

Response to Reviewer 1

<https://egusphere.copernicus.org/preprints/egusphere-2025-121#RC1>

The paper is very useful and timely research.

This would provide a very useful methodology for downscaling climate mitigation scenarios.

Response: Thank you so much for reviewing this paper, we are glad to hear that you find it a useful methodology and timely research.

Here are some comments and suggestions:

"Estimated emissions gap of 19-27 MtCO₂ in 2030" (Line 27) looks too small and needs to be checked.

Response: Thank you for spotting this, the correct unit is GtCO₂, and we have corrected the paper accordingly (Page 1 line 27):

"However, collective efforts stated in the NDCs are not in line with the long term goal of the Paris Agreement (Dafnomilis et al., 2024; den Elzen et al., 2022; Fransen et al., 2023; Geiges et al., 2020; Hausfather and Moore, 2022; Iyer et al., 2022; Meinshausen et al., 2022; Emissions Gap Report 2023, 2024), as temperature is projected to increase to about 2-2.4°C by the end of the century and with an estimated emissions gap of 19-27 GtCO₂ in 2030 (CAT, 2024)."

Line 149~152 - IAM-Driven Path is assumed to use country-specific GDP and population pathways from the SSPs. Does this mean that National Data-Driven Path does not use country-specific GDP and population pathways from the SSPs? Then what projections are used for country-specific GDP and population pathways under National Data-Driven Path?

Response: Thank you for checking this. Yes, both the `NAT` and `IAM-driven` paths use the same socioeconomic projections. We have clarified this in the paper (Page 5-6, lines 159-170). Please find below the updated text:

"When downscaling final energy variables, both the "NAT" and "IAMatt" paths rely on SSP-based national projections of GDP and population. In the "NAT" path the historical relationship between energy intensity and GDP per capita is extended into the future using GDP and population projections for each country. In contrast, the "IAMatt" establishes this relationship using regional trends from IAMs scenarios, and applied to country-level GDP per capita projections, thereby embedding structural changes that may significantly diverge from historical trends.

In a subsequent step, the algorithm downscales the energy structure (energy use by carrier, sectors, and fuels): while the "NAT" path preserves differences across countries by relying on country level data, the "IAMatt" path applies the same regional energy structure to each country. Finally, DSCALE ensures that the sum of country-level results aligns with regional IAMs outcomes in both paths."

Some descriptions and formulas are difficult to understand. Some examples are as follows:

From Line 219,

For total final energy, the "MAIN" sector coincides with "GDP".

FEN_{t,c,s,e} = EI_{t,c,s,e} MAIN_{t,c,s,e} --- (5)

What does MAIN_{t,c,s,e} of (5) mean? Is it GDP? Then, what does GDP for t, c, s, e mean? How is the GDP for sector s and energy e defined?

Response: We have renamed the "MAIN" variable as "Q", so that all final energy variables can be defined as the product of an activity indicator "Q" (e.g. GDP), and an intensity "I" indicator (e.g. the

energy intensity). We have omitted the “e” and “s” indices from Eq. (5) and (6) as they do not have any meaning for the GDP. We have revised the Final Energy (2.1) section (pages 9-15, lines 220-305) and we added more detailed equations in the supplementary information (S2.5). Please find below the updated text of the final energy section:

“Equation (4) can be generalized by representing final energy variable as the product of an intensity indicator “I” and an activity indicator “Q”, as shown in Eq. (5):

$$FEN_{t,c} = I_{t,c} Q_{t,c} \quad (5)$$

At this stage, Eq. (5) intentionally omits the energy carriers (e) and sectors (s) indices, as we aim at presenting a general framework that can be used to downscale various final energy variables, by changing the corresponding activity and intensity indicators, as outlined in table 2. When downscaling total energy demand, the activity indicator “Q” coincides with the GDP, whereas the intensity indicator “I” represents how much energy is used per unit of GDP for the overall economy (hence the energy intensity). For more detailed equations (including all indices), please refer to the supplementary information (S2.5).”

We have added more detailed equations in the supplementary information S2.5 below:

S2.5: Final energy – Detailed equation variants across all steps

185 *Step A): Downscaling total final energy demand*

We reformulate Eq. (5) to calculate total final energy demand by using the equation below, where the activity indicator (Q) corresponds to the GDP:

$$FEN_{t,c,S,E} = EI_{t,c,S,E} GDP_{t,c} \quad (S11)$$

The energy carrier (E) and sector (S) are shown in capital letter, as total final energy is defined as the sum of energy used across all sectors “s” and for all energy carriers “e”.

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We estimate the slope and intercept of the energy intensity (EI) using the equation below:

$$EI_{t,c,S,E} = \begin{cases} \exp\left[\alpha_{S,E} + \beta_{S,E} \log\left(\frac{GDP_{t,R}}{POP_{t,R}}\right)\right] & \text{if } path = IAMatt \\ \exp\left[\alpha_{c,S,E} + \beta_{c,S,E} \log\left(\frac{GDP_{t,c}}{POP_{t,c}}\right)\right] & \text{if } path = NAT \end{cases} \quad (S12)$$

Please note that Eq. (S12) corresponds to Eq. (6), where we replace the generic “intensity” indicator I , with the “energy intensity” EI . Compared to Eq. (6), Eq. (S12) includes the energy carriers (e) and sector (s) indicis, both of them in capital letter as we calculate total final energy demand.

Step B): downscaling energy carriers (liquids, solids, gases, electricity)

Energy demand for individual energy carriers can only be a fraction of total energy demand. Therefore, we modify Eq. (5) by replacing “GDP” with the previously downscaled final energy demand. At the same time, we replace the energy intensity “EI” from Eq. (S12) with “share”, denoting the percentage of energy demand from that energy carrier. Finally, we constrain the share of each energy carrier to be lower than one (e.g. electricity demand cannot exceed total final energy demand)

$$FEN_{t,c,S,e} = \min(1, share_{t,c,S,e}) FEN_{t,c,S,E} \quad (S13)$$

205 Please note that the energy carrier “e” is now shown in lower case, whereas for sectors we keep the upper-case notation ‘S’ as we are not disaggregating them yet. In a similar manner, we rewrite Eq. (6), as shown in the equation below:

$$share_{t,c,s,e} = \begin{cases} \exp \left[\alpha_{s,e} + \beta_{s,e} \log \left(\frac{GDP_{t,R}}{POP_{t,R}} \right) \right] & \text{if } path = IAMatt \\ \exp \left[\alpha_{c,s,e} + \beta_{c,s,e} \log \left(\frac{GDP_{t,c}}{POP_{t,c}} \right) \right] & \text{if } path = NAT \end{cases} \quad (S14)$$

Step C): downscaling end-use sectors (Industry, transportation, and residential & commercial)

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Finally, we break down final energy demand for each energy carrier to the sector level: Industry, transportation, and residential & commercial. As a result, we modify Eq. (7), by replacing total final energy demand with energy demand from the various energy carriers `e`:

$$FEN_{t,c,s,e} = \min(1, share_{t,c,s,e}) FEN_{t,c,s,E} \quad (S15)$$

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Please note that the sector index "s" in Eq. (S15) is now shown using the lower-case notation, as well as in Eq. (S16):

$$share_{t,c,s,e} = \begin{cases} \exp \left[\alpha_{s,e} + \beta_{s,e} \log \left(\frac{GDP_{t,R}}{POP_{t,R}} \right) \right] & \text{if } path = IAMatt \\ \exp \left[\alpha_{c,s,e} + \beta_{c,s,e} \log \left(\frac{GDP_{t,c}}{POP_{t,c}} \right) \right] & \text{if } path = NAT \end{cases} \quad (S16)$$

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Form Line 259, the authors say that we need to assign a "MAIN" sector for each final energy variables, using a hierarchic structure. When downscaling total final energy, we use the GDP as the main sector. Then, we use total final energy as the main sector for each of the energy carriers, essentially calculating a percentage share.. This explanation is difficult to understand.

Response: Thank you very much for your comment, we realized that our explanation was not very clear, and we have restructured this section (pages 9-15). However, as this is a generic equation that is used in several different contexts, we also prefer to keep it generic rather than repeating the same equation throughout the paper.

As mentioned above, we have renamed the "MAIN" variable as "Q", so that all final energy variables can be defined as the product of an intensity indicator "I" and an activity indicator "Q", (page 9, lines 222-225):

- When downscaling total energy demand, the activity indicator "Q" coincides with the GDP, whereas the intensity indicator "I" represents how much energy is used per unit of GDP for the overall economy (hence the energy intensity).
- However, when calculating final energy by energy carriers (and end-use sectors), "I" should be interpreted as a percentage share (e.g. the percentage share of electricity) on total energy demand "Q".

