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Dear Editor,

We thank the Editor for further considering our manuscript and providing additional feedback, in particular, to the issue of the time-dependency of marginal abatement cost (MAC) curves. Following the suggestions from the Editor, we revisited the analysis using time-dependent MAC curves.

The revised manuscript provides a more extended analysis using three IAMs (AIM, POLES, and WITCH), instead of the single IAM (AIM) used previously. The new analysis confirmed our earlier finding: the use of time-dependent MAC curves does not improve the reproducibility of emission scenarios, even though the time-dependent MAC curves provide a better fit to the price-quantity data generated from original IAMs than the time-independent MAC curves. Please see the revised manuscript for detailed discussions.

Overall, our revised analysis has led to a more comprehensive understanding of how our IAM emulator works and how various elements, such as MAC curves, carbon price pathways, and various model constraints, interact in generating least-cost emission pathways. In the attached document, we present the revised analysis using the time-dependent MAC curves, followed by our point-by-point responses to the Editor's comments. We then describe the changes made to the manuscript.

We believe that our revised manuscript has carefully addressed the Editor's remaining concerns and meets the high standards of *Geoscientific Model Development*. We look forward to the Editor's decision for publication.

Yours sincerely,

Katsumasa Tanaka and Weiwei Xiong, on behalf of the author team

Deriving time-dependent MAC curves

While the time-independent assumption of MAC curves is key to simplifying our IAM emulation approach, it raises questions about what this simplification entails. Here, we test time-dependent MAC curves to better understand the limitations of our time-independent approach. Of ten IAMs analyzed in our paper, we selected three IAMs (AIM, POLES, and WITCH) for such a test because, based on our visual inspection, these models provide data suitable for time-dependent MAC curves (Figure R1).

