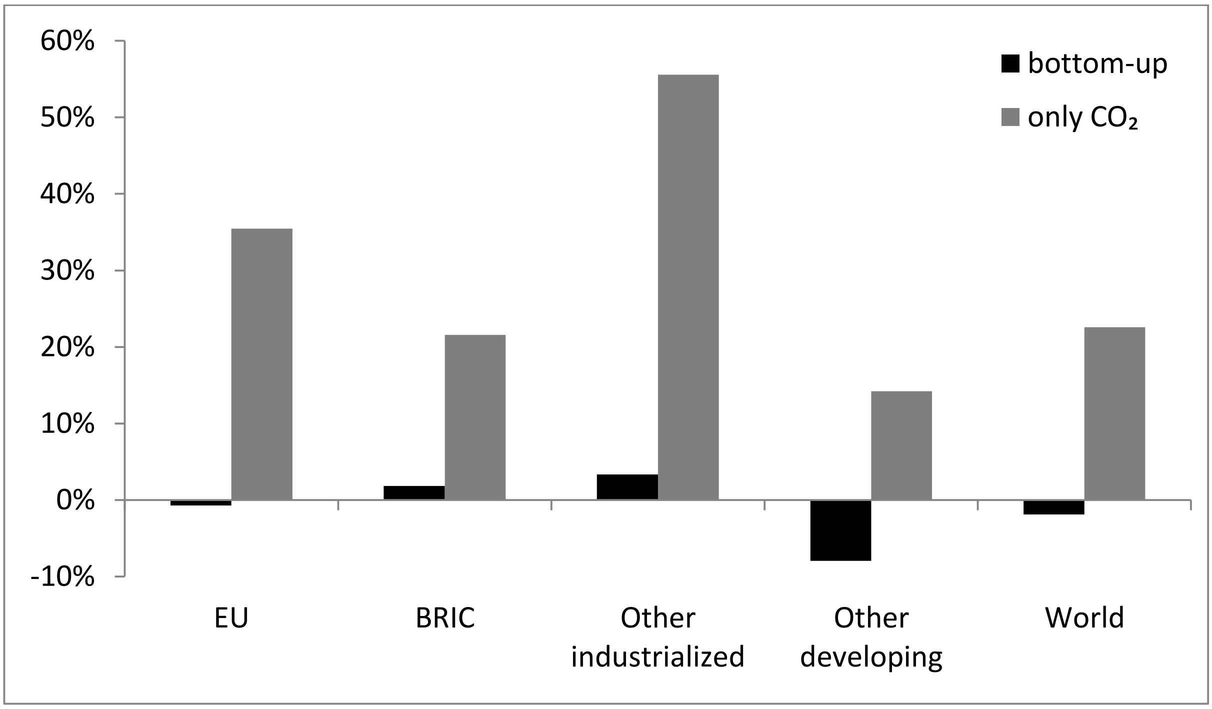

Figure 3: GDP loss for aggregate regions relative to the top-down scenario for 2030.

Figure 4 shows the distribution of abatement for different gases, normalized to total abatement with including non-CO_2 emissions. To make emission reductions comparable for the CO_2 only scenario, emission reductions in this scenario are expressed relative to the total emission reduction in the scenarios that include non-CO_2 emissions. In all regions, the abatement of CO_2 (blue bars) is lower when abatement can also be carried out in other gases. Non-CO_2 abatement ranges between 23% (Other Industrialized Countries) and about one third (EU and Other Developed Countries) of total abatement. When comparing the different modelling approaches for non-CO_2 abatement, the top-down approach leads to about 3% (ranging from 0.3 – 4.5% for different regions) more non-CO_2 abatement globally.

