Response to Anonymous Referee #2

*Throughout the document, the original comments of the anonymous referee are presented sequentially in **black** and italic font.*

The authors' responses are provided in **blue** font to ensure clear distinction.

***Comment**: In order to limit temperature rise, it is essential to explore pathways for reducing greenhouse gas emissions. The methodology presented in this paper is considered valuable in contributing to the transparency of scenarios derived from integrated assessment models (IAMs) that estimate future GHG emission pathways. Therefore, the paper is deemed worthy of publication.*

2 Response: We are grateful to Reviewer #2 for the detailed assessment and thoughtful feedback, which have been instrumental in enhancing the quality of our paper. We provide responses to the individual comments under their corresponding paragraphs below.

However, the following points should be addressed prior to publication.

- ***Comment**: The development of integrated assessment models (IAMs) to support greenhouse gas mitigation strategies in developing countries is expected to become increasingly important.*

  International databases such as those provided by the IEA are widely referenced in the development of IAM scenarios in developed countries. However, a key challenge going forward is how researchers in developing countries can secure access to such existing data, and how they can collect and make use of country-specific information on technologies and socio-economic conditions.

  Therefore, if the piamValidation proves effective in enabling researchers in developing countries to conduct practical scenario development, it would be of considerable significance. In this regard, it would be highly valuable for readers if the paper could elaborate on how such existing data can be utilized by researchers in developing countries.

2.1 Response: We appreciate this important comment. A central goal of piamValidation is to lower the barrier for researchers and stakeholders worldwide in validating IAM scenario data. In this context, the configuration files include collections of open-source reference data, which simplify both data search and preparation. This approach significantly reduces the time and resource requirements for conducting such analyses.

- ***Comment**: The paper lacks sufficient explanation as to why CCS (Carbon Capture and Storage) is considered a viable option in short- and medium-term scenarios.*

  In both the United States and Australia, several CCS projects have failed. According to

a report by the U.S. Government Accountability Office (GAO), seven out of eight CCS projects supported by the Department of Energy (DOE) were canceled. The only project that became operational, Petra Nova, saw NRG Energy withdraw from the project, with JX Nippon acquiring full ownership and shifting to a sole operation structure. Although the facility was restarted in September 2023, its commercial viability remains uncertain. CCS alone does not generate profit. Moreover, if the oil produced through Enhanced Oil Recovery (EOR) is combusted, additional CO_2 is emitted, raising questions—particularly from a life cycle assessment (LCA) perspective—about whether CCS via EOR leads to a net reduction in greenhouse gas emissions. The IEA's Net Zero by 2050 scenario calls for the storage of 1.5 billion tonnes of CO_2 per year by 2030. However, the IEA itself acknowledges that achieving this would require "unprecedented investment and policy support" and that current progress is "seriously off track." This paper also references the long lead time associated with CCS deployment.

Given these points, analyzing CCS as a short- to medium-term mitigation option seems questionable. If CCS is to be proposed as a viable strategy within this timeframe, the paper should include a detailed explanation of where and under what conditions it could realistically be implemented.

2.2 Response: We thank the reviewer for raising this critical point: Historic upscaling of CCS has been much slower than expected in IAM scenarios that follow the stringency of the climate targets set by the Paris Agreement. This is, as the reviewer pointed out, in large part due to the lack of real-world policy support, as CCS does not generate profit by itself, alongside other challenges in implementation. Although the last years have seen substantial new activities and investments (Northern Lights, 2024; Porthos, 2023; Reuters, 2022), near-term deployment will be limited. This makes it all the more important to include this variable in piamValidation, as IAMs have in the past substantially overestimated the potential for massive near-term upscaling of CCS (Fuhrman et al., 2025; Kazlou et al., 2023; Zhang et al., 2024). PiamValidation will flag such overoptimistic upscaling by comparing scenario results against the CCUS database and thus may help modelers implement more realistic upscaling dynamics.