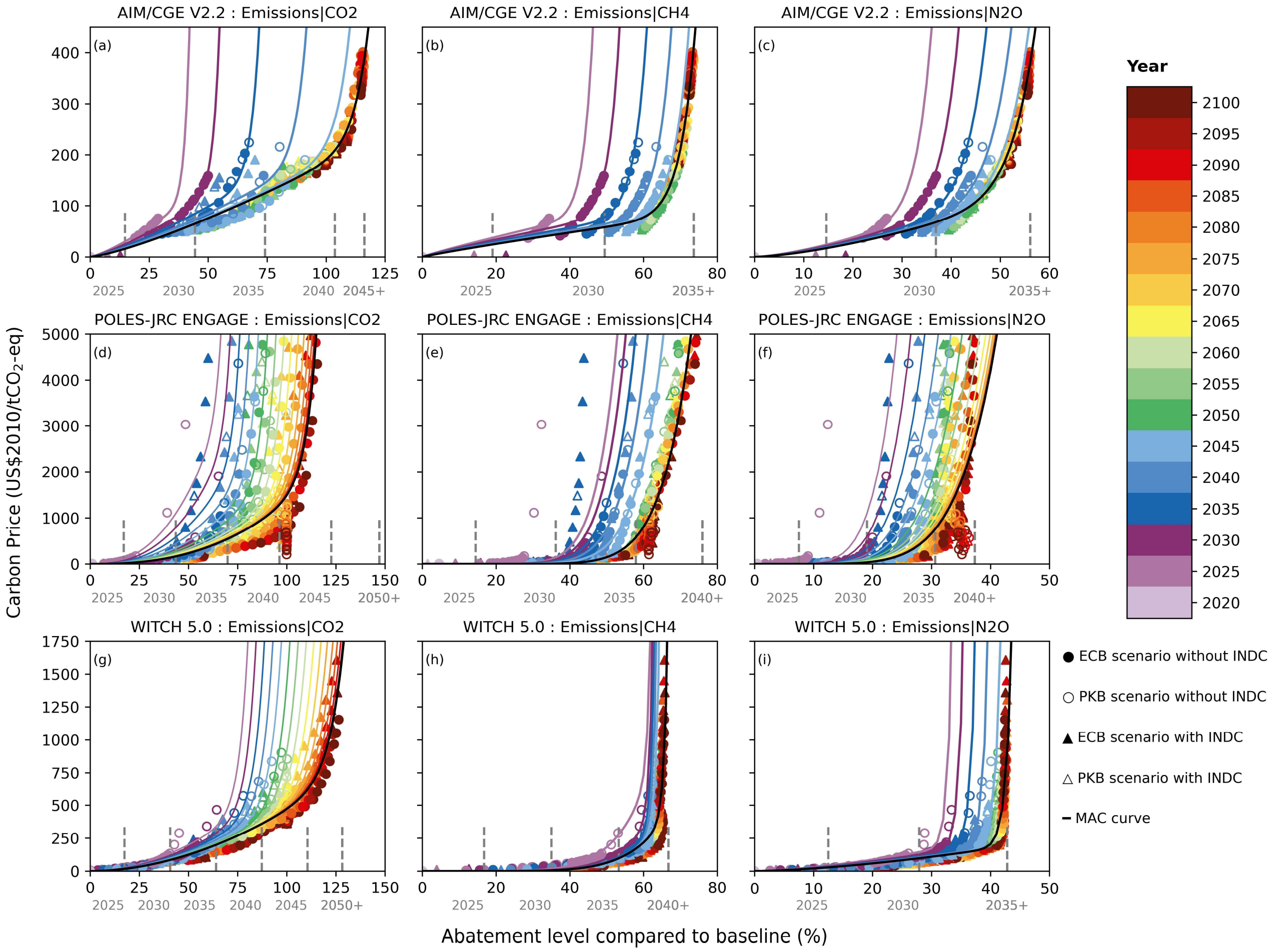

Figure R1. CO_2, CH_4, and N_2O abatement levels and carbon prices from three IAMs (AIM, POLES, and WITCH) and their time-independent (in black) and time-dependent MAC curves (in non-gray colors). For CO_2 and N_2O from POLES and CO_2 from WITCH, the MAC curves are assumed to be time-dependent till 2100. For the remaining cases, the MAC curves are assumed to be time-dependent till 2050 and time-independent from 2050 onwards (same with the time-independent MAC curves presented earlier). The vertical gray bars indicate the maximum abatement levels that can be potentially achieved at each point in time every five years (gray text), which is determined by the upper limits of the first and second derivatives of abatement changes, as well as the upper limit of the abatement level (Table 2).

We introduced the time-dependency to the MAC curves in a way that smoothly extends the time-independent MAC curves originally used. For AIM, the relationships between the relative abatement levels of CO_2, CH_4, and N_2O and the carbon price are adequately captured by the time-independent MAC curves from 2050 onwards. It is thus sufficient to introduce the time-dependency to the MAC curve only before 2050. Namely, we modified the time-independent functional form by introducing time-dependent terms so that the MAC curves can be shifted to the left (or shifted up) as we go back in time from 2050. Regarding the two other IAMs, we also applied a similar approach to CH_4 from POLES and CH_4 and N_2O from WITCH (i.e., time-dependent MAC curve approach till 2050). For the remaining cases (i.e., CO_2 and N_2O data from POLES and CO_2 from WITCH), on the other hand, we stretched the time-dependent MAC curve approach all the way to 2100, as it is evident that the data show a temporary shifting trend until 2100.

Hence, we extended the time-dependent MAC curve approach either to 2050 or to 2100, based on the visual inspection of the data for the relationship between the abatement level and the carbon price from each model and gas. For time-dependent MAC curves that shift until 2050, we used the following functional form for each applicable model and gas.

$$f(x_t) = \begin{cases} a \times (x_t)^b + c \times (x_t)^d, 2050 \leq t \leq 2100 \\ a \times \left(x_t \times (1 + e1 \times (t - t0)^{e2})\right)^b + c \times (x_t \times (1 + f1 \times (t - t0)^{f2}))^d, 2025 \leq t < 2050, t0 = 2050 \end{cases} \quad (1)$$

From 2050 onwards, the equation above is equivalent to the time-independent MAC curve originally used for the respective model and gas. For time-dependent MAC curves till 2100, we used the following functional form.

$$f(x_t) = a \times \left(x_t \times (1 + e1 \times (t - t0)^{e2})\right)^b + c \times (x_t \times (1 + f1 \times (t - t0)^{f2}))^d, 2025 \leq t \leq 2100, t0 = 2100 \quad (2)$$

x_t in equations (1) and (2) is the variable representing the emission abatement level in percentage relative to the assumed baseline level at each point in time t. a, b, c, d are the parameters that take the model- and gas-specific values estimated for the respective time-independent MAC curve (Table 2). We optimized the parameters $e1, e2, f1, f2$ by minimizing the squared deviations from the original price-quantity data between 2025 and 2045 (for equations (1)) or between 2025 and 2095 (for equations (2)) for each model and gas (Table R1). Note that for AIM, $e2$ and $f2$ are assumed to be 2 for the sake of simplicity (optimized for POLES and WITCH), while $e1$ and $f1$ are optimized for all three IAMs. In the previous version of our manuscript, there was just one degree of freedom, where $e1$ was assumed to be equal to $e2$.