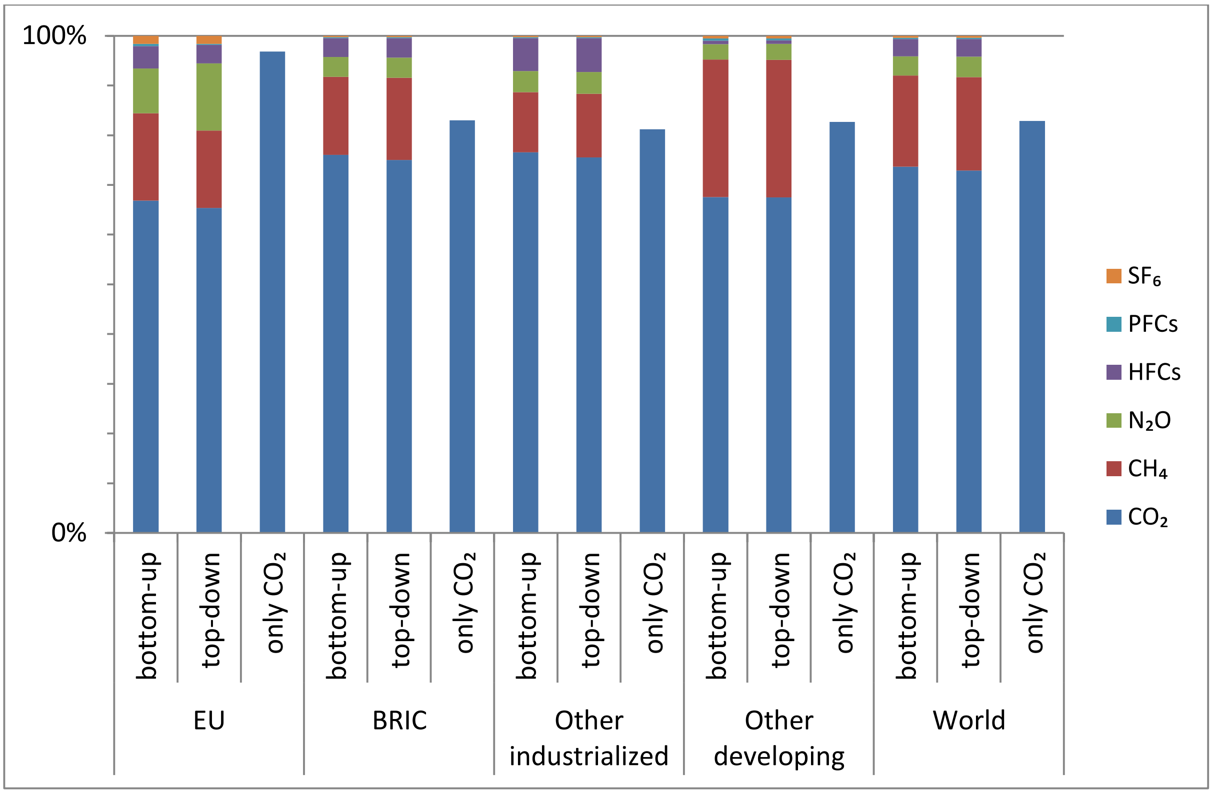

Figure 4: Abatement by region in 2030. Abatement is scaled relative to total abatement in the scenarios including non-CO_2 emissions and abatement.

	absolute abatement cost	average abatement cost
EU	43%	37%
BRIC	15%	10%
Other industrialized	21%	17%
Other developing	72%	72%
World	37%	33%

Table 1: Overestimation of non-CO_2 abatement cost in top-down approach relative to bottom-up approach in 2030.

To explain how using either the bottom-up or the top-down modelling approach translates into differences in GDP impacts, we can look at the model results in more detail. Table 1 lists absolute and average unit expenditures for non-CO_2 abatement purchases in 2030. For all regions, the expenditures are higher in the top-down approach, although the differences for some regions are bigger than for others. The biggest difference in abatement expenditures is for Other Developing Countries. The additional cost can explain why the top-down scenario leads to higher GDP losses. While the quantity of non-CO_2 abatement is very similar in both approaches as mentioned above, the abatement costs are 72% higher.

The average abatement cost reported in Table 1 is cheaper in the bottom-up approach because of the shape of the bottom-up abatement curve. For many region-sector-pollutant combinations, a substantial low cost abatement potential exists. In this area of the marginal abatement cost curve, the estimated curve for the top-down approach often is higher than in the bottom-up approach. For higher carbon prices, this often reverses. To show this non-linearity, we can plot both the bottom-up curve and the fitted curve used for the top-down approach for exemplary region-sector-pollutant combinations (Figure 5). The first two subfigures (a) and (b) show the region-sector-pollutant combinations Rest of World – non-traded-services – CH_4 (mainly emissions from waste) and Northern Africa/Middle East – Crude Oil – CH_4, respectively. These combinations are important in driving the abatement expenditures of other developing countries. For carbon prices in 2030, the fitted green marginal abatement cost curve exceeds to bottom-up curve. Hence, the area under the marginal abatement cost curve, representing the abatement costs, is larger in the top-down approach. For these two combinations, both bottom-up curves are characterized by very cheap abatement potential for 20-40% of emissions. However, after exceeding about 40% emission reduction, further emission reductions become more difficult.