We have revised the Final Energy (2.1) section 2.1 (pages 9-15) and provided additional equations in the supplementary information (S2.5) to clarify the downscaling process. At the same time, we have updated table2 (Pages 11-13), to clarify the sequence of the downscaling steps. Please find below the updated text (page 10-11, lines 245-270):

“The relationship between the energy intensity (represented by the intensity indicator I) and GDP per capita can be determined by regression using data from regional IAM scenarios or from historical country-level data. In the first case we obtain the “IAMatt” path, in the latter case we get the nationally driven “NAT” path. The rationale behind it is that changes in the energy intensity “ I ” are driven by changes in GDP per capita, as observed in historical data, and envisioned by future IAM scenarios. This means that convergence in the energy intensity across countries is conditional on the level of economic development (measured as GDP per capita) as shown in Eq. (6):

$$I_{t,c} = \begin{cases} \exp \left[\alpha + \beta \log \left(\frac{GDP_{t,R}}{POP_{t,R}} \right) \right] & \text{if path} = \text{IAMatt} \\ \exp \left[\alpha_c + \beta_c \log \left(\frac{GDP_{t,c}}{POP_{t,c}} \right) \right] & \text{if path} = \text{NAT} \end{cases} \quad (6)$$

We estimate the parameters of the functional form (the constant α and the slope β) based on historical data at the country level for the “NAT” path. Conversely, in the “IAMatt” path we estimate the parameters using regional IAM scenario results, where all countries c belonging to a region “ R ” will share the same α and β values.

It is important to note that the intensity indicator “ I ” corresponds to the energy intensity when calculating total final energy demand. However, when calculating final energy by energy carriers (and end-use sectors), “ I ” should be interpreted as a percentage share (e.g. the percentage share of electricity) on total energy demand “ Q ”.

Therefore, we rely on the same approach to downscale final energy results for all the sub-sectors including different energy carriers (electricity, solids, liquids, gas) and end-use sectors (transportation, industry, residential and commercial). To do so, we employ on a hierarchical framework: first we downscale the total final energy (step A), by using GDP as the activity variable “ Q ” and the energy intensity as the intensity indicator “ I ”. In a subsequent step (B), we allocate final energy across energy carriers (liquids, solids, gases, electricity), by multiplying a percentage share “ I ” by an activity indicator “ Q ” (total final energy demand). Finally (in step C), we allocate energy consumption by energy carriers to the end use sectors (industry, transportation, residential & commercial). A full description of “ Q ” (activity) and “ I ” (intensity) indicators across all downscaling steps is provided in Table 2, whereas more detailed equations across all downscaling steps are provided in the supplementary information (S2.5).

Table 1 Overview of downscaling steps (from A to C), associated variables to be downscaled, and their respective underlying activity “ Q ” and intensity indicators “ I ”. Units are indicated in square brackets.

| Step | Variables to be downscaled | Activity indicator (Q) | Intensity indicator (I) |
|------|--|--------------------------|--|
| A) | Final Energy [EJ/yr] | GDP PPP [Billion USD/yr] | Energy intensity: The “Energy Intensity” refers to the amount of energy required to produce a unit of GDP. Unit: [EJ/Billion USD] |
| B) | Final Energy Electricity [EJ/yr], Final Energy Solids [EJ/yr], Final Energy Liquids [EJ/yr], Final Energy Gases [EJ/yr] | Final Energy [EJ/yr] | Share of energy carriers: share of each energy carrier within total final energy (e.g. percentage of electricity use in total final energy). |

| | | | |
|----|--|-----------------------------------|--|
| | | | Unit: [percentage share] |
| C) | Final Energy Electricity Industry [EJ/yr], Final Energy Electricity Transportation [EJ/yr], Final Energy Electricity Residential & Commercial [EJ/yr] | Final Energy Electricity [EJ/yr] | Share of sectors within the energy carrier (e.g. percentage of electricity allocated to the industry sector) Unit: [percentage share] |
| | Final Energy Solids Industry [EJ/yr], Final Energy Solids Transportation [EJ/yr], Final Energy Solids Residential & Commercial [EJ/yr] | Final Energy Solids [EJ/yr] | Share of sectors within the energy carrier (e.g. percentage of solids allocated to the industry sector) Unit: [percentage share] |
| | Final Energy Liquids Industry [EJ/yr], Final Energy Liquids Transportation [EJ/yr], Final Energy Liquids Residential & Commercial [EJ/yr] | Final Energy Liquids [EJ/yr] | Share of sectors within the energy carrier (e.g. percentage of liquids allocated to the industry sector) Unit: [percentage share] |
| | Final Energy Gases Industry [EJ/yr], Final Energy Gases Transportation [EJ/yr], Final Energy Gases Residential & Commercial [EJ/yr] | Final Energy Gases [EJ/yr] | Share of sectors within the energy carrier (e.g. percentage of gases allocated to the industry sector) Unit: [percentage share] |

“

With the Alphas and Betas for functional forms (equation 6) estimated based on historical data or IAM scenarios results, how can the time of conditional convergence (tc) as suggested in the paper, such as 2100, 2150, 2200, applied?

Response: Thank you for highlighting this, we have clarified this convergence process in the paper (page 13-14, lines 275-290):

“Finally, we apply Eq. (1) to calculate a “composite” path from the “NAT” and “IAMatt” paths using a time of convergence tc. The time of convergence is scenarios specific, with faster convergence in case of Net Zero 1.5C scenarios in line with the Paris Agreement, and a slower convergence for current

policy scenario. This convergence process applies to final, secondary primary and energy related CO2 emissions variables and it happens gradually over time (t). For the period between 2010 and the time of convergence t_c (e.g., 2150 in our default setting), the final country-level energy intensities are calculated as a linear combination of two paths: "IAMatt" and "NAT". The weighting between these two paths works as follows:

- At the base year, the "NAT" path is weighted fully (weight = 1), and the "IAMatt" path has zero weight.
- Over time, the influence of the "NAT" path linearly declines to zero by the convergence year (t_c), after which the "IAMatt" path fully determines the projections.

For final energy variables, this convergence process is conditional on income per capita, because the intensity indicator " I " is estimated against GDP per capita (see Eq. (6)). This means that even after full convergence (beyond the time of convergence t_c), countries at different income levels will retain different energy intensities, depending on the slope β of Eq. (6). For illustrative purposes, Fig. 3 shows three distinct final energy intensities (defined as total final energy divided by GDP), using a t_c (time of convergence) equal to 2050, 2100, 2150, for each country of the Pacific OECD region of MESSAGE, all of them consistent with a 1.5C scenario."

The explanation for Figure 3 says that the graph displays a range of downscaled results for New Zealand (blue lines), Japan (light blue), and Australia (green lines) under different convergence criteria (fast, medium, and slow) but it is not possible to identify lines for each of different convergence criteria (fast, medium, and slow).

Response: Thank you for spotting this. We agree and we have updated Figure 3. We now show results for a time of convergence (t_c) of 2050, 2100, 2150 to make lines more visible and reduce possible overlapping. At the same time, we have adjusted the size of the figure and adjusted the scale of the X and Y axes (and use the same unit of Figure 2). Please find below the updated text and figure:

"For illustrative purposes, Fig. 3 shows three distinct final energy intensities (defined as total final energy divided by GDP), using a t_c (time of convergence) equal to 2050, 2100, 2150, for each country of the Pacific OECD region of MESSAGE, all of them consistent with a 1.5C scenario."

