

Supplementary information to "Fast energy transitions can reduce climate tipping risks"

Hauke Schlesier^{*1,2}, Nico Wunderling^{*3,4,5}, Gonzalo Guillén-Gosálbez², Harald Desing¹

¹ Technology and Society Laboratory, Empa – Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland

² Institute for Chemical and Bioengineering, Department of Chemistry and Applied Biosciences, ETH Zürich, Zürich, Switzerland.

³ Center for Critical Computational Studies, Goethe University Frankfurt, Frankfurt am Main, Germany

⁴ Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany

⁵ Senckenberg Research Institute and Natural History Museum, Member of the Leibniz Association, Frankfurt am Main, Germany

* corresponding author:

hauke.schlesier@empa.ch

wunderling@c3s.uni-frankfurt.de

Contents

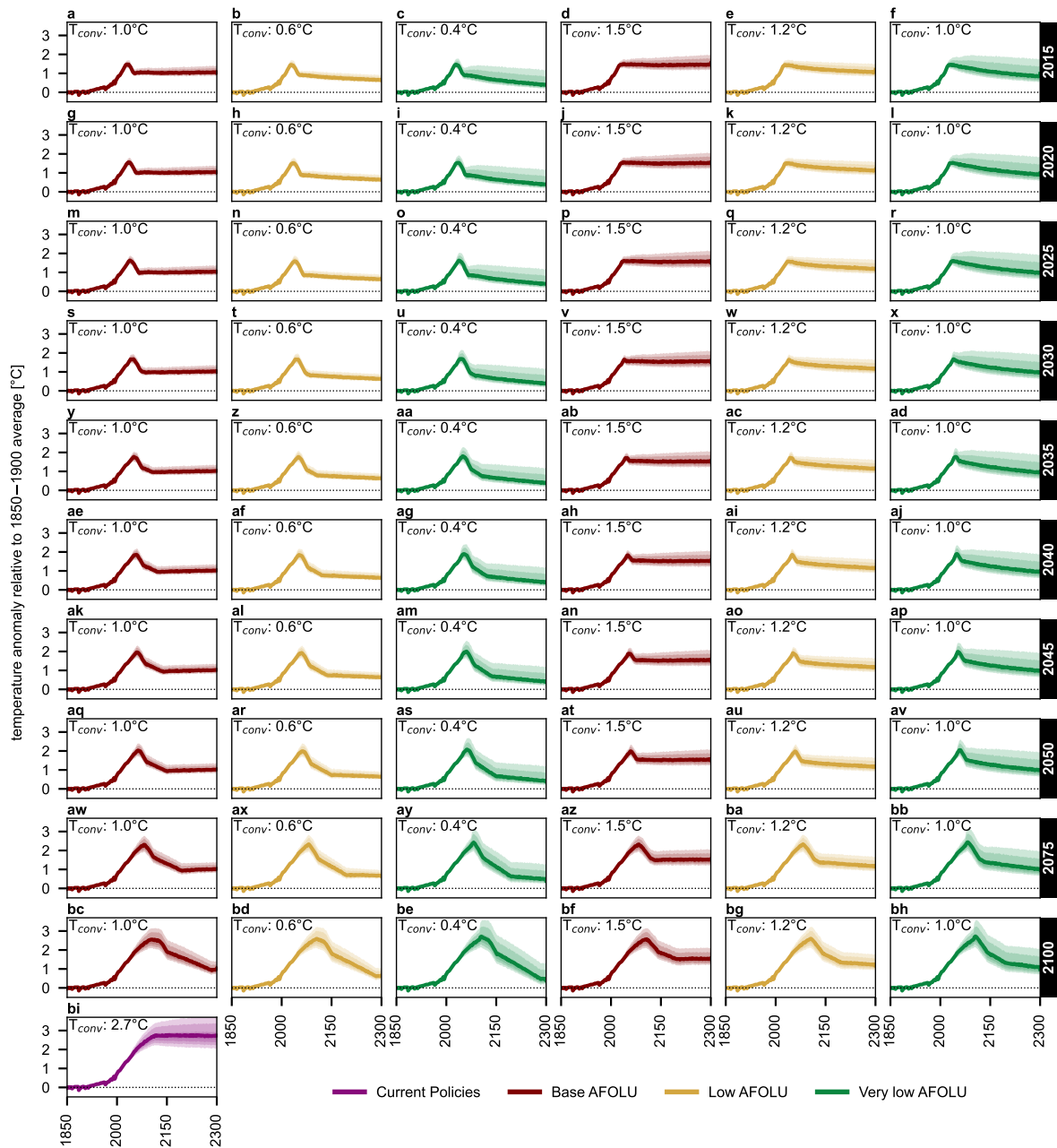
Supplementary Tables	2
Supplementary Table 1: Physical interaction mechanisms between tipping elements.	2
Supplementary Figures	3
Supplementary Figure 1: Temperature trajectory for investigated scenarios.	3
Supplementary Figure 2: Emission pathways for fast energy transition scenarios.	4
Supplementary Figure 3: Medium-term tipping risks for pathways aiming at 1.0°C	5
Supplementary Figure 4: Short-term tipping risks for pathways aiming at 1.0°C	6
Supplementary Figure 5: Long-term tipping risks for pathways aiming at 1.5°C	7
Supplementary Figure 6: Short-term tipping risks for pathways aiming at 1.5°C	8
Supplementary Figure 7: Medium-term tipping risks for pathways aiming at 1.5°C	9
Supplementary Figure 8: Sensitivity of tipping risk regarding emissions from agriculture, forestry, and other land use emissions (AFOLU)	10
Supplementary Figure 9: Tipping risk increase with peak and convergence temperature.	11
Supplementary Figure 10: Energy demand for DACCS	12
Supplementary Figure 11: Exceedance of geological carbon storage capacity under current policies	12
Supplementary Figure 12: Comparison to Integrated Assessment Model scenarios	13
Supplementary References	14

