# Referee #1

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Thank you for the extensive work on the revised manuscript.

I appreciate the effort to respond to the questions raised by adding technical detail on the trade mechanism and providing additional information on the performance of the spatial disaggregation. That said, there remain three main points raised in the previous review that, in this reviewer's opinion, would benefit from further consideration.

Thank you for taking the time to carefully read and comment on the manuscript. We sincerely appreciate the thoughtful feedback. In this revision, we have addressed the aspects that were not adequately covered previously and provide detailed responses to each point below. We believe that the additional details and expanded explanations incorporated following your recommendations have strengthened the paper and improved its clarity and transparency for readers.

**First main point**

The central concern raised in the previous review has not been adequately addressed in this reviewer's opinion in the manuscript.

As stated earlier: "While results are reported at both European-aggregated and individual country levels, the core focus of the paper is on comparing geographic formulations. A more systematic comparison would therefore come from contrasting standard GCAM regional results with the aggregation of the Europe-detailed version.".

The authors acknowledge this point in their reply ("We agree that comparing the core GCAM version with GCAM-Europe is the central objective of these figures"), but ultimately choose not to reflect this emphasis in the main manuscript. Instead, the presentation in the charts continues to focus primarily on demonstrating the capability to produce country-level results. While this is clearly an important feature of the model, in this reviewer's opinion, this choice runs counter to the stated objective of the paper and difficult the real analysis of the model differences and strengths.

Country-level resolution is undoubtedly valuable; however, country-level results alone provide limited insight into systematic differences between model formulations. For this reason, I reiterate my previous suggestion that the main manuscript would be strengthened by presenting systematically comparable regional results (e.g. EU-12, EU-15, Eastern Europe, EFTA, non-EU Europe) when contrasting GCAM and GCAM-Europe. Country-level results

would be better used to assess model realism and internal consistency, or otherwise moved largely to the Supplementary Material.

We would like to thank the reviewer for this comment. In the previous revision, we aimed to strike a balance by ensuring that, as this is a model descriptor paper, all functionalities are presented transparently. However, the reviewer is correct that a core aspect of comparing the five European regions in the core model and GCAM-Europe was not properly highlighted by the additional figures in the SI. At the same time, we also share the reviewer's remark that country-level resolution is undoubtedly valuable and consider that country-level projections are an essential component of GCAM-Europe's added value. Therefore, in this revised version, all main figures have been restructured following the reviewer's recommendation and aiming to strike a balance between systematic comparison of regional results as well as country level projections, to ensure that all functionalities of the model are property highlighted. Each figure (Figures 6 to 12) now includes:

- A top panel comparing the core model and GCAM-Europe across the five aggregated European regions, as well as the entire continent (highlighted). To strengthen the temporal analysis, we now present results for multiple benchmark years (2015, 2030, and 2050; see also our response to the second point).
- A bottom panel presenting country-level projections, which we believe are important to preserve in the main manuscript given the model's intended applications.

We believe this updated figure structure improves the manuscript by providing a clearer and more comprehensive geographic and temporal comparison between the core GCAM regional results and the GCAM-Europe version, while maintaining the policy-relevant country-level detail.

**Second point: model realism and temporal focus**

The manuscript would benefit more from a systematic comparison of historical and near-term results, between both model variants and against historical data, than from a strong emphasis on 2050 outcomes.

The strong emphasis on 2050 results in the figures complicates the model comparison exercise, particularly given that the scenarios differ substantially in underlying population assumptions, among other drivers. In addition, the absence of historical data for comparison limits the ability to assess model realism. While such a focus could be justified in a study primarily aimed at long-term policy assessment, it significantly hinders the paper's stated objective of comparing two model formulations.

The reviewer appreciates the authors' efforts to respond to earlier comments regarding nuclear deployment, biomass availability, and related topics regarding model realism. However, the manuscript would benefit from a more critical self-assessment of the results beyond the example points raised in the previous review.

Below is a non-exhaustive list with examples of issues that require realism checks in order to better situate the potential of both GCAM and GCAM-EU for real-world policy assessments:

Thank you for this comment. We have revised the manuscript to strengthen the realism and empirical grounding of the results. In particular, the updated figures from F6 to F12 (see response to Point #1) give greater attention to historical (2015) and short-term (2030) outcomes, while reducing the previous emphasis on 2050 projections. At the same time, based on each comment below we have further strengthened the discussions in the presentation of results.

More broadly, as part of this realism exercise, the revised manuscript now includes a validation table (Appendix B), which compares GCAM-Europe outputs in 2015 against available historical data from EUROSTAT and shows reasonable alignment in key indicators, including fossil CO2 emissions, final energy (FE) consumption, and the share of renewables in final energy use. We believe this additional validation strengthens confidence in the model's short- and medium-term projections.