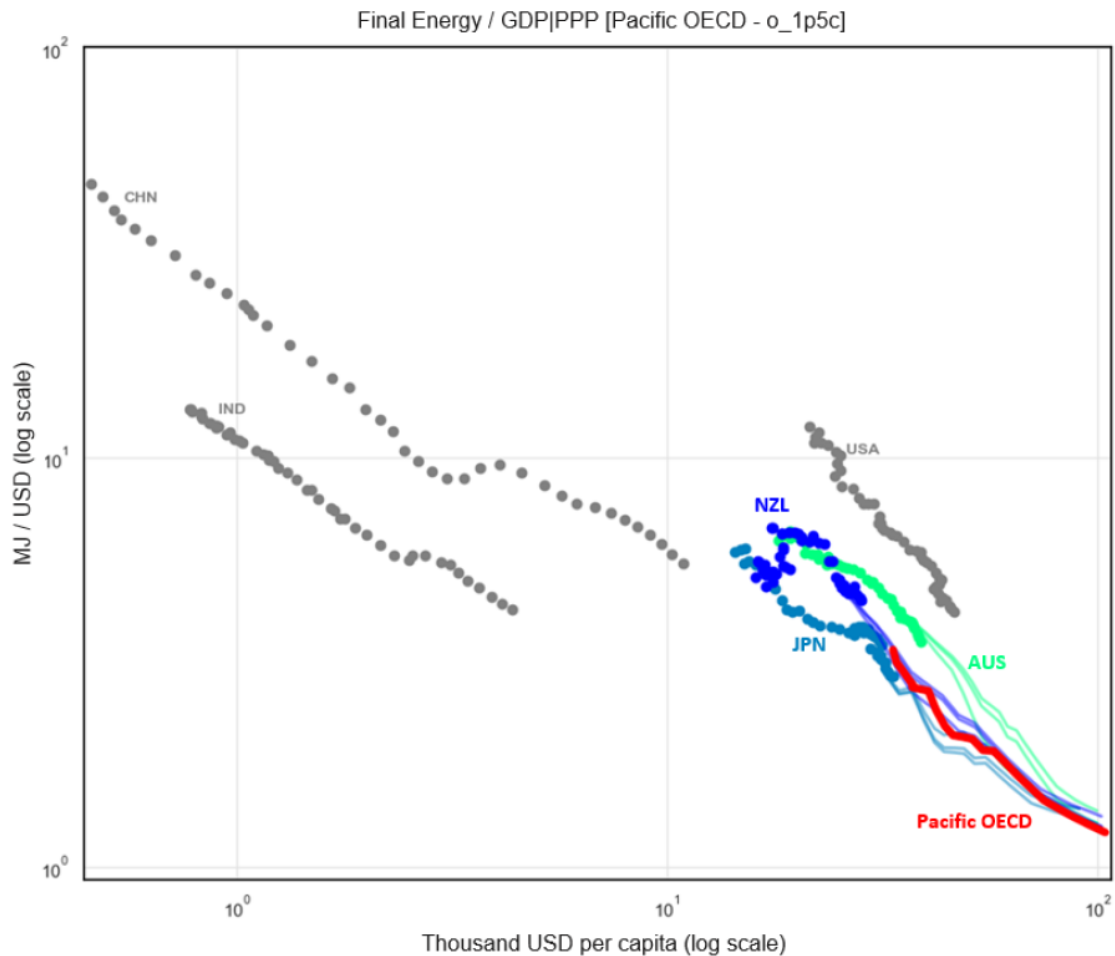


Figure 3 Downscaled total final energy intensity. Historical data are represented by dotted lines, while future downscaled data are shown as continuous coloured lines. The red line represents the Pacific OECD region from the MESSAGE model, according to a 1.5°C pathway from 2010 to 2100. The graph displays a range of downscaled results for New Zealand (blue lines), Japan (light blue), 295 and Australia (green lines) under different `tc` (time of convergence): 2050, 2100, 2150. Historical data for China, India, and the USA are shown only for comparison purposes and are depicted in grey, as these countries are not part of the Pacific OECD region.

PLATTS database (2019) is not available. Need more information on this database.

Response: We have now added the PLATTS database in the references (Page 61, line 1330):

- *Platts: World Electric Power Plants Data Base, <https://www.spglobal.com/commodity-insights/en/products-solutions/clean-energy-technology>, 2019. (last access March 2025).*

The default weights for the criteria for downscaling (Table 5) needs more justification and the mechanism for weight design needs to be developed.

Response: We agree, and we have added additional justification and the mechanism for the weight design (pages 19, lines 386-410):

“For biomass and hydro, we apply an equal weighting of 50% on historical data and 50% on supply cost curves, as these energy sources are typically concentrated in specific countries with favourable

natural conditions. On the one hand historical data capture the role of existing infrastructures. On the other hand, the resources availability and economic potential are reflected in supply cost curves, with the aim of enhancing the future allocation of these resources across countries. For solar and wind, the weights distribution aims at capturing current infrastructures (historical data, 50%), future economic potential (supply cost curves, 35%) as well as support from public institutions (governance indicators, 15%). Historical data (50%) serves as the primary driver in the short term, capturing real-world availability data, shaped by past policy support and market conditions. Supply cost curves reflect each the long-term economic potential for solar and wind deployment in each country. These curves mimic the outcomes of a cost-minimization process, showing where renewables are likely to develop if solely driven by cost efficiency. However, supply curves can produce somewhat abrupt or "stepwise" behaviours, especially when technologies only appear in countries where costs fall below specific thresholds. This makes them less reliable for capturing early-stage deployment patterns, and for this reason we assign to them a lower weight (35%, compared to historical data weight of 50%). Finally, governance indicators reflect the enabling role of institutions in supporting renewables including financial incentives. However, they do not directly reflect physical or economic resource availability, hence we apply a smaller weight (15%). For coal, gas, oil, and geothermal, we equally apply historical data and remaining technical lifetime (50% each) as criteria weights for the downscaling. The rationale is that the future distribution of conventional power generation capacity is strongly influenced by both historical patterns of energy production (providing a baseline for near-term allocation) and remaining operational lifetimes (including announced/planned new capacities). Older plants nearing end-of-life may be phased out sooner, while newer facilities with more remaining capacity are likely to operate longer. For nuclear, we set the weights at 85% for historical data and 15% for governance Indicators, with the aim of reflecting path-dependencies and political sensitivity associated with nuclear development. We use historical data as the main criteria to allocate nuclear energy developments to the country level. However, governance indicators remain a relevant factor, as only countries with high institutional and regulatory capacity are likely to pursue or expand nuclear power programs."

Response to Reviewer 2

<https://egusphere.copernicus.org/preprints/egusphere-2025-121#RC2>

The study and its methodology are transparent, well-written, and provide a solid presentation of the figures. I found the study highly interesting and informative, and I appreciated the clarity with which the methodology was explained. It offers valuable insights, and I read it with great interest. The study presents a very useful tool for downscaling regional pathways to the country level based on an Integrated Assessment Model (IAM) scenario. It is an important study, and the tool is important for researchers as it allows to present national results based on regional scenarios. The authors present a very detailed methodology for downscaling and also present a sensitivity analysis and apply the results for current policies, NDC scenario and 1.5C scenario for the MESSAGE model for four MESSAGE world regions: Sub-Saharan Africa, China, Western Europe and OECD Pacific.

Response: Thank you very much for your comments. We are glad to hear that you consider this manuscript an important study that offers valuable insights.

I would also like to see more country results from the other MESSAGE reasons. I do not fully understand why the authors focused on these four regions, instead of all MESSAGE regions. It

would also be good to test the results with other Integrated Assessment Models with more world regions, or show where this has been done.

Response: We have clarified in the paper the reason why we focus only on four regions, in the results section (page 30, lines 625-635):

“We employ DCSCALE to provide country level downscaled results for the NGFS 2023 project. This paper focuses on the results of four key regions within the MESSAGE model: Sub-Saharan Africa, China, Western Europe, and Pacific OECD. We focus only on four regions as the core objective of this paper is to present the downscaling methodology and to demonstrate its application in the context of the NGFS project with a few examples. We have selected these regions by considering different aspects:

- *Number of countries: including the Sub-Saharan Africa region (48 countries) and the China region (only 2 countries)*
- *Future socio-economic projections across countries: Pacific OECD region (including Japan with ageing population and Australia with increasing population)*
- *Including both regions from the global North and global South:*
 - *Western Europe, with strong convergence in policies in some countries (EU27) as well as possible outliers (e.g. Turkey),*
 - *Sub-Saharan Africa region encompassing low-income countries (e.g. Burundi), upper-middle income countries (such as South Africa and Equatorial Guinea) and high-income countries (Seychelles).”*

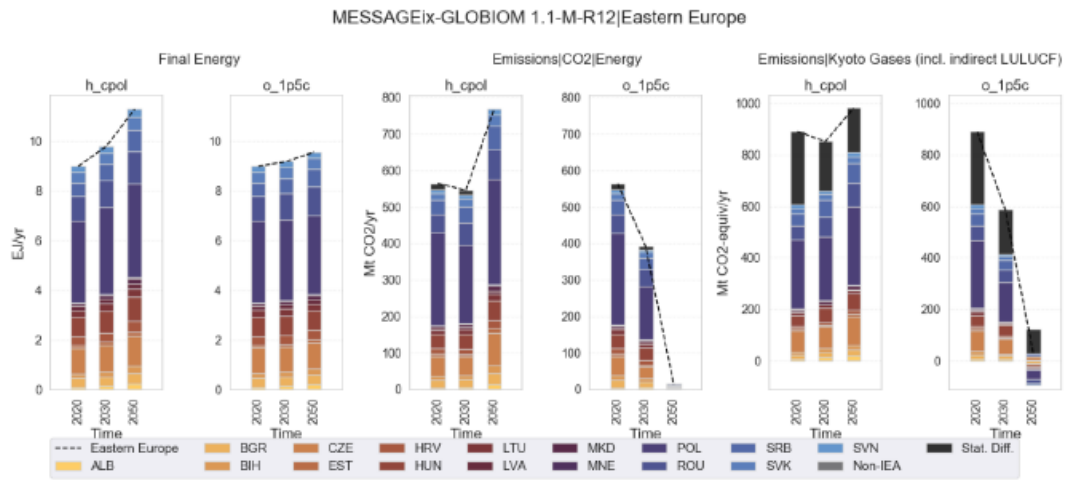
For completeness, we have now added all downscaled results from MESSAGE (across all regions) in the supplementary information S4. We have also added a reference to the NGFS project so that the reader can download all downscaled results from all the 3 models (MESSAGE, GCAM and REMIND) and all regions, page 34, line 705):

“Additional figures for the remaining MESSAGE regions can be found in the supplementary information (S4). The full dataset with the downscaled results across all NGFS models (MESSAGE, GCAM and REMIND) is archived on Zenodo¹.”