Supplementary Tables

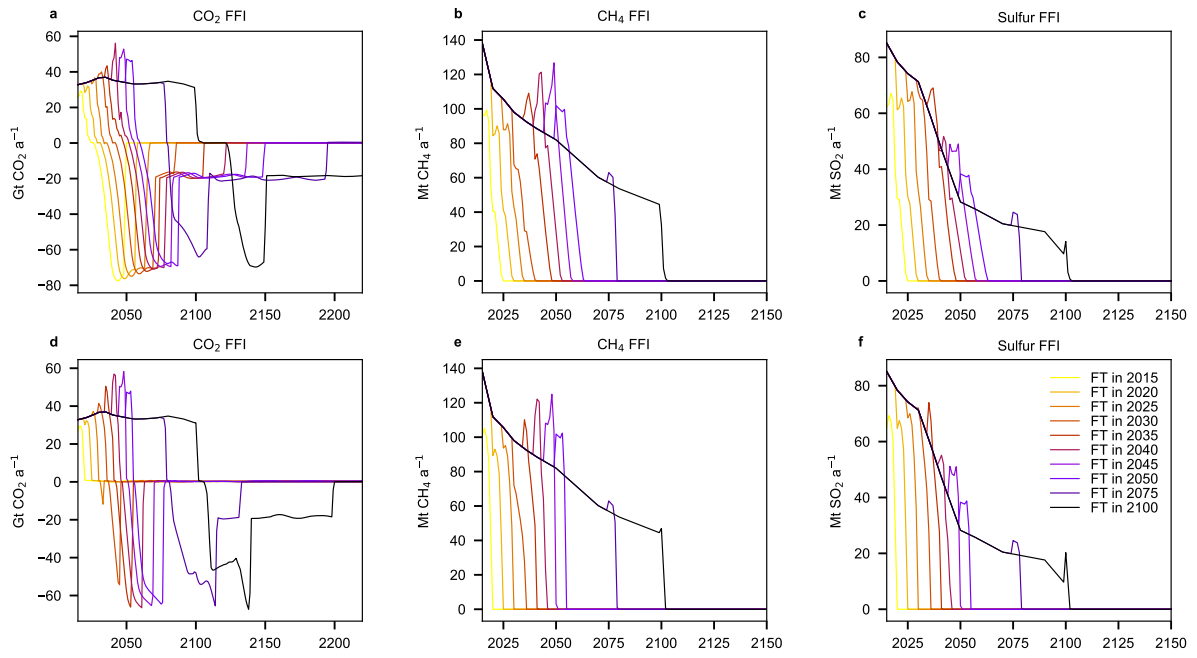
Supplementary Table 1: **Physical interaction mechanisms between tipping elements.** Link strengths of the magnitude of 1 means that the interaction is as strong as the intrinsic dynamic of the tipping element. Positive values indicate destabilizing interactions, negative values indicate a stabilizing effect. GIS=Greenland Ice Sheet, AMOC=Atlantic Meridional Overturning Circulation, WAIS=West Antarctic Ice Sheet, AMAZ=Amazon rain forest.

Interaction from	Interaction to	Link strength [min., max.]	Physical mechanism	Data source
GIS	AMOC	[0.1, 1.0]	Freshwater flux increase	1
GIS	WAIS	[0.1, 1.0]	Sea level rise	1
AMOC	GIS	[-1.0, -0.1]	Reduced heat transfer	1
AMOC	WAIS	[0.1, 0.15]	Southern ocean heat accumulation	1
AMOC	AMAZ	[-0.4, 0.4]	Precipitation change	1
WAIS	AMOC	[-0.3, 0.3]	Increased salinity gradient and advection of freshwater anomaly	1
WAIS	GIS	[0.1, 0.2]	Sea level rise	1