- ***Comment**: While the adoption of electric vehicles (EVs) is progressing in certain regions, there are still areas where uptake remains limited due to persistent consumer concerns such as high costs, range anxiety, and constraints in battery supply. How does the analysis in the paper account for these regional differences? Furthermore, for regions where challenges remain, can the authors provide proposals or suggestions for addressing these issues?*

2.3 Response: *Thank you for this important remark. Besides vehicle investment and operational cost, it is crucial to include local preferences or inconvenience costs shaped, e.g., by infrastructure availability, model availability, and risk aversion towards new technologies for modeling the adoption of electric vehicles in different regions. These assumptions were regionally updated with the help of piamValidation and the comparison to the scenarios*

presented in the global EV outlook (IEA, 2024). For a detailed description of the modeling of electric vehicle adoption in EDGE-Transport, the authors refer to Rottoli et al., (2021).

- ***Comment**: Offshore wind power has also faced negative public perceptions, including concerns about low-frequency noise. More recently, rising material and labor costs have led to higher bid prices and an increasing number of project cancellations. How does piamValidation address or account for these challenges?*

2.4 Response: The validation bounds for wind development are based on external data sources: IRENA (International Renewable Energy Agency) for the current capacity GWEC (Global Wind Energy Council), and BNEF (Bloomberg New Energy Finance) for upcoming additions until 2030. For a more detailed overview on the calculation of the boundary thresholds, please see https://github.com/pik-piam/mrremind/discussions. The validation tool allows for small deviations around current capacities because different models may use sources with slightly different accounting methods. As future development is inherently uncertain, the validation tool adds margins around the projections of external sources: the lower bound, for instance, assumes a high failure rate of announced projects. At the regional level, we acknowledge that the uncertainty is even higher, partly indeed due to labor costs and public perception, and partly due to different region definitions in models and data sources; the validation bounds are therefore much looser and only trigger yellow flags and no red flags.

- ***Comment**: To effectively reduce GHG emissions, demand-side mitigation plays a significant role. Although the paper focuses primarily on technologies, when comparing scenarios, it is also important to consider how demand-side reductions are treated. Please also address demand-side mitigation.*

2.5 Response: We thank the reviewer for also considering the demand-side mitigation pathways. The piamValidation tool can also be used to validate near-term demand trends, under the condition that reliable external data is available to assess future demand. Such data is unfortunately limited, and it remains unclear whether observed changes in demand occur autonomously or result from policy interventions or social dynamics. By contrast, electric vehicles and heat pumps represent trillion-dollar markets, which has led international organizations and corporations such as the IEA and BNEF to invest considerable resources in producing and updating detailed market forecasts. These forecasts in turn provide benchmarks for piamValidation to evaluate the short-term realism of IAM pathways.

Previous studies on demand-side mitigation strategies (Muessel et al., 2025; van Heerden et al., 2025) find that electrification is the main driver of greenhouse gas reduction, which is why integrated assessment modeling focuses on improving its representation. However, additional research on demand-side mitigation is needed to understand its effects on emissions and other indicators (Creutzig et al., 2022), as well as to provide reliable reference data.

- ***Comment**: The paper states that "IAM scenarios contribute to the IPCC assessments," but the primary purpose of IAMs is to support policy formation, not to contribute directly to the IPCC.*

  Indeed, IAM analyses are an important component of IPCC reports, and being reviewed and synthesized by the IPCC helps convey findings widely to policymakers, which is highly meaningful.

  However, it is important to clarify that the original role of IAM scenario development is to present options and impact assessments for real-world policy challenges, maintaining its independent purpose.

2.7 Response: We agree with this assessment and will amend the misleading wording in the revised manuscript.

- ***Comment:** "The explanation of how scenarios can be improved through the use of the piamValidation is insufficient."*

2.8 Response: Thank you for this remark. In the revised manuscript, we will further improve the description of the piamValidation applicability, focusing on two aspects:

1. **Demonstrating versatility through additional application cases**: We add a section that illustrates the versatility of piamValidation by applying it to open-source NGFS scenarios. This section demonstrates how the tool can be employed for multi-model overviews, and for the intercomparison of models, scenarios, or periods. Further details are provided in the response letter to Referee 1, Response 1.1.