Note that we did not fundamentally change the functional form nor adopted a completely new functional form so as to avoid making any additional changes in the shape of MAC curves. However, as discussed above, we introduced more elaborated time-dependent terms than those used previously. With this change, our current time-dependent MAC curves can better capture the data for the relationship between the abatement level and the carbon price than our previous time-dependent MAC curves (compare Figures R1 and R1', in particular, for CO_2).

Model	Gas	Parameter			
		*e*1	*e*2	*f*1	*f*2
AIM	CO_2	9.991×10^{-4}	2.000	2.974×10^{-3}	2.000
	CH_4	9.684×10^{-4}	2.000	9.610×10^{-4}	2.000
	N_2O	4.099×10^{-4}	2.000	9.593×10^{-4}	2.000
POLES	CO_2	8.580×10^{-8}	3.794	4.554×10^{-5}	2.229
	CH_4	6.353×10^{-2}	6.276×10^{-1}	0.000	0.000
	N_2O	1.609×10^{-7}	3.541	0.000	0.000
WITCH	CO_2	1.091×10^{-10}	5.038	1.369×10^{-4}	1.953
	CH_4	6.854×10^{-8}	4.573	1.851×10^{-2}	4.161×10^{-1}
	N_2O	1.291×10^{-4}	2.390	6.551×10^{-3}	1.192

Table R1. Values of additional parameters used in the time-dependent MAC curves for three IAMs. For the definitions of parameters, see equations (1) and (2) and the related text.

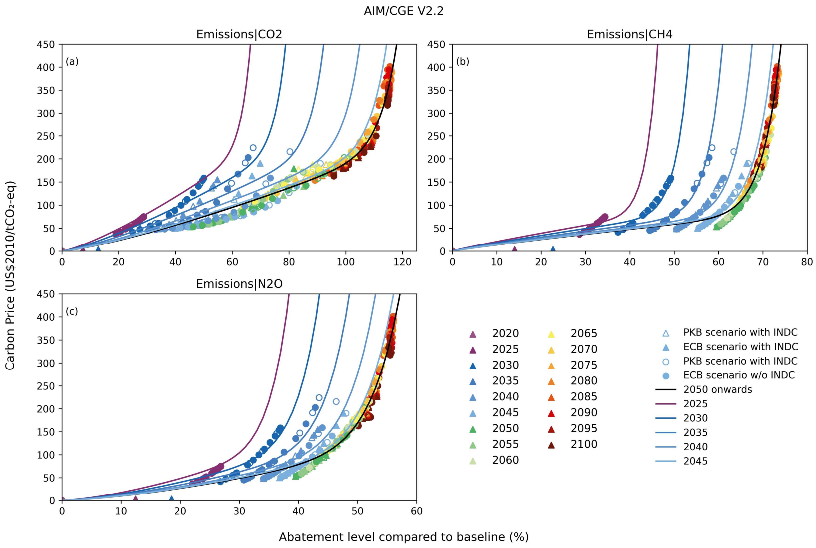

Figure R1'. Previous version of the time-dependent MAC curves for AIM. This figure was copied from our previously submitted manuscript. This figure should be compared to Figure R1.

The time-dependent MAC curves generally well captured the temporary shifting data from the three IAMs, compared to the time-independent MAC curves (Figure R1). The time-dependent MAC curves maintain shapes comparable to the original time-independent MAC curves and, as the time goes, converge to respective time-independent MAC curves either in 2050 or 2100. Those time-independent and time-dependent MAC curves serve as a basis to explore how the time-dependency in MAC curves contributes to reproducing scenarios.

Reproducing the IAM scenarios with the time-dependent emulator: methods

Now we implement the time-dependent MAC curves to the IAM emulator (simple climate-economy modeling framework ACC2). For each carbon budget pathway from the original IAMs, we imposed the same remaining carbon budget to the IAM emulator as a constraint and calculated the least-cost pathway for CO_2. This approach is equivalent to Test 1 for CO_2 discussed earlier. We focus on this test because this is the most direct and simplest way to evaluate the performance of MAC curves. In this test, our emulator derives CO_2 emission pathways in the same way as the IAMs do (i.e., with the remaining carbon budget as the constraint for intertemporal optimization models and with the carbon price pathways (exogenously computed from the remaining carbon budget) as the constraint for recursive dynamic models). Other tests (Tests 2, 3, and 4) use the temperature target as the constraint, which is not used in the IAMs, although these tests are also useful for other purposes (e.g., to show how the MAC curve approach works in a climate-economy setting). Also note that the carbon cycle and climate modules in ACC2 are not used for Test 1 – Test 1 is only about emissions without considering their implications to concentrations and temperatures.