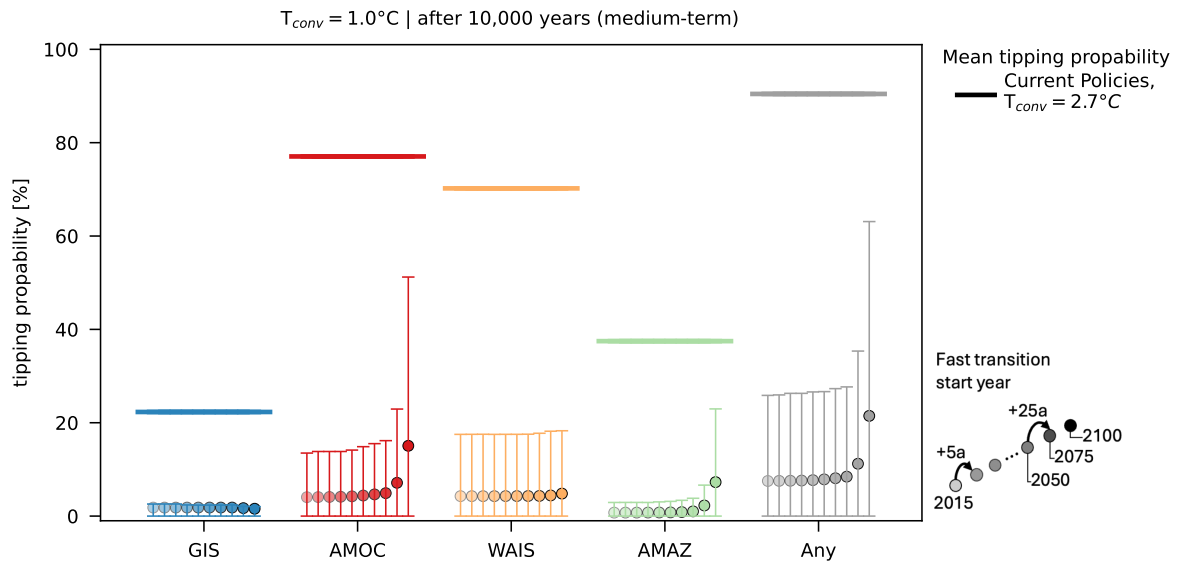
Supplementary Figures



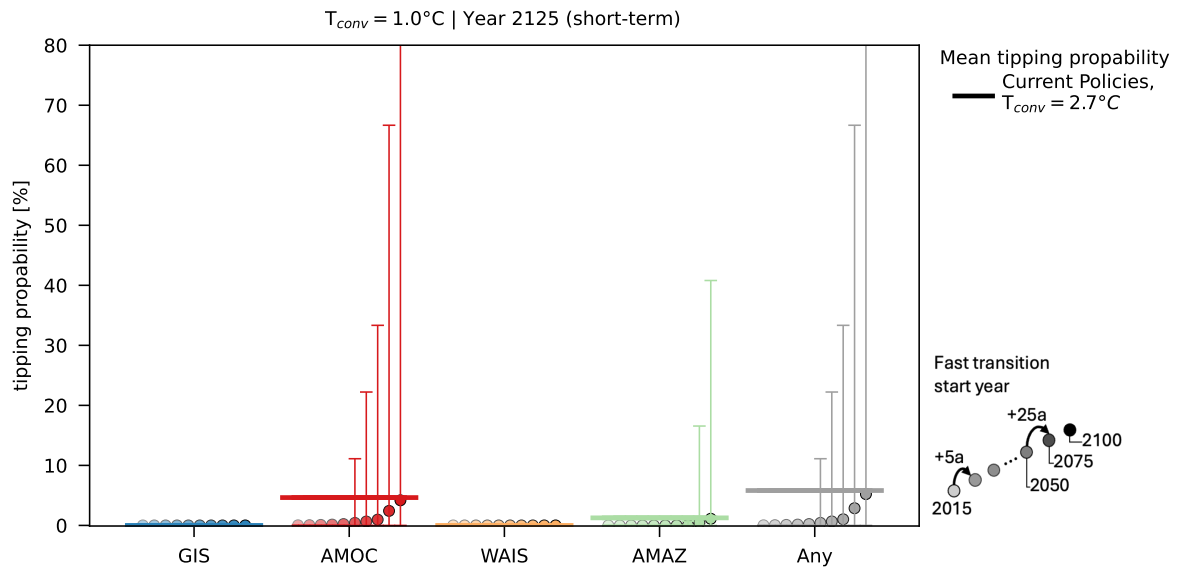
Supplementary Figure 1: **Temperature trajectories of investigated scenarios.** Temperature trajectories of 41 emission pathways of the main ensemble and 20 additional 'very low' AFOLU emission pathways assuming the 5th percentile of AR6 C1/C2 emissions pathways² (shaded areas depict 1st to 9th temperature decile). Rightmost boxtitles show the fast transition start year for pathways in the corresponding row. We extend the trajectories by 50,000 years at their 2300 levels. Data source for (bi) Current Policies pathway: ref.² t_{start} =fast transition start year, T_{conv} =convergence temperature, AFOLU=agricultural, forestry, and other land use emissions.



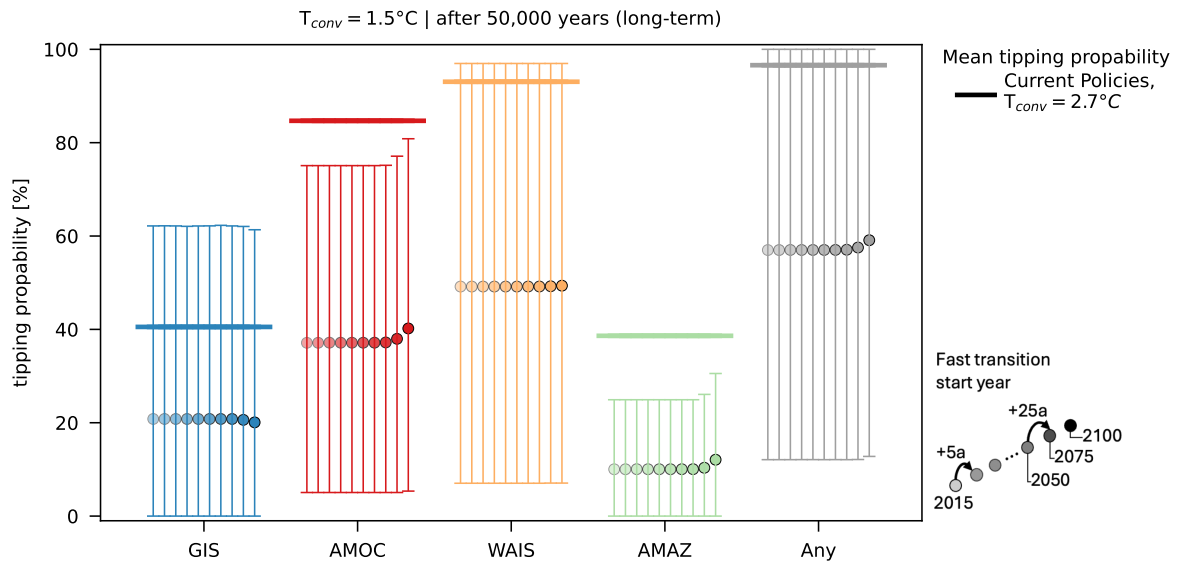
Supplementary Figure 2: **Emission pathways for fast energy transition scenarios.** Emission time-series from 2015 to 2300 for fast transition (FT) scenarios returning to (a–c) 1.0°C and (d–f) 1.5°C. The 3-Machine energy transition model³ accounts for (a, d) CO₂, for (b, e) methane (CH₄), and (c, f) sulfur emissions from fossil fuels and industry (FFI).