Table 1 can only indirectly explain why the bottom-up approach leads to higher GDP costs than the top-down approach for the BRIC countries and non-EU industrialized countries (cf. Figure 3). Total abatement expenditures are higher in these world regions in the top-up approach; however, these do not translate to higher GDP losses in the top-down approach. Instead, in these regions, the bottom-up approach leads to lower abatement in non-CO_2 emissions, and hence an increase in emissions in CO_2 emissions. This increases the carbon price and economic cost of abatement.

For China, this is driven by abatement in one sector, crop-based agriculture. Here, most CH_4 emissions originate from rice farming. The underlying abatement cost curve shows almost no reduction potential below 60 USD_{2011}, however a large option for emission reduction at this cost (Figure 5(c)). In the bottom-up abatement approach, less than 1% of emissions are abated; in the top-down approach about 23% of emissions are abated. As CH_4 emissions in this sector is relatively large, it shows the implications of having step functions to describe abatement technologies. Without CH_4 abatement in agriculture in the bottom-up modelling, China has to do more abatement in other sectors, which is more costly for the economy and explains the lower GDP.

The remainder of Figure 5 shows some exemplary pollutant-region-sector combinations to give an impression on how good the functional form chosen in eq. (7) performs in approximating bottom-up cost information. While the fit for subfigure 5(d) is very good, subfigure 5(e) shows the limitations of smooth approximation methods when the curve is very non-linear. Subfigure 5(f) finally shows an approximation that works reasonably well but again illustrates difficulties at following non-regular parts of the bottom-up data.