In this test, we also used the upper limits of the abatement level and of the first and second derivatives of abatement changes. We adopted the same upper limits used with the time-independent MAC curves (Table 2). These limits interact with the MAC curves, as they define the segment of MAC curves that can be utilized at each time step (vertical gray bars in Figure R1) (i.e., in the near term, only a low range of MAC curves can be exploited by the IAM emulator due to the first and second derivative limits). We therefore performed a sensitivity analysis with respect to those derivative limits. In sum, we have a total of four cases for each IAM: time-independent or time-dependent MAC curves and with or without the abatement limits.

We focus on the end-of-century budget scenarios without INDCs, among three other sets of scenarios (the peak budget scenarios with INDCs, peak budget scenarios without INDCs, and end-of-century budget scenarios with INDCs). This set of scenarios provides cleanest data for testing how well the MAC curves reproduce the original scenarios because this set of scenarios is free of constraints for net-zero emissions and INDC target levels, which cannot be captured by MAC curves.

MAC curves		Time-independent	Time-dependent	Time-independent	Time-dependent
Upper limits of 1st and 2nd derivatives		Included		Excluded	
AIM	r_P	0.9859	0.9757	0.9856	0.9758
	r_C	0.9796	0.9648	0.9804	0.9651
	MAE	3.3244	4.4760	3.1482	4.4452
	RMSE	4.3878	5.8783	4.2717	5.8526
POLES	r_P	0.9891	0.9862	0.9764	0.9835
	r_C	0.9891	0.9831	0.9738	0.9815
	MAE	2.0402	2.6271	2.8913	2.7222
	RMSE	2.7512	3.5772	4.1323	3.7007
WITCH	r_P	0.9748	0.9725	0.9743	0.9724
	r_C	0.9625	0.9584	0.9654	0.9602
	MAE	3.7224	3.8778	3.4942	3.7722
	RMSE	4.6483	4.9326	4.4011	4.7899

Table R2. Statistical validations of CO_2 emission pathways reproduced from the IAM emulator against the original emission pathways from the three ENGAGE IAMs (AIM, POLES, and WITCH). This table compares the scenario reproducibility between the time-independent and time-dependent approaches. The statistical parameters indicating higher reproducibility are shown in red and blue for cases with and without the upper limits of 1st and 2nd derivatives, respectively.