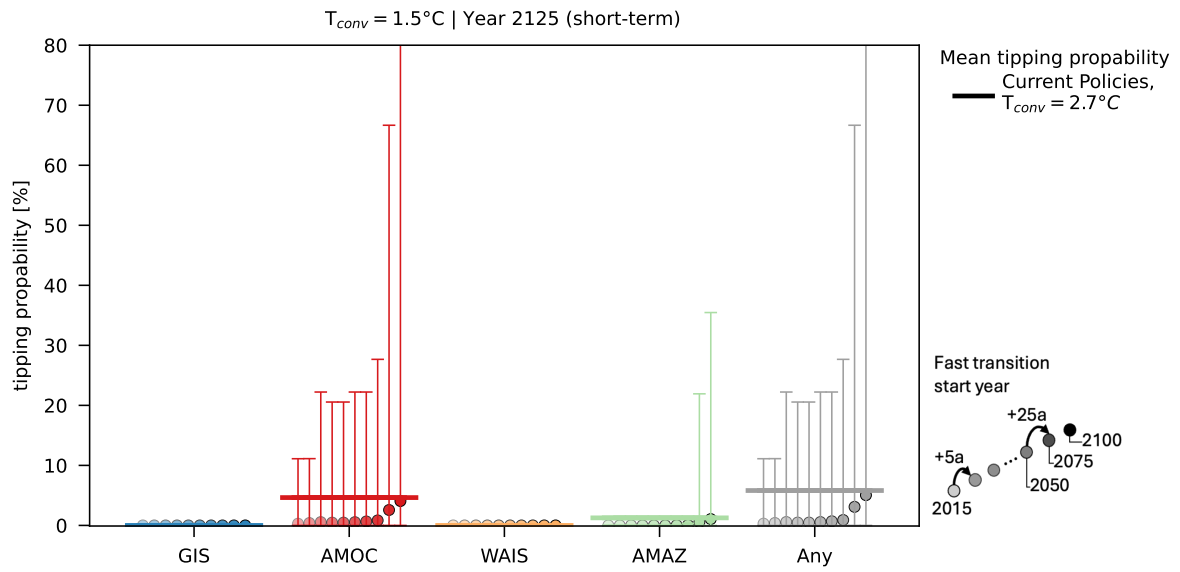
Supplementary Figure 3: **Medium-term tipping risks for pathways aiming at 1.0°C .** Dots show medium-term (10,000 years after 2025) mean tipping probability of fast energy transition pathways aiming at 1.0°C (median temperature trajectory) starting in 2025 to 2050 in five year intervals plus the years 2075 and 2100. Error bars show 10th to 90th percentile of tipping probability. Tipping probability uncertainty is captured using a Monte Carlo of $N=500$, with Latin hypercube sampling within elicited range of critical temperatures, tipping timescales, and the link strength between tipping element interactions. The horizontal lines show the mean tipping probability of the Current Policies pathway. T_{conv} =convergence temperature, a=year.