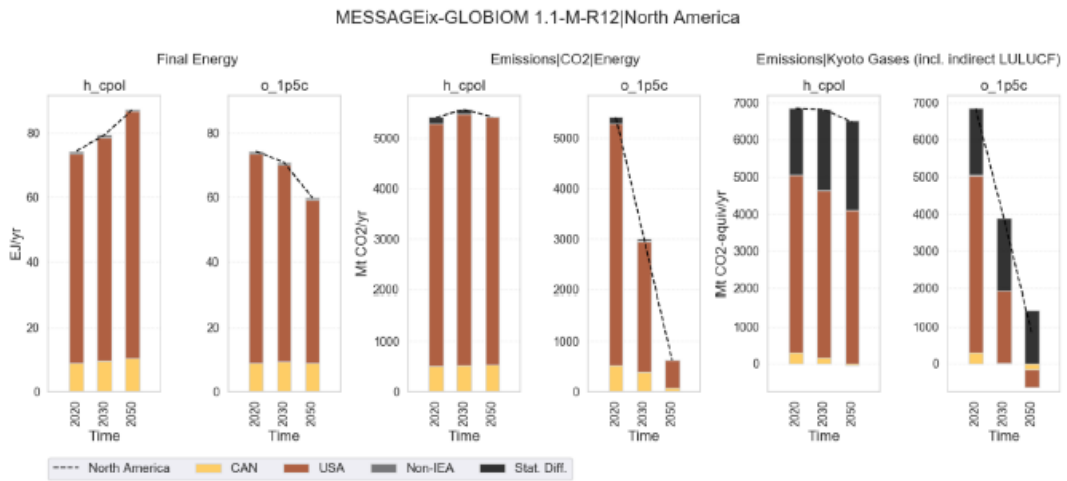
¹ <https://doi.org/10.5281/zenodo.10807824> (Richters et al., 2024)

Supplementary S4: Downscaled results for the remaining regions of the MESSAGE model

295 (A)

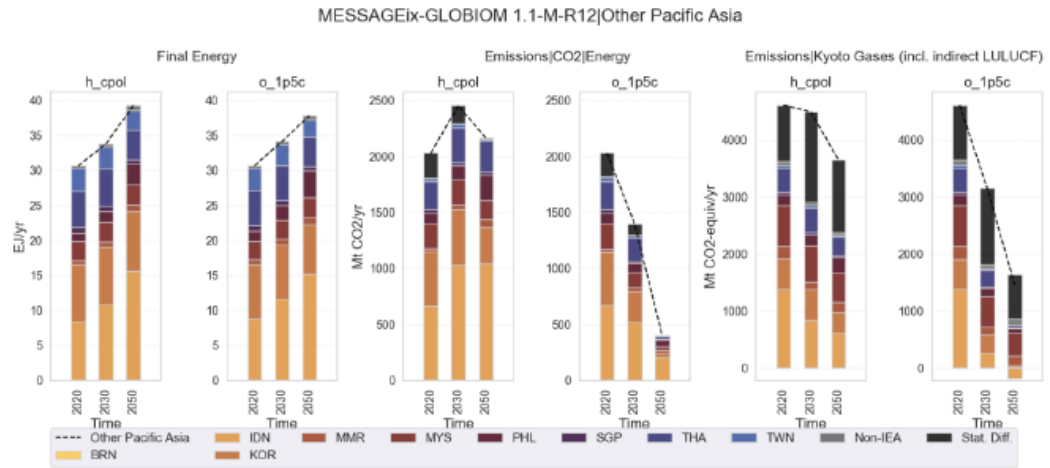


(B)

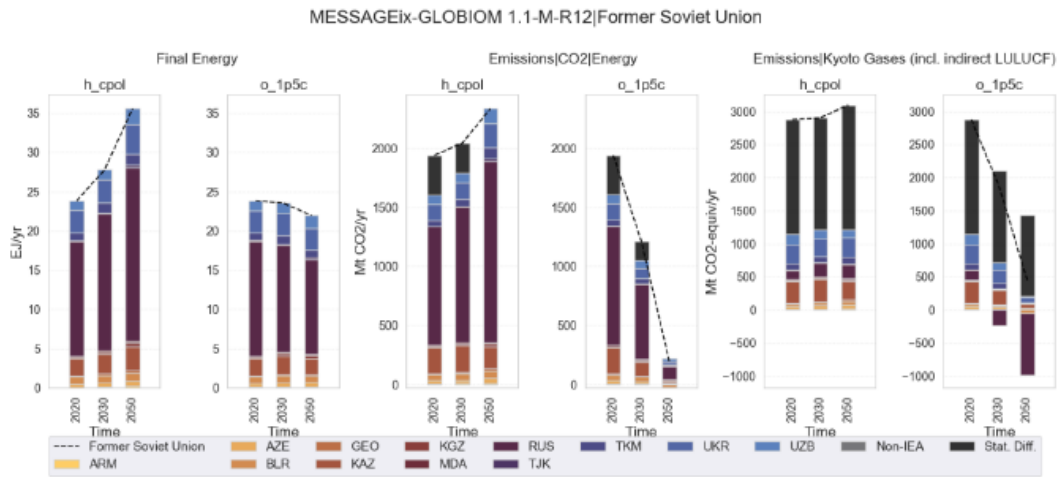


300

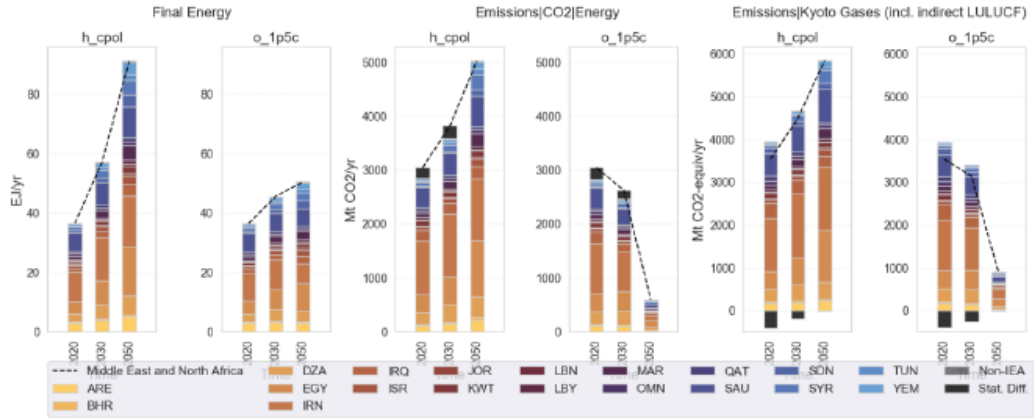
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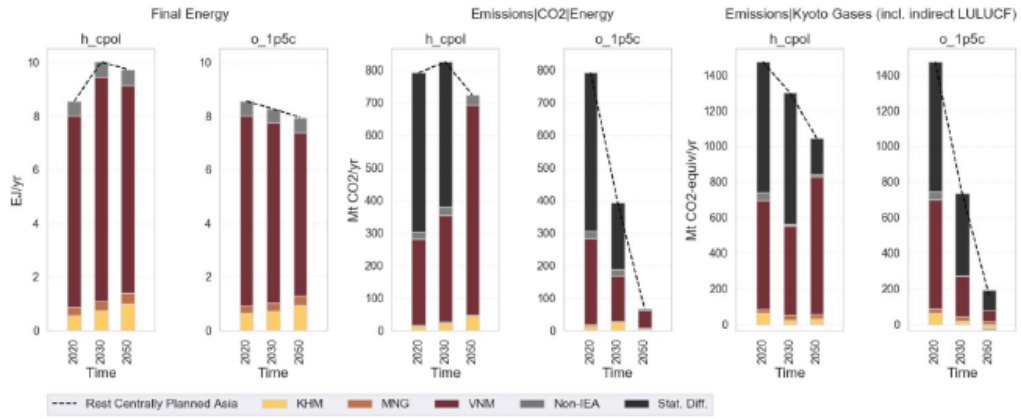
(D)