2. **Clarifying limitations and user responsibility**: Furthermore, we want to stress the limits of the piamValidation tool and precisely point out how and where the responsibility of the user starts in a refined description of the tool. Further details are provided in the response letter to Referee 1, Response 1.5.

- ***Comment:** The statement "Early IAM applications date back to the late 1990s (Cointe et al., 2019)" appears to be inaccurate; it would be more appropriate to say "the late 1980s" or "the early 1990s."*

  For instance, James Edmonds and his colleague published Global Energy: Assessing the Future (Oxford University Press, New York) in 1985, in which they analyzed future pathways using a model.

  In addition, the IPCC First Assessment Report (AR1) published in 1990, the Supplementary Report published in 1992, and Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC 92 Emissions Scenarios all

included analyses of future GHG emissions pathways and their implications for temperature projections.

Furthermore, regarding the IMAGE model referenced by Cointe et al. (2019), IMAGE 1.0 was developed by Rotmans in 1990, and IMAGE 2.0 was edited by Alcamo in 1994.

2.9 Response: Thank you for pointing this out and providing the detailed explanation. We entirely agree and will correct this in the revised manuscript.

References

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., Figueroa, M., Grubler, A., Lamb, W.F., Leip, A., Masanet, E., Mata, É., Mattauch, L., Minx, J.C., Mirasgedis, S., Mulugetta, Y., Nugroho, S.B., Pathak, M., Perkins, P., Roy, J., de la Rue du Can, S., Saheb, Y., Some, S., Steg, L., Steinberger, J., Ürge-Vorsatz, D., 2022. Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nat. Clim. Chang. 12, 36–46. https://doi.org/10.1038/s41558-021-01219-y

Fuhrman, J., Lane, J., McJeon, H., Iyer, G.C., Edwards, M.R., Thomas, Z., Edmonds, J.A., 2025. Rate and growth limits for carbon capture and storage. Environ. Res. Lett. 20, 064034. https://doi.org/10.1088/1748-9326/add9af

IEA, 2024. Global EV Outlook 2024 – Analysis.

Kazlou, T., Cherp, A., Jewell, J., 2023. Feasible deployment trajectories of carbon capture and storage compared to the requirements of climate targets. https://doi.org/10.21203/rs.3.rs-3275673/v1

Muessel, J., Pietzcker, R., Hoppe, J., Verpoort, P., Klein, D., Luderer, G., 2025. An integrated modeling perspective on climate change mitigation and co-benefits in the transport sector. Environ. Res. Lett. 20, 094011. https://doi.org/10.1088/1748-9326/adf23f

Northern Lights, 2024. Accelerating decarbonisation. URL https://norlights.com/what-we-do/

Porthos, 2023. CO2 reduction through storage under the North Sea. URL https://www.porthosco2.nl/en/project/

Reuters, 2022. China's CNOOC completes first offshore carbon capture site. URL https://www.reuters.com/business/environment/chinas-cnooc-completes-first-offshore-carbon-capture-site-2022-06-15/

Rottoli, M., Dirnaichner, A., Pietzcker, R., Schreyer, F., Luderer, G., 2021. Alternative electrification pathways for light-duty vehicles in the European transport sector. Transportation Research Part D: Transport and Environment 99, 103005. https://doi.org/10.1016/j.trd.2021.103005

van Heerden, R., Edelenbosch, O.Y., Daioglou, V., Le Gallic, T., Baptista, L.B., Di Bella, A., Colelli, F.P., Emmerling, J., Fragkos, P., Hasse, R., Hoppe, J., Kishimoto, P., Leblanc, F., Lefèvre, J., Luderer, G., Marangoni, G., Mastrucci, A., Pettifor, H., Pietzcker, R., Rochedo, P., van Ruijven, B., Schaeffer, R., Wilson, C., Yeh, S., Zisarou, E., van Vuuren, D., 2025. Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050. Nat Energy 1–15. https://doi.org/10.1038/s41560-025-01703-1

Zhang, Y., Jackson, C., Krevor, S., 2024. The feasibility of reaching gigatonne scale CO2 storage by mid-century. Nat Commun 15, 6913. https://doi.org/10.1038/s41467-024-51226-8