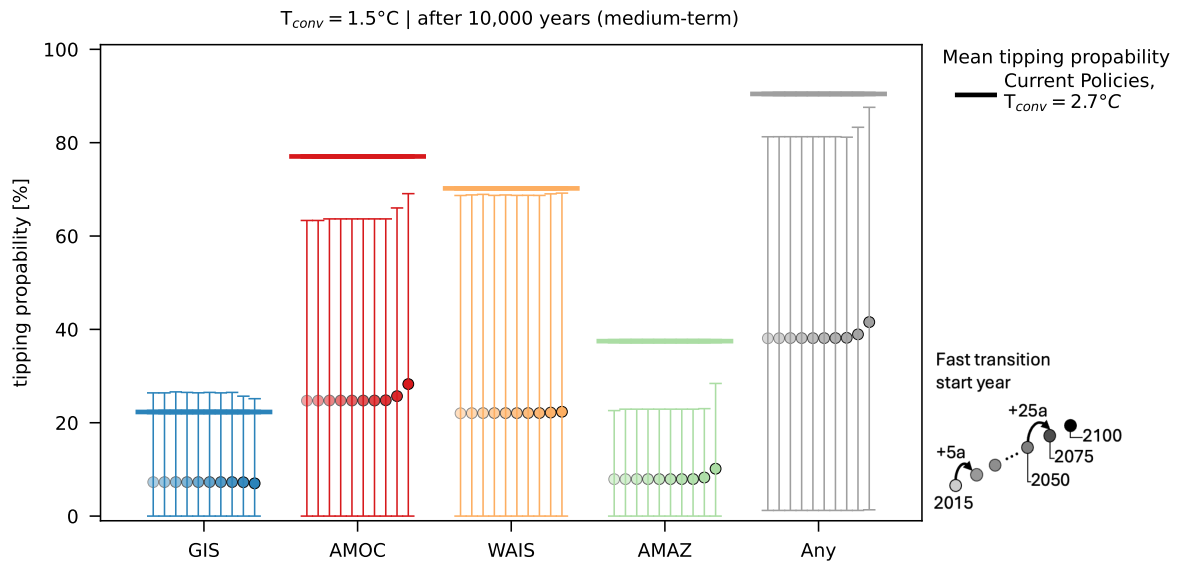
Supplementary Figure 4: **Short-term tipping risks for pathways aiming at 1.0°C.** Dots show short-term (next hundred years from 2025) mean tipping probability of fast energy transition pathways aiming at 1.0°C (median temperature trajectory) starting in 2025 to 2050 in five year intervals plus the years 2075 and 2100. Error bars show 10th to 90th percentile of tipping probability. Tipping probability uncertainty is captured using a Monte Carlo of N=500, with Latin hypercube sampling within elicited range of critical temperatures, tipping timescales, and the link strength between tipping element interactions. The horizontal lines show the mean tipping probability of the Current Policies pathway. T_{conv} =convergence temperature, a=year.



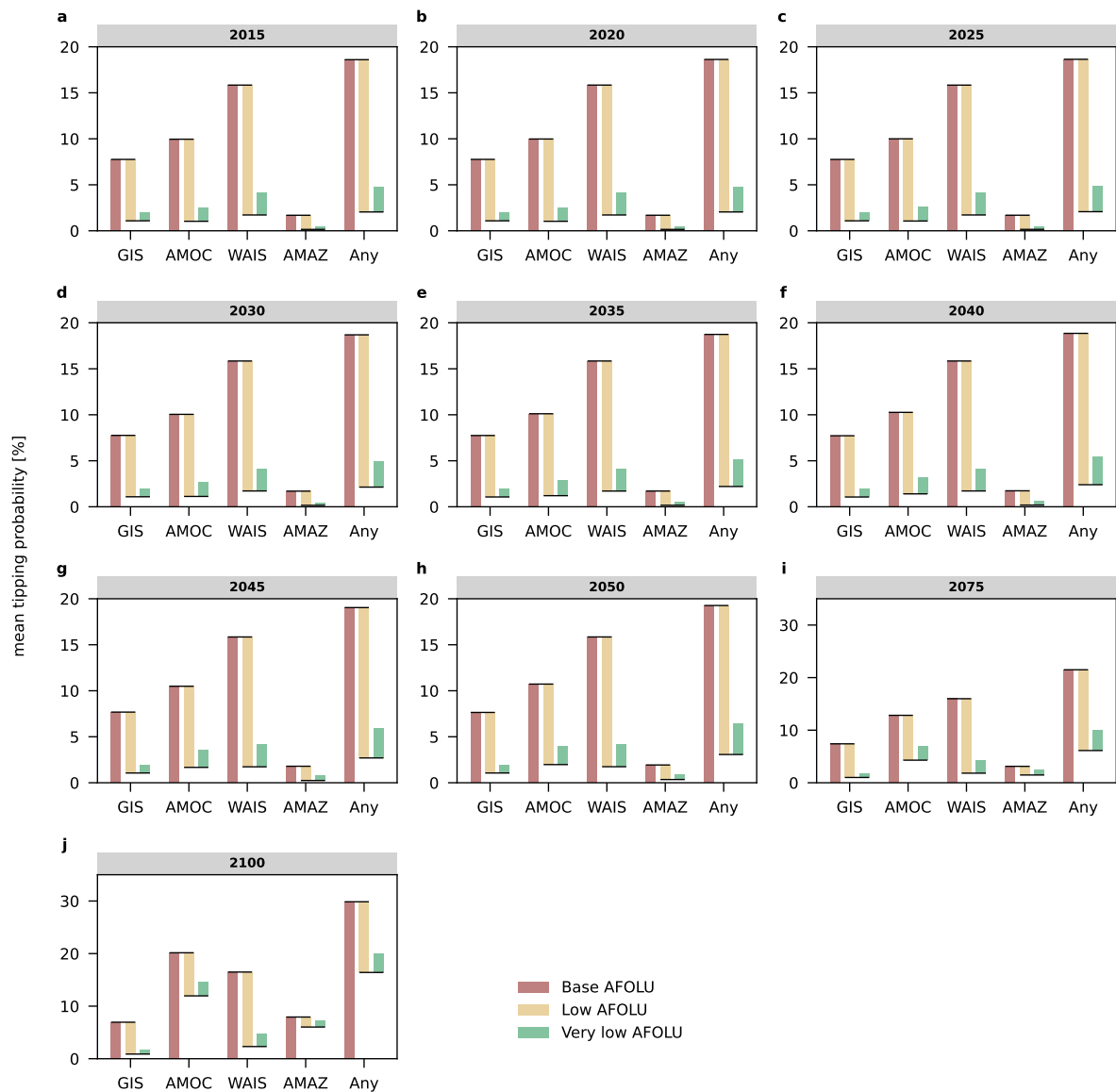
Supplementary Figure 5: **Long-term tipping risks for pathways aiming at 1.5°C.** Dots show long-term (50,000 years after 2025) mean tipping probability of fast energy transition pathways aiming at 1.5°C (median temperature trajectory) starting in 2025 to 2050 in five year intervals plus the years 2075 and 2100. Error bars show 10th to 90th percentile of tipping probability. Tipping probability uncertainty is captured using a Monte Carlo of N=500, with Latin hypercube sampling within elicited range of critical temperatures, tipping timescales, and the link strength between tipping element interactions. The horizontal lines show the mean tipping probability of the Current Policies pathway. T_{conv}=convergence temperature, a=year.