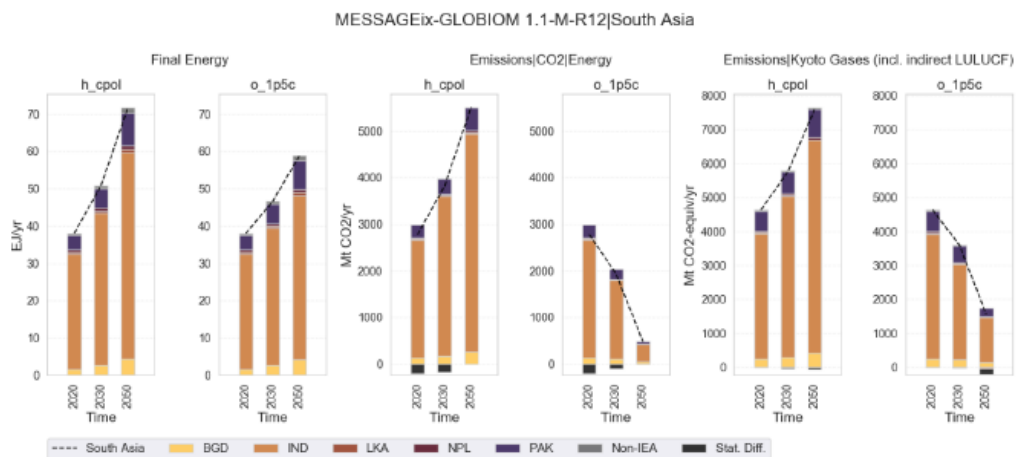


MESSAGEix-GLOBIOM 1.1-M-R12|Middle East and North Africa

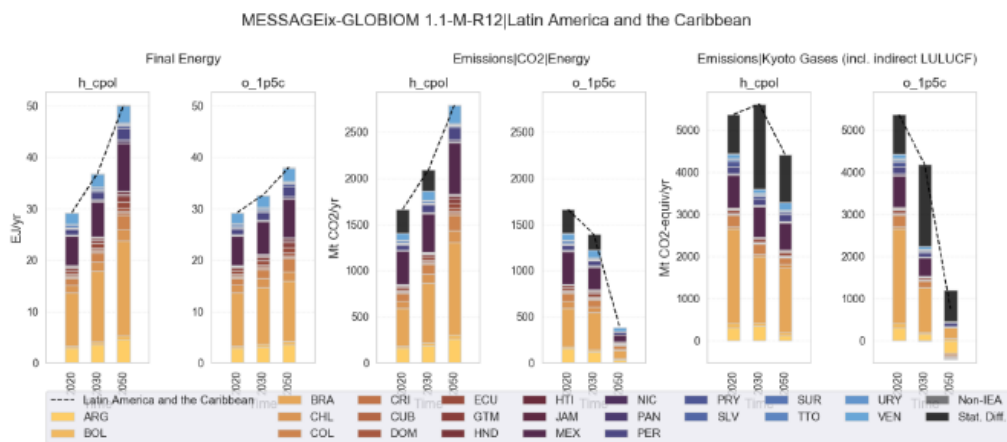


MESSAGEix-GLOBIOM 1.1-M-R12|Rest Centrally Planned Asia





H)



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Figure S15 Downscaled results for the remaining regions of the MESSAGE model: A) Eastern Europe, B) North America, C) Other Pacific Asia, D) Former Soviet Union, E) Middle East and North Africa, F) Rest of Centrally Planned Asia, G) South Asia, H) Latin America and the Caribbean.

The method for downscaling looks in general good and builds on earlier research. However, I think the methodology has some limitations and short-coming, in particular for the current policies and NDC scenarios. It would be valuable for the authors to include a discussion section addressing the limitations of the downscaling methodology. In this section, the authors could discuss the challenges and potential inconsistencies that arise when applying the methodology across regions with such diverse national circumstances, policies, and targets. This would provide a clearer understanding of the assumptions made and the trade-offs involved, especially when downscaling regional results to the country level. I have indicated my main comments below.

Response: Thank you for your feedback. We have added a “discussion” section to highlight challenges associated with the downscaling, pages 49-52:

"6 Discussion

In this study we downscale 12 MESSAGE regions to individual countries, to provide a consistent assessment of national pathways in line with the NGFS scenarios. We rely on the regional-country mapping definitions as provided by the IAM teams, which is based on the UN definition of countries (with associated ISO-3 codes). In addition, we rely on future socioeconomic projections from the SSPs storylines (Bauer et al., 2016, 2017; Fricko et al., 2017; Riahi et al., 2017a, b), and on historical data

from the International Energy Agency (IEA, 2022), which are not always available for all countries. It is also important to note that there are methodological challenges in translating idealized pathways (based on cost minimization or welfare maximization approaches) from global regions into plausible country level trajectories. DSCALE addresses this issue by combining historical trends with IAMs scenarios in a way that preserves realism, while remaining consistent with future regional pathways. To this end, in our default assumption, the energy intensity projections are modelled as a function of GDP per capita where steepest structural changes are assigned to higher-income countries, that are better equipped to lead the transition. Therefore, SSPs storylines play an important role when projecting final energy demand. The NGFS project relies on income per capita projections from the SSP2 (Middle of the road) storyline, where GDP per capita is generally assumed to grow across all countries. However, other SSP narratives like SSP3 (Fujimori et al., 2017b) or SSP4 (Calvin et al., 2017), may envision stagnation or decline in income per capita projections, hence affecting the pace of energy system transformation in some countries.

The relationship between energy intensity and GDP per capita has been widely assessed in the literature (Energy Inefficiency in the US Economy: A New Case for Conservation, 2024; Energy Primer. Online Textbook based on Chapter 1 of the Global Energy Assessment (GEA), 2021; Nakicenovic et al., 1990, 1998; Nakićenović et al., 1993). We apply similar relationships when downscaling final energy across different sectors (industry, transportation and residential & commercial) and energy carriers (electricity, liquids, solids, gases). However, these relationships may weaken as we go further with the disaggregation process, leading to higher uncertainty in future projections. To mitigate this issue, DSCALE ensures a strict order of disaggregation:

A. Total Final energy demand is downscaled first to serve as a constraint for energy carriers (e.g. electricity use cannot exceed total energy demand)

B. Energy carriers (e.g. electricity) are downscaled to serve as constraints for sectors

C. Final allocation to sectors, where the uncertainty is higher (e.g. electricity used in Industry), is bound by previous steps

This layered process, combined with regional constraints from IAMs (sum of country level results should align with regional data), limits the uncertainty range. Nonetheless, projections for highly disaggregated sectors remain more uncertain, and future work may consider using machine learning techniques to enhance robustness. However, the use of such methods may hinder the interpretability and transparency of the results.

Regarding national policies, DSCALE optionally integrates targets from NDCs (Nationally Determined Contributions) and LTS (Long Term Strategies). In this context, it should be noted that some countries express their NDCs targets as range, depending on the level of international climate finance. Due the ongoing stalemate in negotiations regarding finance, the NGFS project considers only unconditional NDC targets, and the DSCALE tool adopts the same approach.

Additionally, some countries specify their targets as a percentage reduction below a BAU (Business as Usual) scenario. In this context (Rogelj et al., 2017) emphasizes that the primary source of the uncertainty in the NDCs emissions range stems from the future socioeconomic assumptions. Under the NGFS project we use a consistent set of GDP and population projections across all countries, based on the SSP2 (Middle of the Road) storyline. This approach substantially reduces potential inconsistencies in the interpretation of NDCs targets.

This "national policy" feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work.

DSCALE operates under the assumption that countries can align emissions with their own NDC and LTS targets by increasing the use of BECCS (biomass with CCS), up to a maximum of 50% of the national emissions gap. It is important to note that DSCALE will not increase the overall amount of BECCS, as results must be aligned to match regional IAMs results. DSCALE can only allocate the

regional amount of BECCS across all countries within that region. This means that if BECCS is not available at the regional level in a given time period (e.g. 2030), it will not be allocated to any country, regardless of their emission gap. Moreover, DSCALE will maintain the same level of biomass that was initially allocated to each country (before the “national policy” adjustment): the only parameter that can vary is the percentage of biomass combined with CCS. This adjustment of BECCS is more relevant for countries meeting their net-zero targets and play a very limited role for meeting the NDC targets. A comparison of MESSAGE scenarios against official national projections from (Smith et al., 2025), reveals that downscaled BECCS results are generally lower than the level anticipated by governments by 2050. This comparison is available in the supplementary information S5. In conclusion, the amount of BECCS (biomass with CCS) cannot exceed the biomass already in use within each country, and the total BECCS collectively employed in all countries must align with regional IAMs results. These constraints effectively limit the use of BECCS in 2030 and ensure that the results remain plausible in the long term, including by mid-century.

In the NGFS project, negative emissions can be achieved only by using BECCS or via the land use sector. Additional CDR (Carbon Dioxide Removal) technologies (such as enhanced weathering, direct air capture etc.) are not considered by the NGFS scenarios nor by DSCALE.