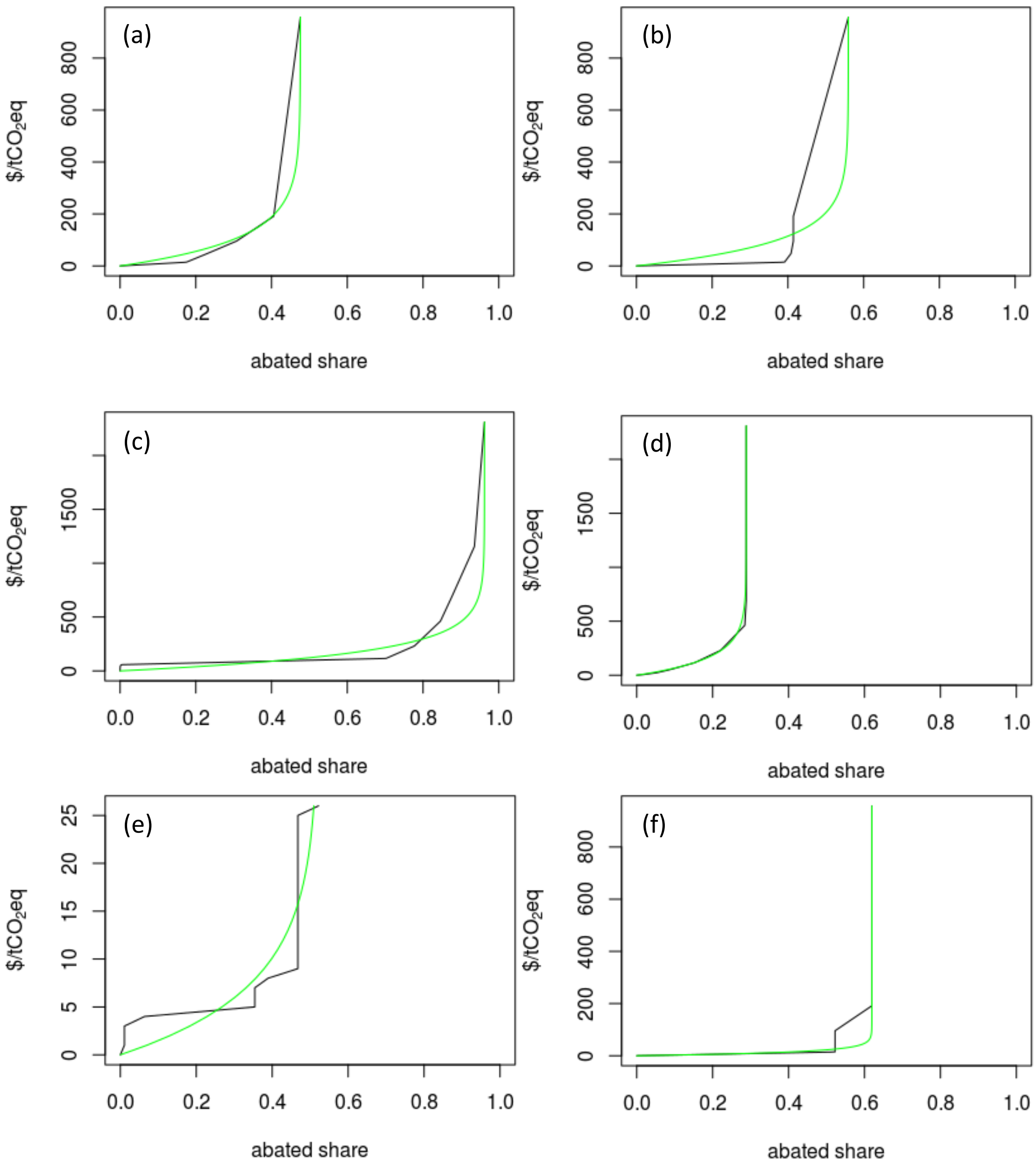

Figure 5: Bottom-up abatement curve (black) and fitted marginal abatement cost curve (green) for individual pollutant-region-sector combinations for 2030. Subfigure (a) shows Rest of World – non-traded-services – CH_4, (b) shows Northern Africa/Middle East – Crude Oil – CH_4, (c) shows China – crop-based agriculture – CH_4, (d) shows Rest of World – livestock – CH_4, (e) shows Czech Republic – coal mining – CH4, and (f) shows USA – non-ferrous metals – PFCs.