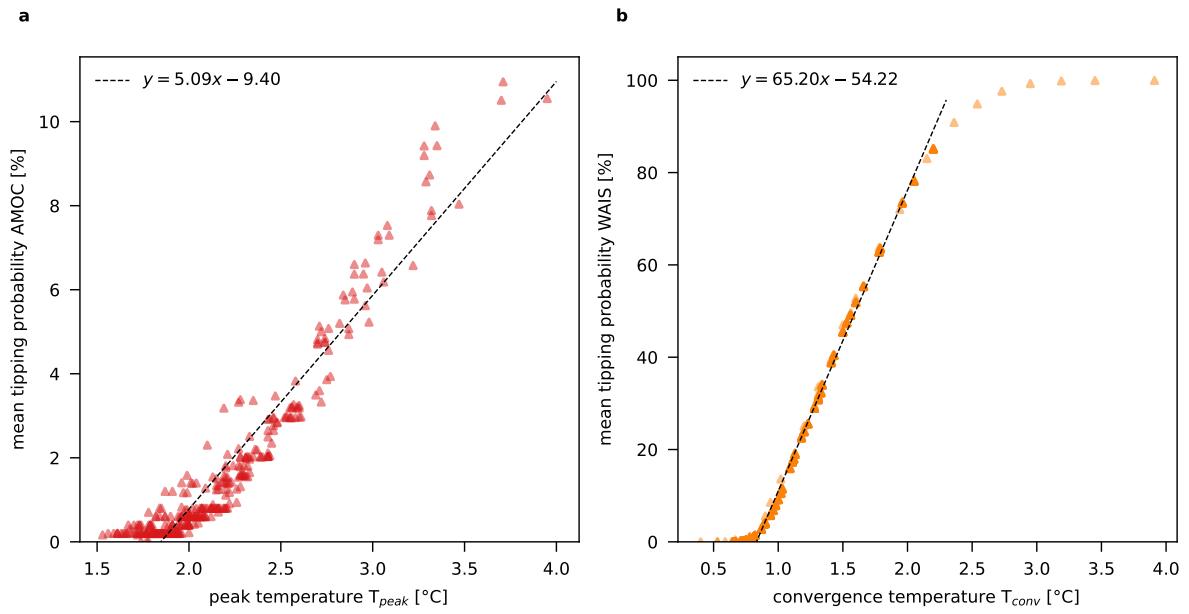
Supplementary Figure 6: **Short-term tipping risks for pathways aiming at 1.5°C.** Dots show short-term (next hundred years from 2025) mean tipping probability of fast energy transition pathways aiming at 1.5°C (median temperature trajectory) starting in 2025 to 2050 in five year intervals plus the years 2075 and 2100. Error bars show 10th to 90th percentile of tipping probability. Tipping probability uncertainty is captured using a Monte Carlo of N=500, with Latin hypercube sampling within elicited range of critical temperatures, tipping timescales, and the link strength between tipping element interactions. The horizontal lines show the mean tipping probability of the Current Policies pathway. T_{conv} =convergence temperature, a=year.