"*While the model applies various data transformation from the crude input data towards the final GCAM inputs to account for structural model issues, Appendix B shows that GCAM-Europe outputs for 2015 align reasonably well in terms of (fossil) CO2 emissions, final energy (FE) consumption, and renewables in FE use. Aggregates for EU-27 closely match FE and renewables reported by EUROSTAT, while country-specific estimates differ in some cases, especially in smaller countries. These country level mismatches are mostly related to structural accounting differences for energy transformation processes, such as (bio-)liquids refining and electricity production. For CO2 emissions, the EU-wide comparison shows a minor deviation of roughly 5% due to the use of globally uniform CO2 emission factors for fossil fuels in GCAM-Europe. When using the model to develop scenarios that align with specific EU and/or member-state policy targets, it is therefore important to scale official targets to base year values in GCAM-Europe for a proper representation of future dynamics (Frilingou et al., 2025).* "

Below, we provide detailed responses to each of the dimensions highlighted by the reviewer.

- **Primary energy differences** (Figure 5): The substantial differences in primary energy in historical years imply very different primary-to-final energy conversion efficiencies in between both models, with direct implications for emissions. These differences need to be explained, and historical values should be explicitly shown in the figure. Presenting EU sub-regional results would also help assess whether this issue is region-specific.

Thank you for flagging this issue. The discrepancy in primary energy shown in the previous version of Figure 5 was due to a coding error in the data processing stage. Specifically, a small number of countries were inadvertently excluded from the GCAM-Europe aggregation. This has now been corrected, and the revised figure shows that primary energy levels between the two model versions are much more closely aligned in the historical period.

• **Biomass availability**: In the reply the authors attest that they consider internally sourced biomass levels of 15–17 EJ to be consistent with literature estimates of European biomass potential. This reviewer finds this an overly generous assumption of this model framework for a reference scenario when compared to the available literature. This is of particular importance because the higher spatial disaggregated version of the model is even more generous on the biomass availability which is crucial for the future mitigation alternatives availability.

To ensure clarity in the commentary, we have adapted the text to refer to EU-28 countries only rather than Europe in total, which was the source for the 15-17 EJ potential, and which can be compared with the 13 EJ production observed in GCAM-Europe for EU-28 countries. While we understand the point that this is indeed slightly higher than in the aggregated version of the model, and may still be high for a reference scenario, we note that typically it is a common practice to constrain global biomass consumption in mitigation scenarios, given the well-documented sustainability concerns that may rise as a result of high demand for backstop technologies such as BECCS. The model by default does not account for sustainability issues when remaining unconstrained, and produces biomass based on pure economics and land availability. We have adapted the text to reflect on this discussion:

*"European biomass production (excluding Russia) rises in GCAM-Europe relative to the core model (17 EJ versus 15 EJ). Of that production, 13 EJ are produced in EU-28, which is comparable with recent biomass production potential estimates of 15-17 EJ for the region (Ruiz et al., 2019). This may still be relatively high for a scenario without climate policy, though typically in IAM modelling exercises, global biomass consumption is explicitly constrained in mitigation scenarios to account for sustainability limits (Reid et al, 2020)."*

• **Nuclear power**: It is important to show historical values to disentangle model realism versus scenario design results as argued in the authors reply for German and other regions result.

• **Wind and solar**: As the authors reply for the wind decreased share is centered in low historical uptake, historical realism is again a center point that needs to be expressed in the manuscript. Historical deployment should be shown alongside both model scenarios to corroborate model realism on the analysis of the strong changes observed in the results.

(These comments have been addressed together). Thank you for this recommendation. As noted in our response above, we now report historical values in all figures in Section 3. This allows readers to clearly distinguish between model realism in the historical period and differences that arise from scenario design.

In addition, we have expanded the manuscript text to explicitly demonstrate the alignment of our power sector results with historical observations. First, we clarify the consistency in total electricity generation:

"*Focusing on the power sector, electricity production in the GCAM-Europe baseline scenario shows a steady increase during the entire century. Total generation accounts for approximately 14 EJ in 2015, consistent with the 14.7 EJ reported by the IEA, and is projected to rise to around 24 EJ by 2100.*"

Following the reviewer's suggestion, we have also added specific discussion of wind and nuclear power to further substantiate historical realism:

"*Likewise, there are large differences in wind power generation. In 2015, wind generation in both GCAM-Europe and the core model amounts to 1.15 EJ, consistent with the value reported by the IEA. However, while it represents around 18% of the total electricity mix in 2050 in the core, this share decreases to 7% in the GCAM-Europe baseline.*"

"*Nuclear energy follows a broadly similar trajectory in both scenarios. In 2015, generation amounts to 3.5 EJ, consistent with the IEA data, and it is projected to supply roughly 18% of Europe's electricity mix by 2050 in both model versions.*"

Together, these additions clarify that the historical baseline is well aligned with observed data and that there are no inconsistencies in historical calibration.

• **Electricity final energy**: Reporting historical and projected shares of electricity in final energy by sector would help clarify structural differences between the model variants and assess the realism of electrification levels and historical alignment.