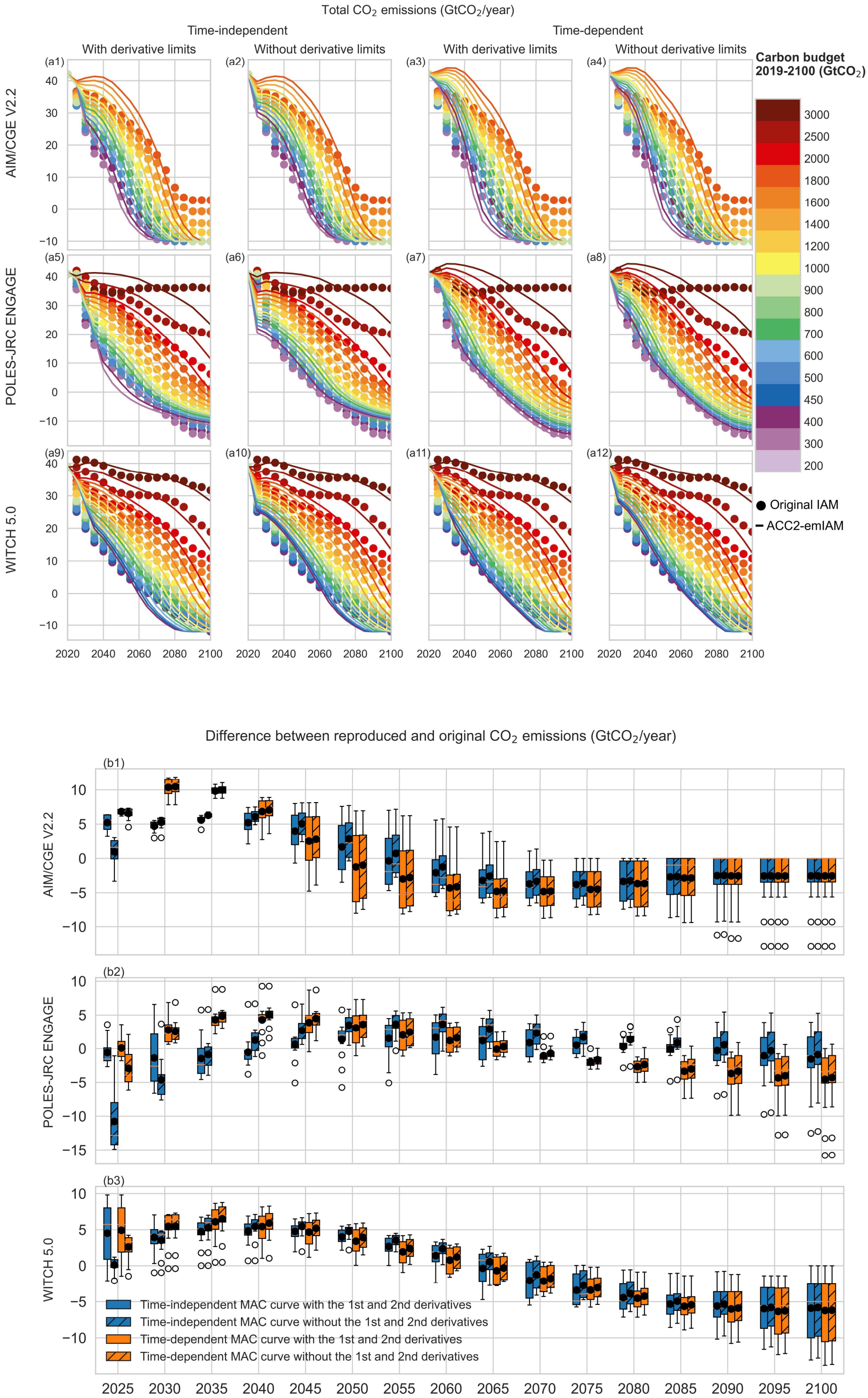

Figure R2. Comparison between the reproduced CO_2 emissions from the IAM emulator and the original emissions from the IAMs. The figure shows the end-of-century budget scenarios without INDCs. In the lower set of panels (b1 to b3), the differences are positive when reproduced emissions are higher than original emissions. The box indicates the 25-75% range, the whisker the 2σ range, and the filled and open circles the mean and the outlier, respectively.

Reproducing the IAM scenarios with the time-dependent emulator: results

Four statistical indicators show that the use of the time-dependent MAC curves did not generally result in a higher reproducibility of emission scenarios (Table R2). For all three IAMs, the reproducibility was, in fact, slightly decreased with the introduction of the time-dependency to the MAC curves. To understand why the time-dependency did not improve the scenario reproducibility despite the better fit to the original price-quantity data from IAMs, in particular in the near term, we look into the results from each model below.

<u>AIM</u>

The time-dependent approach tends to give higher emissions in the near term and lower emissions later in the century than the time-independent approach (Figure R2). This finding can be expected from the relative positions of the time-independent and time-dependent MAC curves. Because the time-dependent MAC curves are higher than the time-independent MAC curves before 2050, mitigation becomes more costly in the near term with the time-dependent MAC curves, resulting in higher emissions in the near term. The results are opposite later in the century. Because the same remaining carbon budget must be conserved, emissions later in the century become lower with the time-dependent MAC curves to compensate for the higher emissions earlier.

Hence, the time-independent approach overestimated the emissions in the near term and underestimated the emissions later. Those deviations were not reduced by the adoption of the time-dependent approach; it was rather increased, despite the better fit of the time-dependent MAC curves to the data than the time-independent MAC curves.

Our implicit hypothesis was that the time-dependent approach yields a higher scenario reproducibility than the time-independent approach; however, this hypothesis proved wrong in our experiments. To understand the unexpected outcome, we found that it is important to consider the carbon price. Here we refer to two different yet associated quantities from the emulator that can be characterized as the carbon price: i) the value of the MAC curve and ii) the shadow price. The shadow price is always higher than the value of the MAC curve, as the shadow price is not influenced by various model constraints. We compare both quantities with the carbon price from AIM (available in the ENGAGE Scenario Explorer) (Figure R3). We presume that the carbon price from recursive dynamic models, such as AIM and POLES, is more comparable to the MAC estimate from the emulator, whereas the carbon price from intertemporal optimization models, such as WITCH, is more comparable to the shadow price from the emulator.