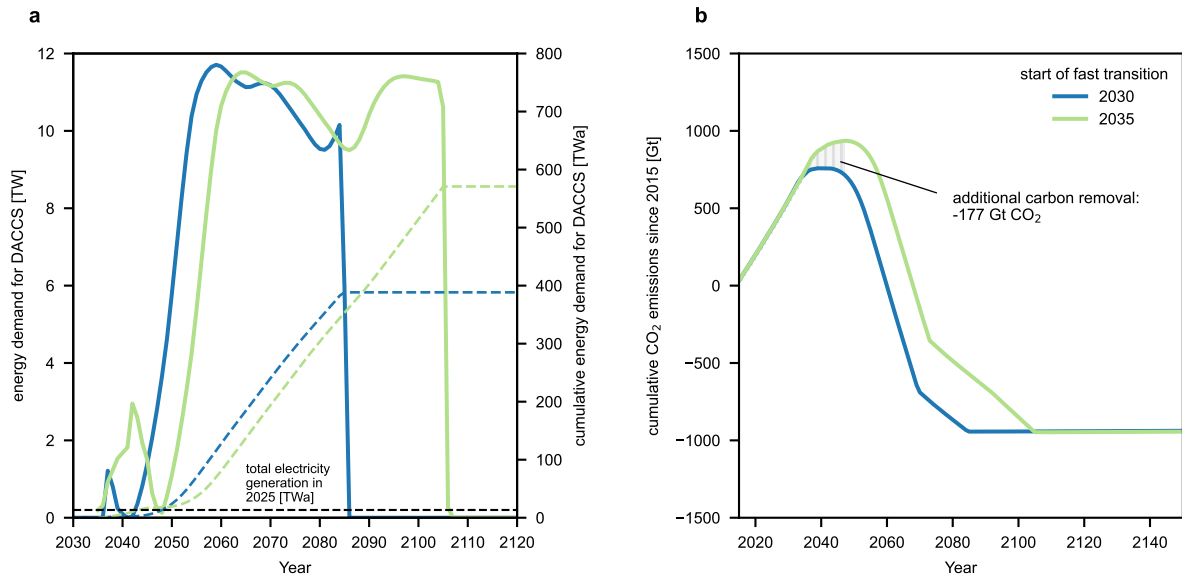
Supplementary Figure 7: **Medium-term tipping risks for pathways aiming at 1.5°C.** Dots show medium-term (10,000 years after 2025) mean tipping probability of fast energy transition pathways aiming at 1.5°C (median temperature trajectory) starting in 2025 to 2050 in five year intervals plus the years 2075 and 2100. Error bars show 10th to 90th percentile of tipping probability. Tipping probability uncertainty is captured using a Monte Carlo of N=500, with Latin hypercube sampling within elicited range of critical temperatures, tipping timescales, and the link strength between tipping element interactions. The horizontal lines show the mean tipping probability of the Current Policies pathway. T_{conv}=convergence temperature, a=year.



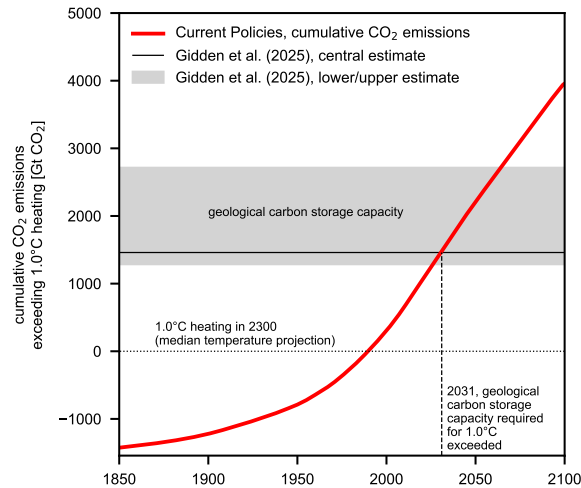
Supplementary Figure 8: **Sensitivity of tipping risk regarding emissions from agriculture, forestry, and other land use emissions (AFOLU).** The leftmost bars (red) show the mean long-term (after 50,000 years) tipping probability of a fast energy transition starting in different years (a–j) and base AFOLU emissions (95th percentile of C1/C2 scenarios²) for each tipping element and for tipping at least one element ('Any'). The yellow and green bars show the change in mean long-term tipping probability when reducing AFOLU to 'low' (median of C1/C2 scenarios) and 'very low' levels (5th percentile of C1/C2 scenarios²), respectively.



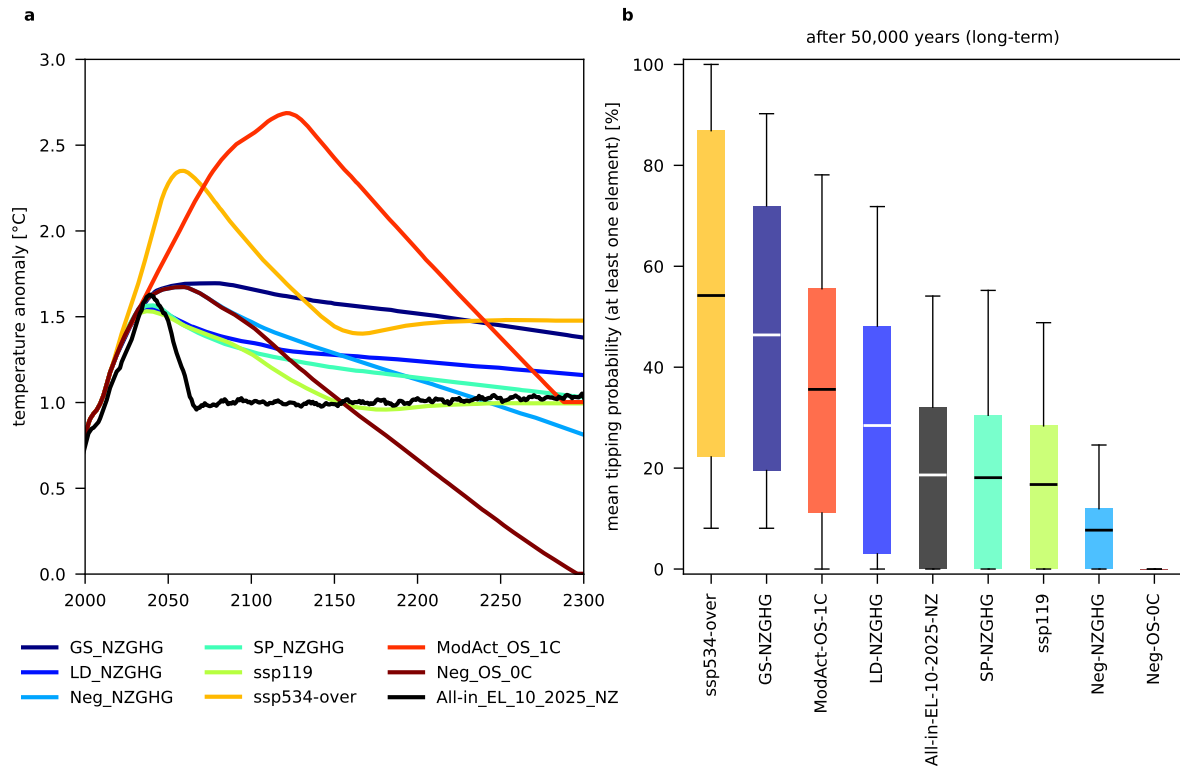
Supplementary Figure 9: **Tipping risk increase with peak and convergence temperature.** **a**, Short-term (year 2125) mean tipping probability for tipping the Atlantic Meridional Overturning Circulation (AMOC) over peak temperature for 549 individual temperature trajectories (61 scenarios $\times$ 9 temperature deciles; Supplementary Fig. 1). Dotted line shows linear best fit in the range of 1.8–4.0°C peak temperature. **b**, Long-term (50,000 years after 2025) mean tipping probability for tipping the West Antarctic Ice Sheet over convergence temperature for 549 individual temperature trajectories. Dotted line shows linear best fit in the range of 0.8–2.3°C convergence temperature.