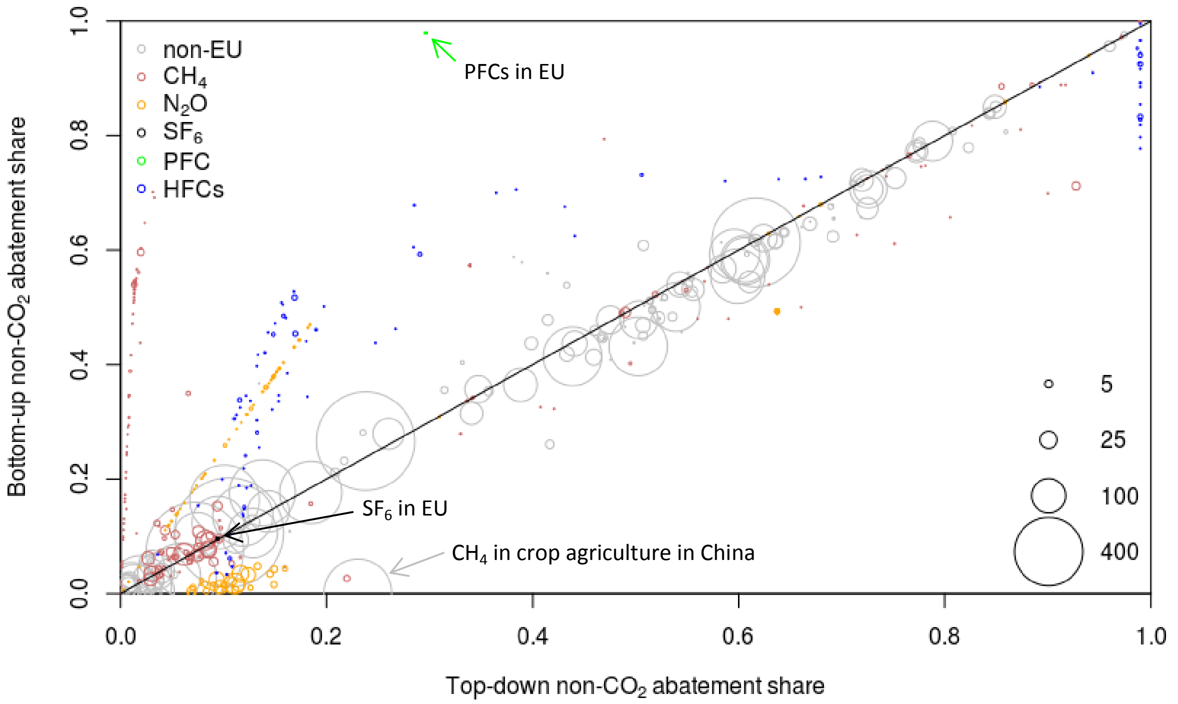

Figure 6: Abatement in the bottom-up relative to top-down approach in 2030. Each circle represents a country-sector-pollutant combination for non-CO_2 emissions in JRC-GEM-E3. Combinations including non-EU regions are coloured in grey; for the 28 EU countries, different colours are used for different greenhouse gases. The area of the circles is scaled to baseline emissions in Mt CO_2-eq.

To better grasp the overall differences and similarities between the bottom-up and top-down modelling approaches, Figure 6 plots the abatement share relative to the baseline for all country-sector-pollutant combinations. Since different data sources were used for EU28 member states and non-EU regions of the model, the figure is coloured to reflect this difference. For the non-EU combinations, there is generally better agreement between both approaches, i.e. the circles are close to the diagonal line which indicates equal abatement for both modelling approaches. This holds especially for the larger circles that represent country-sector-pollutant combinations with high emissions in the baseline. Aggregating sub-sectors and regions can lead to a smoothing of the (marginal) abatement cost curve (e.g. in Figure 5(d) which shows the relatively large "Rest of the World" region). A smoother bottom-up curve will lead to a better fit in the top-down approach and can explain why many of the large combinations are represented very similar in both methods. One of the important country-sector-pollutant combinations that does not follow the pattern of good agreement in both methods was already discussed above (China-agriculture-CH_4).

For the EU, patterns emerge when analysing the fit of the two methods by different greenhouse gases. For CH_4, agreement for both modelling approaches is generally better than for the gases. For SF_6 and PFCs, there is limited regional and sectoral variation in the bottom-up data, so all points coincide. The patterns for N_2O and HFCs are quite distinct and deserve a closer look. For these gases, often only a very few options with distinct steps are reflected. A smooth approximation has difficulty following these steps. For HFCs in particular, it is possible to see the steps in the figure leading to combinations where the bottom-up approach substantially deviates from the top-down approach. This illustrates the potential for overestimating or underestimating costs. While these estimations for individual country-sector-pollution combinations are most pronounced in the EU, they do not have a large macroeconomic effect in our particular example. Here, they mostly cancel at the aggregate level; however, this is not guaranteed to always be the case.

4. Extensions

The basic framework described above can be easily extended along various dimensions. In the following, we line out implementation strategies for promising avenues. First we describe how this approach was used in the JRC-GEM-E3 model to represent carbon capture and storage (CCS), and second, how this approach could potentially be used to model air pollution abatement and for modelling of abatement technologies that are able more influence emission levels of more than one pollutant.

4.1. Extension for carbon capture and storage

While the discussion above was mainly focussed on end-of-pipe abatement technologies of non-CO_2 emissions, the mathematical concept can be easily transferred to capture and storage (CCS) technologies, which in principle also represents an end-of-pipe abatement option (i.e., the abatement technology changes the ratio of inputs to emissions, but does not lead to reduced emissions from alternative input choices).

In terms of implementation, the equations presented in section 2.2 will have to be adjusted minimally, as CCS is modelled on emissions related to *inputs* to rather than *output* of production. Hence, in eq. (2) above, emissions no longer depend on output x_j, but on inputs related to carbon emissions. Likewise, in eq. (5) not *output* prices, but *input* prices will be increased to bear the cost of abatement. The framework would also be able to reflect an adjustment of the capture rate in response to the carbon price faced by producers, by specifying different CCS technologies with different capture rates for which deployment depends on the carbon price.