Regarding land use emissions, different accounting schemes may be used. IAMs usually report only direct land use emissions, while national inventories normally report the sum of both direct and indirect emissions, leading to a global mismatch of about 5.5 GtCO₂ (Gidden et al., 2023; Grassi et al., 2021). To tackle this issue, we enrich the IAMs scenario data by providing downscaled land use emissions results that include both direct and indirect land use emissions. On the one hand, direct land use emissions are fully consistent with regional IAMs results, as their sum across countries matches the regional data. On the other hand, we add indirect land use emissions, which are not reported by IAMs (but that are included in national inventories). Projections of indirect land use emissions are affected by climate variables, including temperature and CO₂ concentration (Grassi et al., 2021) and therefore will vary across different NGFS scenarios. By using this approach, DSCALE provides national pathways that are consistent with IAMs scenarios (for the direct land use emissions component) and that are also harmonized with national inventories (by adding the indirect land use emissions component, not considered by IAMs).

Some parameters within DSCALE are currently set based on expert judgment. These include the default weights used to allocate electricity generation by fuel type, as well as assumptions regarding the time of convergence “tc”. Future work could focus on estimating these parameters empirically, through hindcasting analyses designed to maximize the overlap with observed historical data. However, these optimal configurations may vary based on the regional-country mapping used (hence across different models).

IAMs often provide results for various sets of regions. For instance, they usually provide aggregated results for the so-called “R5 regions”, which include OECD, Asia, Middle East and Africa, Latin America and Reforming Economies. At the same time, they offer more disaggregated “native” regions such as Western Europe, China, Sub-Saharan Africa, and Pacific OECD, in the case of MESSAGE. In this context, a country like Germany belongs to the “R5 OECD” region as well as the “Western Europe” region. In this context, we recommend downscaling the results from the more disaggregated (native) regions, such as “Western Europe”, to ensure consistency with the IAMs results. Moreover, it is important to note that there are different versions of IAMs and some of them can provide results for a handful of individual countries. In this case, we advise using IAMs results for these individual countries directly.

Finally, downscaled results represent a first order translation of IAM scenarios at the country level. These results are derived from top-down IAMs scenarios to evaluate the implications of global scenarios for national pathways. Future efforts may focus on integrating downscaled IAM results with bottom-up models, to analyse outcomes at a finer spatial scale (sub-regions), temporal scale (yearly, monthly, daily, hourly data), finer technological resolutions (e.g. different types of wind turbines, solar PV technologies), including impacts on air quality and on jobs. This would enable a

better assessment of the implications of climate change scenarios at the national scale, including potential co-benefits of mitigation strategies. “

Main general comments:

1/ I have a specific comment regarding the development of the NDC and current policies scenarios. To my knowledge, there is an established methodology for deriving emissions and energy targets for the MESSAGE regions based on countries' NDCs and current policy targets, as thoroughly described in the Methods section of Rogelj et al. (2017)

<https://www.nature.com/articles/ncomms15748> .

I think this is a solid method, as it requires calculating NDC targets based on all countries within a region. However, how does the methodology presented in this study relate to the downscaling method described here? Could it lead to inconsistencies between the countries' NDC targets (in terms of energy and emissions), which are used to construct the NDC scenario in the MESSAGE model, and the country-level results obtained after applying the downscaling method?

For example, if Argentina has an NDC target expressed as a range of emissions and this is used to construct the regional NDC target in the MESSAGE scenario, and then the regional LAM NDC target is downscaled back to Argentina, does the resulting target for Argentina still match its original NDC range? Similar concerns may arise for specific targets, such as renewable energy or non-fossil energy targets, particularly for countries like China and India, whose detailed national targets were used in the MESSAGE NDC scenario.

I think it would be important to address this potential issue and offer some reflection or discussion in the paper

Response: Thank you for highlighting the complex situation of aligning NDC outcomes in IAM outputs and country level results. We want to stress here first that the main objective of this manuscript is to document the methodology of downscaling in general, and not to evaluate the NDC targets of individual countries.

Running DSCALE with `national policy` is an optional downscaling feature, and it should be applied only if the IAMs embed national targets, like scenarios from the NGFS project.

Currently, DSCALE considers only economy-wide emissions targets. Lower-level sectorial targets (e.g. emissions standards in the transport sector) or energy targets (e.g. minimum share of renewable energy in the electricity mix) are an active area of further development beyond the basic method documented in this manuscript.

We clarified this in the paper (pages 50-51, lines 991-995):

“This "national policy" feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work.”

Regarding the interpretation of the emissions targets, all IAMs in the NGFS project (including MESSAGE) use unconditional targets for the NDC scenario, and the DSCALE algorithm follows the same approach. The paper from Rogelj et al. (2017) (<https://www.nature.com/articles/ncomms15748>), provides a very useful framework for addressing national policies and highlights that the dominant driver of the uncertainty in the NDCs emissions range lies in the future socioeconomic assumptions. Under the NGFS project we use consistent SSPs projections using an SSP2 (Middle of the Road) storyline, which reduces substantially the uncertainty on how to interpret the NDCs targets.

We have offered some reflections on this aspect in the `discussion` section (page 50, lines 982-990):

“Regarding national policies, DSCALE optionally integrates targets from NDCs (Nationally Determined Contributions) and LTS (Long Term Strategies). In this context, it should be noted that some countries express their NDCs targets as range, depending on the level of international climate finance. Due the ongoing stalemate in negotiations regarding finance, the NGFS project considers only unconditional NDC targets, and the DSCALE tool adopts the same approach.

Additionally, some countries specify their targets as a percentage reduction below a BAU (Business as Usual) scenario. In this context (Rogelj et al., 2017) emphasizes that the primary source of the uncertainty in the NDCs emissions range stems from the future socioeconomic assumptions. Under the NGFS project we use a consistent set of GDP and population projections across all countries, based on the SSP2 (Middle of the Road) storyline. This approach substantially reduces potential inconsistencies in the interpretation of NDCs targets.”

2/ Even more complicated: I think the methodology of Rogelj et al. is assumed also being used for the calculation of the policies scenarios of the MESSAGE model, where you also have countries with a region that have different types of current policies. Can you also discuss how the method for the construction of a policies scenario in MESSAGE relates to the method you use here to downscale the results back to the country level? For current policies scenario it becomes even more complicated given the diversity of energy targets from countries, within a region.

Response: Thank you for highlighting this, your point is very well taken.

DSCALE currently considers only economy-wide emissions targets, whereas the “current policy” scenario from the IAMs may encompass a variety of sectorial targets (e.g. renewables share and energy efficiency targets). For this reason, the downscaled results for the “current policy” scenario may not be fully aligned with sectorial targets at the country level.

This has been identified and discussed as area for further improvement, and we are currently working on enhancing the downscaling sectoral details of Current Policy and NDC targets. We have added a “discussion” section to highlight this issue (pages 50-51, lines 982-995):

“Regarding national policies, DSCALE optionally integrates targets from NDCs (Nationally Determined Contributions) and LTS (Long Term Strategies). In this context, it should be noted that some countries express their NDCs targets as range, depending on the level of international climate finance. Due the ongoing stalemate in negotiations regarding finance, the NGFS project considers only unconditional NDC targets, and the DSCALE tool adopts the same approach.

Additionally, some countries specify their targets as a percentage reduction below a BAU (Business as Usual) scenario. In this context (Rogelj et al., 2017) emphasizes that the primary source of the uncertainty in the NDCs emissions range stems from the future socioeconomic assumptions. Under the NGFS project we use a consistent set of GDP and population projections across all countries, based on the SSP2 (Middle of the Road) storyline. This approach substantially reduces potential inconsistencies in the interpretation of NDCs targets.

This "national policy" feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work.”

3/ An even more complex issue arises when considering the current policies scenarios. As I understand it, the methodology from Rogelj et al. is also used to construct the current policies scenarios in the MESSAGE model, where countries within a region may have a wide variety of policy types and targets. Could you also clarify how the methodology used to construct the policies scenario in MESSAGE relates to the approach you use here to downscale results back to the country level?

For the current policies scenario, this becomes even more challenging due to the diversity of national energy targets within a single region. For example, countries may differ not only in the stringency of their policies, but also in the type of targets—ranging from renewable energy shares, energy efficiency goals, to technology-specific commitments. How does the downscaling method account for these variations, and is there a risk of inconsistency between the country-level policies and the results obtained after regional aggregation and subsequent disaggregation? It would be valuable to discuss these complexities and reflect on the implications for the accuracy and credibility of the country-level results.

Response: Thank you for your comment. The current version of DSCALE uses the same economy-wide emission targets of the MESSAGE model. However, sectorial targets are not considered in DSCALE. This is clear area for further improvement (see response to comment 2/ above). We have discussed these complexities in the discussion section (pages 50-51, lines 990-995):

“This “national policy” feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work.”