We now ask why the time-independent approach overestimated the near-term CO_2 emissions and underestimated the long-term CO_2 emissions for AIM. For the period till mid-century, the emission overestimations are primarily caused by the difference in carbon prices between the emulator and the IAM.

The MAC estimates are generally lower than the corresponding carbon prices of AIM, with differences depending on the carbon budget of the scenario. The generally lower MAC estimates largely explain the emission overestimations till mid-century. In later in the century, on the other hand, the MAC estimates become higher than the AIM carbon prices, resulting in the emission underestimations. The MAC estimates from different carbon budgets converge after the emissions reach the lower limit defined by the maximum abatement level (116.2% relative to the baseline (Table 2)).

The emission overestimations in 2025 stem from the upper limits of the first and second derivatives of abatement changes, which do not allow a rapid emission reduction required to follow the original AIM scenario. If these assumed upper limits are dropped, the 2025 emissions become substantially lower and better reproduce the original emission levels (the time-independent approach of Figure R2b1). Furthermore, the effects of those upper limits can be clearly seen in the MAC estimates from the time-independent approach (solid lines in Figure R3a). On the other hand, such effects are less evident in the MAC estimates from the time-dependent approach (dashed lines in Figure R3a) because the very short-term emissions are more strongly constrained by the steep MAC curves.

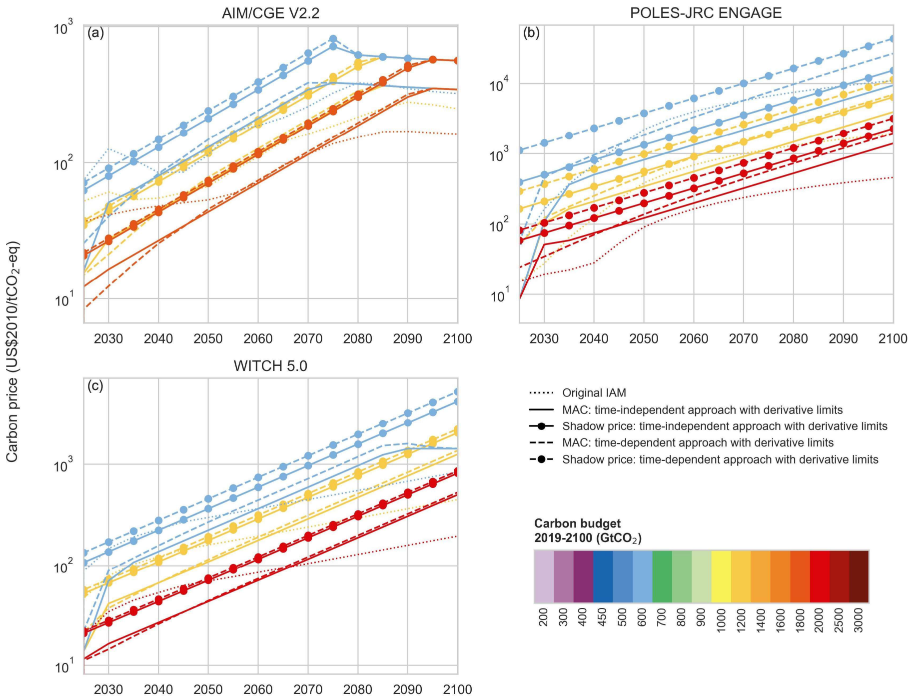

Figure R3. Carbon price pathways from the time-independent and time-dependent emulator approaches and the three IAMs. MAC indicates the value of the MAC curve at each period under each scenario. Shadow price indicates the change in the total policy cost (the area of the MAC curves) for an infinitesimal change in emissions from the optimal level. Selected three carbon budget scenarios are shown for each IAM. The upper limits of the first and second derivatives of abatement changes and of the absolute abatement level are considered. Vertical axes are on a logarithmic scale.

POLES

The time-independent approach slightly underestimated the emissions in the near term. Similarly to the results from AIM, the time-dependent approach overcorrected this negative discrepancy and resulted in the emission overestimations in the near term. This is a consequence of two competing factors: the higher MAC estimates (except for high scenarios) and steeper MAC curves from the time-dependent approach. Later in the century, the time-dependent approach overcorrected the discrepancy in the opposite way and resulted in the emission underestimations.