Most bottom-up studies reporting cost of adding CCS technology will do so by reporting a change in the output cost, e.g. in the changes of the levelized cost of electricity. However, in this framework the cost of CCS equipment will be embedded in the price of the polluting input rather than the output, hence some data adjustments are commonly required. In principle, the cost has to be transformed into a cost of abatement, i.e. the difference in the unit cost of the output is divided over emissions reduced per unit of output. The deployment of CCS comes along with lower conversion efficiency, i.e. more fuel input is needed to produce the same quantity of electricity. This can easily be reflected by an appropriate choice of λ_{ij}, so that the use of abatement technology i requires additional use of fuel as an input. This will then endogenously adjust the abatement cost of CCS when fuel prices change e.g. in response to a climate policy scenario.

The use of CCS in industry and electricity generation can hence be added in a similar fashion as other abatement technologies. Even an addition of a CCS option to electricity generated from biomass (bioenergy with carbon capture and storage, BECCS) is feasible and allow for net negative emissions with careful choices of default options. In particular, if technology producing electricity from biomass is present in the model, the only addition for BECCS is to replace the term $(1 - A_j)$ by $-A_j$ in eqs. (2) and (5).

4.2. Extension to air pollution

Like the abatement of non-CO_2 emissions, reductions of local air pollutant emissions, such as SO_2 and particulate matter, can be achieved by end-of-pipe abatement technologies. Recent studies (Vandyck et al., 2018; Markandya et al., 2018) have estimated co-benefits of climate policy on the reduction of air pollutants, focusing on fuel shift and activity reductions. An assessment of an integrated climate-air quality policy, however, requires explicit modelling of air pollution abatement options and their interactions with climate policy. Previous work (Bollen, 2015; Rafaj et al., 2013; Rive, 2010) has shown, for instance, that climate policy can reduce the cost to reach air pollution targets in general, and particularly in the power sector. Future work could instead take air pollution control policy as a starting point of the analysis, given that related health effects may push up air quality in the priority list of governments in both low- and high-income regions.

The mathematical framework described in section 2.2 is already set-up for the implementation of air pollution modelling. As some air pollutants might be tied to the use of inputs rather than outputs, the modification described for CCS modelling (section 4.1) might prove helpful in this case. The limiting case for implementation therefore rather is not the modelling capabilities but the required data for marginal abatement cost curves for pollutants. In fact, Rive (2010) uses a comparable bottom-up accounting approach in modelling air pollution in Western Europe.

4.3. Extension to abatement technologies affecting multiple pollutants

The description of the modelling framework above was limited to a one-to-one mapping between abatement technologies and pollutants. It could be possible that abatement technologies have the potential to tackle more than one pollutant. Only some small modifications to the equations would be required to implement such a feature. Due to a lack of data, we have not implemented these in the model, and hence only sketch out the required modifications to the framework to demonstrate its versatility.

With multiple pollutants *k* to be abated by a single abatement technology a_i, the deployment of an abatement technology could affect several aggregate abatement levels A_{jk} through different abatement abilities ϕ_{ik} in eq. (1). Against this backdrop, the (marginal) incentives for deployment of the abatement technology *i* are altered. In particular, the marginal value of the technology increases and on the right hand side of eq. (4), taxes for all relevant pollutants have to be added.[8] This is a convenient feature that will endogenously (re-)sort technologies along marginal benefits to producers. For example, a technology that is slightly more expensive but can also abate another pollutant can now become preferable to a producer. Finally, the cost equation (5) will have to be modified to avoid levying the cost of the technology to producers more than once.

Our current implementation in JRC-GEM-E3 is limited to the modelling of end-of-pipe abatement options for non-CO_2 gases and CCS for CO_2. We see little potential for specific abatement

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[8] This will also require introducing a weighting scheme as technologies will be likely abate different pollutions at different rates. In eq. (4), this cancels as the abatement cost and emission tax are expressed in the same unit of pollution.

technologies to abate several non-CO_2 gases jointly and data is scarce. However, we are more optimistic for this implementation in models where production is also related to emission of (local) air pollutants, as it is more likely that abatement technologies influence either several local pollutants or GHGs and local pollutants jointly.