4/ I find line 165 unclear—specifically the claim that the method “ensures that the sum of country-level results aligns with regional IAM outcomes.” If the NAT path method is used, as I understand it, the results are fully harmonized with historical national data, which differs from the model-simulated regional data. Therefore, I don’t see how the country-level results can be fully aligned with the regional IAM outcomes.

This issue seems particularly relevant for LULUCF emissions, where there is often a significant mismatch between national inventories and IAM data. In such cases, harmonizing to national inventories may actually increase the divergence from regional IAM totals rather than ensuring consistency. It would be helpful to clarify how this alignment is handled in practice, and whether deviations are allowed or corrected in the downscaling process

Response: Both the `NAT` and `IAMatt` paths are harmonized to match regional IAMs results. In a second step, these paths are merged into a `composite` path, using Eq.(1). Finally, the `composite` path is harmonized to match the historical data. We have clarified this in section 2.9 “Historical data harmonization” page 28, lines 601-605.

“As explained in the method section, both the “NAT” and “IAMatt” paths are harmonized to match regional IAMs results. These paths are then merged into a “composite” path, using Eq. (1). Finally, results from the “composite” path are harmonized to match historical data, using a base year of 2020.”

Regarding LULUCF emissions, IAMs provide results only for “direct” land use emissions, whereas national inventories consider the sum of “direct” and “indirect” emissions. This leads to a global mismatch of about 5.5 GtCO₂ (Grassi et al 2021), when comparing IAMs results with national inventories.

To address this issue, the downscaling algorithm enriches the IAMs results by adding the `indirect` emissions component:

- “Direct” emissions are fully harmonized with regional IAMs results
- “Indirect” emissions are harmonized to match historical inventories data.

Therefore, downscaled results are fully consistent with regional IAMs results when considering “direct” emissions only. And they are fully consistent with national inventories when considering the

sum of “direct” and “indirect” emissions. We have clarified this aspect in the discussion section (page 51, lines 1013-1022):

“Regarding land use emissions, different accounting schemes may be used. IAMs usually report only direct land use emissions, while national inventories normally report the sum of both direct and indirect emissions, leading to a global mismatch of about 5.5 GtCO₂ (Gidden et al., 2023; Grassi et al., 2021). To tackle this issue, we enrich the IAMs scenario data by providing downscaled land use emissions results that include both direct and indirect land use emissions. On the one hand, direct land use emissions are fully consistent with regional IAMs results, as their sum across countries matches the regional data. On the other hand, we add indirect land use emissions, which are not reported by IAMs (but that are included in national inventories). Projections of indirect land use emissions are affected by climate variables, including temperature and CO₂ concentration (Grassi et al., 2021) and therefore will vary across different NGFS scenarios. By using this approach, DSCALE provides national pathways that are consistent with IAMs scenarios (for the direct land use emissions component) and that are also harmonized with national inventories (by adding the indirect land use emissions component, not considered by IAMs).”

We have also clarified this in section 2.9 “historical data harmonization” (page 29, lines 612-624):
“While harmonizing the downscaled results to historical datasets, we create additional “statistical difference” variables, defined as the difference between IAMs results and the sum of (harmonized) country-level data across all regions. This statistical difference normally approaches zero by 2050 to preserve the long-term emissions from IAMs and implications for global warming. However, when downscaling total Kyoto Gases, the statistical difference captures “indirect” LULUCF emissions that are not included by IAMs. Currently, this different method leads to a mismatch of around 5.5 GtCO₂ globally (Grassi et al., 2021). To address this issue, the downscaling algorithm enriches the IAMs results by adding the “indirect” emissions component:

- *“Direct” emissions are fully harmonized, so that the sum across countries align with regional IAMs results*
- *“Indirect” emissions are harmonized to match historical inventories data (using a constant offset over time).*

Therefore, on the one hand downscaled results are fully consistent with regional IAMs results when considering “direct” land-use emissions only. On the other hand, they are aligned with national inventories when considering the sum of “direct” and “indirect” land-use emissions. “

5/ Related to 1/ . Line 305. How is the current policies scenario handled in cases where countries within a region have heterogeneous renewable energy (RE) targets? For example, some countries may have RE capacity targets (e.g., gigawatts of installed renewable capacity), others may define targets as a share of total energy or electricity, while some countries may not have any RE policies in place at all. For example, the MESSAGE region *Western Europe (WEUR)* includes Turkey, a country with national circumstances, NDC targets, and energy policies that differ significantly from those of the other countries in the region. How does the downscaling methodology account for this diversity in policy types and ambition levels when translating regional IAM results back to the country level? It would be helpful to clarify whether these differences are explicitly considered in the downscaling approach, and if so, how the method ensures consistency with the diverse national policy frameworks.

Response: The version of DSCALE documented in this manuscript only considers economy-wide emissions targets. It does not yet consider energy related (e.g. renewable energy) targets (please see response to comments 2/ and 3/). We have clarified this in the discussion section (pages 50-51, lines 991-995) and this is an important future development:

“This “national policy” feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the

MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work."

6/ Related to 1/ . How exactly is an NDC target scenario constructed in the model? Across regions, countries may have very different types of NDCs—some define absolute GHG reduction targets, others specify reductions relative to a BAU trajectory, while some have intensity targets, emissions ranges, or no quantitative targets at all. A clear example of regional heterogeneity can be seen in the MESSAGE region *Western Europe (WEUR)*, which includes Turkey alongside EU countries. Turkey's NDC target is notably less ambitious—set well above projected emissions under its current policies—whereas most EU countries have adopted far more stringent and ambitious targets that go well beyond their current policy trajectories. In constructing regional NDC scenarios, how are these diverse national targets aggregated?

I understand that one approach is to define regional targets based on countries' shares within a region. However, this raises questions when downscaling results back to the country level. How is the heterogeneity in target types handled in this process? For instance, if a region includes countries with absolute targets, BAU-relative targets, and countries without any targets, how are these differences reconciled when constructing a consistent regional pathway—and how is that pathway then fairly disaggregated back to the country level?

It would be useful to clarify how this is addressed in your methodology, particularly since the process seems to work in the opposite direction—from a harmonized regional target down to national implications—rather than aggregating national targets upward.

Response: DSCALE currently considers only economy-wide emission targets, which are exactly the same as those used in the MESSAGE models. However sectorial policies may not be fully aligned. We have clarified this in the discussion section (pages 50-51, lines 986-995):

"Additionally, some countries specify their targets as a percentage reduction below a BAU (Business as Usual) scenario. In this context (Rogelj et al., 2017) emphasizes that the primary source of the uncertainty in the NDCs emissions range stems from the future socioeconomic assumptions. Under the NGFS project we use a consistent set of GDP and population projections across all countries, based on the SSP2 (Middle of the Road) storyline. This approach substantially reduces potential inconsistencies in the interpretation of NDCs targets.

This "national policy" feature enhances the realism of the downscaled results. However, the current version of DSCALE only applies economy-wide targets consistent with the input assumptions of the MESSAGE model, while disregarding sectorial targets. Therefore, the overall national targets are consistent in both DSCALE and MESSAGE, although the sectorial targets may not be fully aligned. This is a clear area for improvement that we will address in future work."

Please also refer to responses to comments 1/ and 2

7/ I have serious concerns with the assumptions made in lines 505–520 regarding the use of BECCS to fill the emissions gap. The reliance on BECCS as a default option raises several questions. Could you provide a clear rationale for why BECCS is chosen in this context, rather than other mitigation measures—such as enhancing LULUCF sinks, which may be more immediately actionable or politically feasible in certain countries?

Moreover, for many countries, particularly those with rising emissions trajectories through 2025, it may already be unrealistic to achieve their NDC targets by 2030. In such cases, assuming that BECCS can simply "fill the gap" may not reflect real-world feasibility, given the technological, economic, and land-use constraints associated with large-scale BECCS deployment—especially in the near term.

It would be important to acknowledge these limitations and provide a more transparent justification for this modeling choice, or at least discuss the implications and alternatives.

Response: Thank you, if DSCALE worked as you describe here, we would also be concerned. Hence, we'll try to clarify here and have addressed this issue in the discussion section (page 51, lines 995-1010):

“DSCALE operates under the assumption that countries can align emissions with their own NDC and LTS targets by increasing the use of BECCS (biomass with CCS), up to a maximum of 50% of the national emissions gap. It is important to note that DSCALE will not increase the overall amount of BECCS, as results must be aligned to match regional IAMs results. DSCALE can only allocate the regional amount of BECCS across all countries within that region. This means that if BECCS is not available at the regional level in a given time period (e.g. 2030), it will not be allocated to any country, regardless of their emission gap. Moreover, DSCALE will maintain the same level of biomass that was initially allocated to each country (before the “national policy” adjustment): the only parameter that can vary is the percentage of biomass combined with CCS. This adjustment of BECCS is more relevant for countries meeting their net-zero targets and play a very limited role for meeting the NDC targets. A comparison of MESSAGE scenarios against official national projections from (Smith et al., 2025), reveals that downscaled BECCS results are generally lower than the level anticipated by governments by 2050. This comparison is available in the supplementary information S5. In conclusion, the amount of BECCS (biomass with CCS) cannot exceed the biomass already in use within each country, and the total BECCS collectively employed in all countries must align with regional IAMs results. These constraints effectively limit the use of BECCS in 2030 and ensure that the results remain plausible in the long term, including by mid-century.”