Supplementary Figure 10: **Energy demand for DACCS.** **a**, Energy demand for operating the global capacity of direct air capture and carbon storage (DACCS) in fast energy transition scenarios starting in 2030 and 2035 (power input: solid line, cumulative energy demand: dashed line). For comparison, the total global electricity generation in 2025 is shown as a black dashed line (Data source: ref. ⁴). TWa=Terawatt years. **b**, Cumulative energy-related carbon emissions since 2015 in fast energy transition scenarios starting in 2030 and 2035. Hatched area shows additional carbon removal required for reaching 1.0°C heating.



Supplementary Figure 11: **Exceedance of geological carbon storage capacity under current policies.** The red line shows the cumulative CO₂ emissions after exceeding 1.0°C (median temperature projection in 2300; equivalent to 1543 Gt CO₂) from fossil fuels, agriculture, forestry, and other land use emissions from 1850 on when following current policies (see Methods section in main manuscript for details). The black line shows the central estimate of the global carbon storage capacity in geological formations according to ref. ⁵ (gray shaded area shows lower and upper estimate).



Supplementary Figure 12: **Comparison to Integrated Assessment Model scenarios.** **a**, Temperature trajectories (median projection) of extended Integrated Assessment Model (IAM) scenarios (data source: ref.⁶) and fast energy transition in 2025 (*All-in_EL_10_2025_NZ*). **b**, Tipping probability distribution for tipping at least one out of four tipping elements. Box shows inter-quartile range, line shows mean probability, and whiskers show 10th to 90th percentile (N=500; Monte Carlo simulation across elicited range of critical temperatures, tipping timescales, and link strength). Details on IAM scenarios in ref.⁷ SSP=Shared Socio-economical Pathway; RCP=Representative concentration pathway; ssp534-over=SSP5 'Fossil-fueled development' RCP 3.4 W/m overshoot; GS-NZGHG=Gradual strengthening net-zero greenhouse gas emissions; ModAct-OS-1C=Moderate action, overshoot 1°C; LD-NZGHG=Low demand net-zero greenhouse gases; All-in-EL-10-2025-NZ=All-in energy limit, 1.0°C fast transition start 2025, net-zero; SP-NZGHG=Shifting pathways net-zero greenhouse gases; ssp119=SSP1 'Sustainability' RCP 1.9 W/m; Neg-NZGHG=Negative emissions net-zero greenhouse gases; Neg=OS-0C=Negative emissions, overshoot then decline to 0°C.

Supplementary References

- [1] E. Kriegler *et al.* *Imprecise probability assessment of tipping points in the climate system*. Proc. Natl. Acad. Sci. U.S.A. **106**, 5041–5046 (2009). <https://doi.org/10.1073/pnas.0809117106>.
- [2] E. Byers *et al.* *AR6 Scenarios Database*. Zenodo (2022). <https://doi.org/10.5281/zenodo.5886911>.
- [3] H. Desing *et al.* *The 3-Machines Energy Transition Model: Exploring the Energy Frontiers for Restoring a Habitable Climate*. Earth's Future **10** (2022). <https://doi.org/10.1029/2022EF002875>.
- [4] Ember & Our World in Data. Electricity production by source, World. Our World in Data dataset, based on Ember, *Yearly Electricity Data Europe* and Ember, *Yearly Electricity Data* (2026). <https://ourworldindata.org/grapher/electricity-prod-source-stacked>.
- [5] M. J. Gidden *et al.* *A prudent planetary limit for geologic carbon storage*. Nature **645**, 124–132 (2025). <https://doi.org/10.1038/s41586-025-09423-y>.
- [6] Lamboll, R., Rogelj, J. & Schleussner, C.-F. Scenario emissions and temperature data for PROVIDE project. Zenodo (2022). <https://doi.org/10.5281/zenodo.7194542>.
- [7] Lamboll, R., Rogelj, J. & Schleussner, C.-F. A guide to scenarios for the PROVIDE project. ESS Open Archive (2022). <https://doi.org/10.1002/essoar.10511875.1>.