5. Conclusions

We present a framework for modelling end-of-pipe abatement technologies, preserving information from bottom-up technology studies. The framework is very flexible and can easily be extended to other applications, such as modelling CCS and air pollution abatement. Despite having implemented about 3000 abatement technologies in a large scale model, a solution is generally found reliably.

We illustrate this with an emission reduction scenario for 2030 to compare this bottom-up approach with a top-down modelling approach that uses the bottom-up information in an aggregated fashion. In addition, we evaluate the importance of including non-CO_2 emissions into economic analysis of mitigations costs in the first place. The importance of modelling non-CO_2 abatement follows from different relative reduction rates for CO_2 and non-CO_2 under a common carbon price. Not including non-CO_2 abatement opportunities hence can significantly overestimate the cost of abatement for 2030. However, this finding might reverse, when projecting further forward into the future as in low emission pathways (e.g. leading to 1.5°C) non-CO_2 emissions take up a greater share in remaining emissions (Rogelj et al., 2018). Therefore, it is crucial to properly capture non-CO_2 abatement options both for abatement potential and abatement costs.

When comparing the modelling framework using bottom-up information to representing end-of-pipe pollution emissions with a fitted curve of the bottom-up data, our framework has important advantages. First, it covers directly the technological detail of the bottom-up data and therefore reproduces abatement levels and costs from bottom-up estimations. Better capturing non-linearities from bottom-up data avoids overestimating or underestimating abatement costs. In our application, we found that for specific regions-sector-pollutant combinations marginal abatement costs are non-linear and cannot be well matched with the functional form chosen for the top-down approach. Given that there are many combinations, these effects could add up and influence macroeconomic cost of emission reduction. However, for our specific application, differences in broad macroeconomic indicators differed less between top-down and bottom-up implementations. These small differences could however be well explained by analysing differences in abatement levels, highlighting the channels how the two approaches can lead to different outcomes.

Second, specific abatement technologies can be identified and inform how a sector responds to different carbon prices. This can be helpful for discussion with industry stakeholders or policy makers. Including technologies from a bottom-up model into a top-down model also allows for better representation interactions between abatement services and the rest of the economy. For example, costs of abatement technologies can depend on the endogenous costs of inputs required for their deployment. This could also endogenously change the order at which abatement technologies are deployed. However, data limitations currently prevent us from fully making use of this ability. Additional data or expert judgement would be required to input coefficients for various technologies represented in bottom-up data. In general, the data demand of the framework is quite high as costs for specific technologies are needed. While the aim was to use the best available data source for each region or sector, the use of different datasets can introduce inconsistencies as the data generation process for different data products uses different methods. Furthermore, not all of the data used is publically available and some would benefit from an update.

Third, the framework can be easily extended. While we focussed on non-CO_2 emission abatement in the application presented in the paper, the model also makes use of the methodological framework for the representation of CCS. Future applications could include other short-lived climate pollutants such as black carbon, and could study joint climate-air quality strategies by explicitly incorporating end-of-pipe abatement of local air pollutants.

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Appendix

Energy sectors

- Coal
- Crude Oil
- Refined Oil
- Natural Gas
- Electricity Supply
- Coal fired electricity
- Oil fired electricity
- Gas fired electricity
- Nuclear electricity
- Biomass electricity
- Hydro electricity
- Wind electricity
- Solar electricity

Other Sectors

- Ferrous Metals
- Non-ferrous metals
- Chemical Products
- Paper Products
- Non-metallic Minerals
- Electric Goods
- Transport Equipment
- Other Equipment Goods
- Consumer goods
- Construction
- Market Services
- Non-market Services
- Agriculture (Crops)
- Agriculture (Animals)
- Forestry
- Air Transport
- Land Transport
- Water Transport

Table A1: Sectors in the JRC-GEM-E3 model.

Aggregate regions	Individual regions in JRC-GEM-E3
EU	Individual regions for each EU member state
BRIC	Brazil; Russia; India; China
Other industrialized	USA; Canada; Japan; Australia and New Zealand; Rest of Europe and Turkey; Ukraine, Belarus, Moldova
Other developing	North Africa and Middle East; Rest of World

Table A2: Regions in the JRC-GEM-E3 model and aggregate regions used for reporting in Figure 3 and 4 and Table 1.