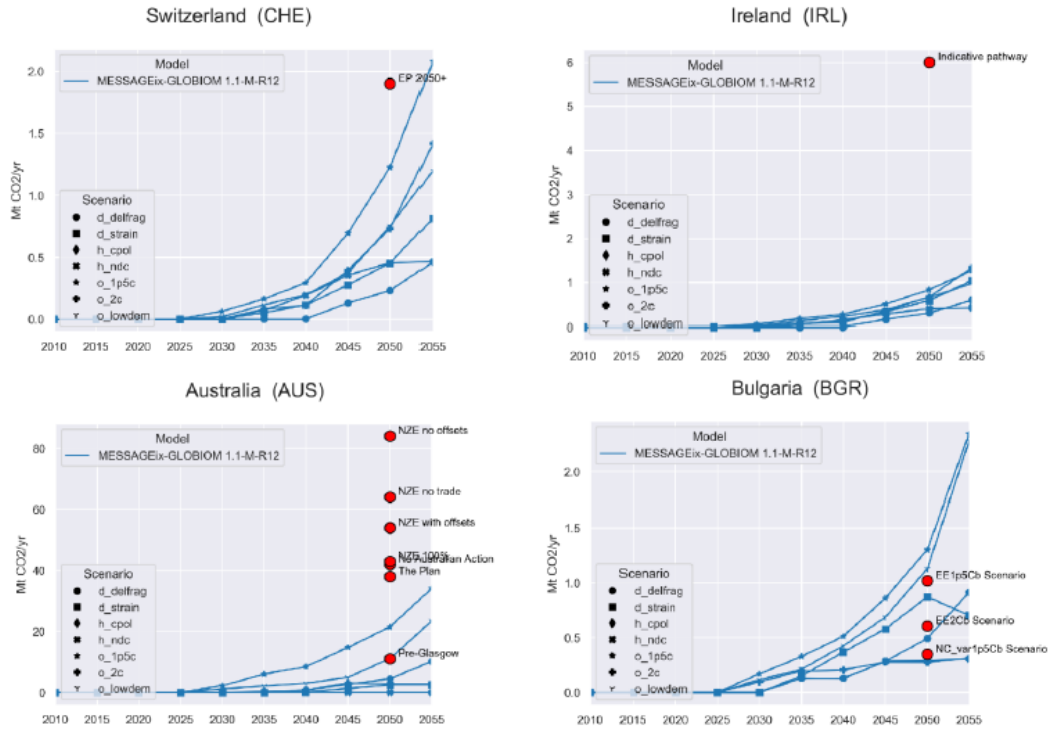
First, DSCALE only re-allocates BECCS within a region, and to the extent it is available in the underlying IAM scenario (which is often quite limited in the near-term). This means that if BECCS is not available at the regional level in a given time period (e.g. 2030), it cannot be allocated to any country. Second, DSCALE only re-allocates BECCS to countries where bioenergy is already available based on the allocations before running the policy-adjustment: the only parameter that we here vary is the share of CCS within total biomass. At the same time, the total amount of BECCS across countries needs to match the regional IAMs results. This adjustment of BECCS is more relevant for countries meeting their net-zero targets, and plays a very limited role for meeting NDC targets. Finally, we added comparisons of downscaled BECCS results against government's projections in the supplementary information S5. This comparison shows that downscaled BECCS results (blue lines) are usually lower than the official mid-century projections from Governments (Smith et al., 2025)² (red circles):

² Smith, H. B., Vaughan, N. E., and Forster, J.: A dataset of emissions and removals from scenarios and pathways within long-term national climate strategies – the LTS-SP dataset, *Sci. Data*, 12, 485, <https://doi.org/10.1038/s41597-025-04804-4>, 2025.

330 **Supplementary S5: Comparison of downscaled BECCS (Biomass with CCS) results against Government projections**

This section compares downscaled BECCS results (across all MESSAGE scenarios) against Government projections. This comparison is limited to countries for which we have BECCS projections available from (Smith et al., 2025)¹. Please note that the dataset from (Smith et al., 2025) reports negative values for BECCS, while the NGFS project convention is to report these values as positive. Therefore, we compare the data by using the absolute values, as shown in the figure below.

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¹ Smith, H. B., Vaughan, N. E., and Forster, J.: A dataset of emissions and removals from scenarios and pathways within long-term national climate strategies – the LTS-SP dataset, *Sci. Data*, 12, 485, <https://doi.org/10.1038/s41597-025-04804-4>, 2025.

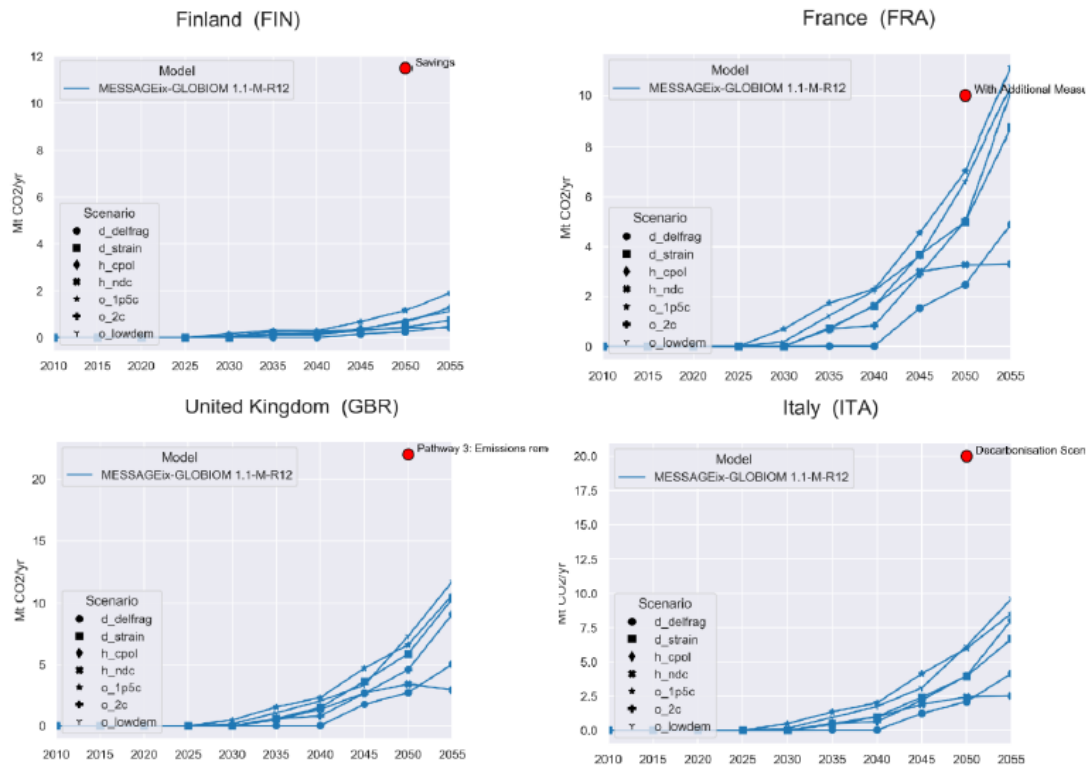


Figure S15 Comparison of downscaled 'Carbon Sequestration CCS|Biomass' results (blue lines) against Government projections (red circles) from (Smith et al., 2025), for all MESSAGE scenarios: delayed transition (d_delfrag), fragmented world (d_strain), current policy (h_cppl), Nationally Determined Contributions (h_ndc), Net Zero 1.5C (o_1p5c), Below 2C (o_2c), Low demand (o_lowdem).

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In conclusion, the amount of BECCS (biomass with CCS) cannot exceed the amount of biomass already downscaled to each country, and the total BECCS collectively employed in all countries must align with regional IAMs results. These constraints effectively limit the use of BECCS in 2030 and ensure that the results remain plausible in the long term, including by mid-century. Regarding the land use sector, we are exploring ideas on how to enhance the downscaling of land use emissions (so that can be used for meeting domestic targets). This could be done by coupling DSCALE with a detailed land use model or by using supply-cost curves. This would be a nice feature, and something to be considered for future work.