WITCH

The differences in the results between the time-independent and time-dependent approaches are the smallest for WITCH. This may be related to the fact that WITCH is an intertemporal optimization model, as is our IAM emulator. The results also indicate the general deviation trend seen from other models: emission overestimations in the near term and emission underestimations later in the century. This general trend can be explained by the shadow price pathways. The shadow price is somewhat lower than the carbon price in WITCH early in the century but becomes higher from mid-century onwards. Furthermore, the comparison of the carbon prices indicates that the discount rate in WITCH may be lower than the assumed discount rate of 5% used in our emulator. As discussed earlier, in the absence of information on the discount rate used by all but a few IAMs, our emulator assumes 5% for all IAMs. The discount rate in IAM may follow the Ramsey rule, meaning that the discount rate is time-dependent, depending on the future economic growth.

Discussions

The time-dependent MAC curves better captured the IAM generated price-quantity data than the time-independent MAC curves. However, when the time-dependent MAC curves were applied to calculate least-cost emission scenarios under the respective carbon budgets, the original IAM scenarios were generally not better reproduced than the case with the time-independent MAC curves.

While the reasons for the discrepancy depend on the IAM, carbon budget, period, and abatement limits, an important factor to consider is the carbon price pathway. Ultimately, emission scenarios will be perfectly reproduced, if the following two conditions are met: first, the original IAM data (the relationship between the abatement level and the carbon price) are perfectly captured by the MAC curve; second, the carbon price pathways are also perfectly reproduced by the emulator. While the first condition can be adequately satisfied with the use of time-dependent MAC curves, the second condition cannot necessarily be met due to various constraints in the IAMs that cannot be captured by the emulator. For example, the AIM carbon price pathways have first peaks in the near term, followed by second peaks later in the century. Such complex carbon price pathways, which are exogenously given in recursive dynamic models, cannot be captured by our simple intertemporal optimization method, which internally optimizes the carbon price over time. Even for the intertemporal optimization model WITCH, the carbon price pathways are not the same as our shadow price pathways. This highlights the importance of investigating carbon price pathways to further improve the IAM emulator.

The potential benefit of using the time-dependent approach for reproducing IAM scenarios was not apparent here due to other confounding factors, most notably carbon price pathways. Nevertheless, testing the time-dependent approach was useful in clarifying the dynamics of capturing the complex behavior of

IAMs through the simplified emulation approach and in identifying issues for future improvements of the IAM emulator.

Our point-by-point responses to the Editor's comments

I appreciate the author's effort in further revising the manuscript. Most of the remaining comments by the reviewers were addressed adequately.
However, I am not convinced by the discussion around time dependence, and have some further questions:

[Response]
We thank for the insightful feedback from the Editor. Our point-by-point responses to the Editor's comments are in blue text below.

• Fig R1: It is somewhat surprising that a fit with four (!) free parameters delivers such a poor fit, in particular for CO2, on seemingly nicely aligned data points. I would expect e.g. a simple polynomial fit like a*x^3 + b* x^2 + c*x + d to perform substantially better. (a,b,c can be restricted to positive values to ensure monotony). Have you tried such alternative fits?

[Response]
We now use a slightly more complex functional form, as described above in section "Deriving time-dependent MAC curves." Our revised time-dependent MAC curves have four free parameters (two free parameters for AIM), as opposed to just one free parameter in the previous version. The revised time-dependent MAC curves can better capture the original data from AIM, especially for CO_2 (compare Figures R1 and R1'). The revised time-dependent MAC curves also provide a good fit to the data from the other two IAMs (Figure R1).

The functional form of the time-dependent MAC curves is kept similar to that of the time-independent MAC curves. The parameters commonly used in both types of MAC curves take the same values as computed before. If we use a completely different functional form, it would introduce an additional factor in our comparison between the time-independent and time-dependent results, which can make our comparison less tractable. This point is also mentioned in section "Deriving time-dependent MAC curves."

• This poor fitting will affect of course the performance of the time-dependant emulators. I would expect that better fits affect the comparison of time-dependent vs. time-independent emulation substantially.

[Response]
This is a very important point, and we have given a lot of thought to it. Our initial hypothesis was also that the time-dependent MAC curves will substantially improve the emulation results; however, our results indicated otherwise. For this revision, we have refined the time-dependent MAC curves and tested with three IAMs (instead of just one IAM previously); however, the hypothesis still turned out to be negative. By thoroughly examining the results, including carbon price pathways, we now better understand why the time-dependent approach did not improve the emulation results. This is because the deviations from the

original IAM scenarios are primarily caused by the difference in carbon price pathways between the emulator and the IAMs. In other words, the potential benefit of using the time-dependent approach was not apparent due to the difference in carbon price pathways, most notably. See above for more detailed discussions.