Following this recommendation, we have added two new figures (Fig. S7 and Fig. S8) to the Supplementary Information to clarify the evolution of electrification in both model versions.

- Fig. S7 presents the share of electricity in total final energy demand, indicating the slight divergence between the two model versions over time. We have also explicitly verified and stated in the revised manuscript that the 2015 electricity share (around 20% across Europe) is consistent with historical data reported by IEA (IEA, 2017), ensuring proper alignment with observed values.
- Fig. S8 reports sectoral electrification levels (buildings, industry, and transport). We confirm in the main text that the 2015 shares (33% in buildings, 22% in industry, and less than 5% in transport) are closely aligned with historical statistics.

We believe that these new figures, along with the added text in the main manuscript (below), provide further confidence that both model versions are well calibrated to historical conditions before projecting future electrification trends.

"*As a result, the two model versions show divergent shares of electricity in total final energy demand (Fig. S7). In 2015, this share was approximately 20% in Europe, consistent with the 21.7% reported by the IEA (IEA, 2017). However, the lower growth in electricity generation in GCAM-Europe leads to a slightly lower share by 2050 compared to the core model, at 28% versus 30%, respectively. This pattern is observed across all European regions in the core GCAM model. Similarly, sectoral electrification levels align well with historical data: in 2015, electricity represents 33% of final energy use in buildings, 22% in industry, and less than 5% in transport (Fig S8). Both model versions project gradual increases in electrification across these sectors over time, following comparable trajectories.*"

• **Overall recommendation**: More generally, a slightly more critical (rather than primarily descriptive) discussion of the difference between the model results and their historical consistency would help to clearly articulate the strengths and limitations of both models throughout the entire manuscript.

Thank you for this suggestion. In the revised manuscript, we have incorporated a more critical discussion of the differences between the model results, based on the comments raised above. This crucially includes the addition of the new table in Appendix B, benchmarking model results with historical values from EUROSTAT to ensure consistency.

We would like to clarify that this manuscript primarily serves as a model descriptor paper. The presented results are based on a no-policy reference scenario and a stylised policy experiment, designed to illustrate model behaviour and structural characteristics rather than to provide policy-relevant projections. For this reason, we aimed to avoid overinterpreting scenario outcomes beyond what is appropriate for demonstrating model properties.

Still, the revised figures included in this revised version provide enhanced regional and temporal detail, improving the interpretation of model performance, and offering a clearer assessment of their alignment with historical observations.

**Finally, on Table S1 and the discussion of spatial granularity**

The comparison of regional granularity presented in Table S1 is incomplete and potentially misleading. If included, it should more carefully reflect the current state of the art in EU-focused IAM analysis. For example, models such as REMIND have configurable spatial resolution and already have published applications with disaggregated EU results that go far beyond the mentioned 12 regions.

As currently presented, the table adds limited value in situating GCAM's spatial disaggregation relative to existing modeling approaches. Moreover, it should be acknowledged more clearly that country-level formulations are not necessarily the preferred option. As the authors

themselves note, increasing spatial resolution can limit global assessments due to computational challenges. Many IAMs deliberately adopt a sub-regional EU aggregation to balance regional detail with global model scope for policy assessment and not due to technical limitations. On this we could cite again analysis made with EU developed models like IAMs such as REMIND, or partial equilibrium models like for example ETM-UCL, …

We would like to thank the reviewer for the suggested correction on the REMIND information. Indeed, the spatial resolution mentioned for the model reflected older versions of the model. We have corrected this, presenting the 21 global and 8 EU regions spatial representation as the latest available information on the model from recent publications. We have also added a disclaimer noting that REMIND has a configurable spatial resolution.

*"*REMIND features configurable spatial resolution; the 21-region setting (including 8 EU regions) corresponds to recent applications of version 3.3.1 (Schreyer et al., 2025)."*

The reviewer is also correct to point out that country-level formulations are not always the preferred option. In response, we have clarified in the manuscript that sub-regional EU aggregation in IAMs is often a deliberate modelling choice to balance regional detail with global scope. We further emphasise that GCAM-Europe is intended as a complementary tool that enables Member State–level analysis within a globally consistent and computationally tractable framework, thereby expanding the available modelling toolkit for EU-focused policy assessments. See the following addition after Table S1:

*"Table S1 highlights a gap in terms of fully open-source models (including the execution environment) with a high regional disaggregation at the EU-level, including representing all EU member states separately. Although GCAM-Europe aims to fill this gap, it should be noted that country-level formulations are not necessarily always the preferred option. IAMs may deliberately adopt a sub-regional EU aggregation to balance regional detail with global model scope for policy assessment, especially in the light of potential computational limitations. In this context, GCAM-Europe should be seen not as a substitute for existing aggregated EU representations, but as an additional tool of the climate-economy modelling community that enables Member State–level analysis within a globally consistent framework, while remaining computationally tractable for policy applications."*