• You only demonstrate the superiority of time-independent MACs for AIM but not for other models. Again, I find that unconvincing. You also state "REMIND is used in the rest of the manuscript as an illustrative case, but we found that REMIND is not suitable for this exploration because the outliers mainly originate from peak-budget scenarios, which may have caused by constraints associated with the net-zero target." There are no additional constraints in these scenarios other than the limitation of peak budget. If the problem realates to the INDC2030 fixing (i.e., delayed uniform climate policies) that would be understandable, but could be resolved by simply excluding these INDC2030 cases.

[Response]
As described above, we expanded the time-dependent analysis to three IAMs in the revised manuscript. To validate the scenario reproducibility, we focused on the end-of-century budget scenarios without INDC. In section "Reproducing the IAM scenarios with the time-dependent emulator: methods", we provide the rationales as below:

> "We focus on the end-of-century budget scenarios without INDCs, among three other sets of scenarios (the peak budget scenarios with INDCs, peak budget scenarios without INDCs, and end-of-century budget scenarios with INDCs). This set of scenarios is most suitable for testing how well the MAC curves reproduce the original scenarios because this set of scenarios is free of constraints for net-zero emissions and INDC target levels, which cannot be captured by MAC curves."

• In respnse to the reviewer's comments on time-dependence, the authors added a paragraph pointing to learning as a key explanation. In fact, learning is not even represented in many IAMs. However, capital stock inertia is an even more important factor resulting in pathdependencies, e.g. via fossil carbon-lock in. Please add this aspect to the discussion

[Response]
We thank the Editor for pointing out this. We added "capital stock" to the discussion and further generalized the processes and factors that can cause inertia in IAMs. We revised the text at two places as follows (underlined text is the revised text):

> "These barriers to rapid emission reductions and the associated costs could also be introduced by more complex functional forms internally in the MAC curves (Ha-Duong et al., 1997; Schwoon and Tol, 2006; De Cara and Jayet, 2011; Hof et al., 2021), but we applied such limits externally on the MAC curves. <u>Processes and factors that can cause inertia in IAMs, including capital stock, growth rate constraints on technology expansion, availability of new technologies, learning by doing, and learning with </u>time (Gambhir et al., 2019; Krey et al., 2019; Tong et al., 2019; Shiraki and Sugiyama, 2020), are not explicitly considered in our MAC curve approach, but are partially captured in our approach, which describes percentage reduction rates relative to rising baseline scenarios."

> “Since most of the baseline scenarios are rising as noted above, the same amount of emission abatement in absolute terms can become smaller with time in percentage terms, which inadvertently but effectively captures the influences from time-dependent processes in IAMs.

Given the importance of near-term dynamics for any policy facing IAM research, I need to insist on clarifying and addressing these questions.

[Response]
We have addressed all of the Editor’s points by using the refined formulation of the time-dependent MAC curves and the data from three IAMs. While the time-dependent MAC curves were shown to be more suited for capturing the relationship between the abatement level and the carbon price from the three IAMs than the time-independent MAC curves, we did not see an improvement in reproducing scenarios with the time-dependent MAC curves. As stated above, the potential benefit of using the time-dependent approach was not apparent due to other confounding factors, most notably carbon price pathways. Nevertheless, testing the time-dependent approach was useful in clarifying the dynamics of capturing the complex behavior of IAMs through the simplified emulation approach and in identifying issues for future improvements of the IAM emulator.

Summary of the changes made in the manuscript

The time-dependent MAC section (Section 4.5 of the previous version of our manuscript) has been replaced with a new Section 5 to present the new analysis above. Relevant figures and tables (Figures R1 to R3 and Tables R1 and R2) have been also added to the main text, instead of the Supplement, as the importance of this section has been elevated through the new analysis. We only slightly modified the text to make it suitable for the main text of the paper. For example, the text referring to changes from the previous version of our manuscript was not included in the main text. As shown in the manuscript with track changes, there are very minor changes in the figures and tables due to the update of color schemes and some corrections for the data presented, but these do not influence the results and discussion of this paper.

We further note that, through the additional analysis presented above, we realized the important role of carbon price pathways, which is also relevant to the rest of the analysis in our manuscript. However, we have decided to keep the remaining manuscript in the present form, so as not to further expand the already extensive manuscript. We will instead pursue this elsewhere, as part the ongoing study that aims to develop a new emulator of REMIND-MAgPIE and extended scenarios for the two Horizon Europe projects, as discussed in our previous review round.

New references

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