Supplement of Geosci. Model Dev., 19, 8081–8113, 2026
https://doi.org/10.5194/gmd-19-8081-2026-supplement

Geoscientific Model Development
Open Access

Supplement of

AD-MERGE 2.0: an integrated assessment of the Nexus among energy transitions, climate impacts, and adaptation responses

Kamyar Amirmoeini et al.

Correspondence to: Kamyar Amirmoeini (kamyar.amirmoeini@hec.ca) and Olivier Bahn (olivier.bahn@hec.ca)

This supplementary material provides additional technical documentation, focusing on the mathematical formulation, calibration logic, and internal model mechanisms that support the analysis presented in the main manuscript for AD-MERGE 2.0. It is intended to clarify how the macroeconomic, energy-system, climate, damage, adaptation, and welfare components interact within the integrated assessment framework, while avoiding unnecessary duplication of the main text.

S1 Intertemporal welfare and Negishi weights

AD-MERGE 2.0, following the approach of the MERGE model family, uses an intertemporal welfare-maximization structure with logarithmic utility of consumption, which implies positive but diminishing marginal utility. This formulation provides a compact representation of intertemporal consumption-investment trade-offs (Manne et al., 1995). In simplified notation, regional intertemporal utility can be written as:

$$U_r = \sum_t d_{r,t} \ln(C_{r,t}), \tag{S1}$$

where $C_{r,t}$ denotes regional consumption and $d_{r,t}$ is the region- and period-specific utility discount factor.

The discounting procedure is internally linked to the intertemporal optimality condition of the growth model. Following the MERGE formulation, the utility discount factor is calibrated consistently with the relationship between the marginal productivity of capital, economic growth, and the rate of pure time preference. Rather than applying a single ex-post discount factor uniformly to all reported outcomes, the model updates the annual utility discount factor by region and period using the assumed marginal productivity of capital and the regional growth path. In simplified form, the annual utility discount factor can be represented as:

$$d_{r,t} = 1 - m_t + g_{r,t}, \tag{S2}$$

where m_t denotes the marginal productivity of capital and $g_{r,t}$ is the regional economic growth rate. The cumulative utility discount factor used in the welfare objective is then obtained by compounding this annual factor over the number of years represented by each model period. This structure ensures that the valuation of consumption over time is consistent with the model's intertemporal investment logic, rather than being introduced only as an external reporting assumption.

The global welfare objective aggregates discounted regional utilities across regions. In simplified form, the objective is:

$$W = \sum_r \omega_r U_r, \tag{S3}$$

where ω_r denotes the regional Negishi weight. These weights are introduced after the definition of discounted regional utility because they determine how regional utilities enter the global welfare objective. They are not interpreted as externally imposed ethical or distributional weights; instead, they are calculated internally through the Negishi procedure to recover a Pareto-efficient equilibrium across regions.

AD-MERGE 2.0 follows the MERGE approach in representing the world economy as a set of intertemporally optimizing regional agents linked through international markets for traded commodities and a global welfare function. In this framework, regional utilities are aggregated using Negishi weights, which are not imposed as normative equity weights but are calculated internally to recover a Pareto-efficient competitive equilibrium. The economic logic is that each region faces an intertemporal budget constraint, while global markets clear through endogenous prices for traded goods. If a global welfare function were solved with fixed arbitrary weights, the resulting allocation could imply large artificial transfers across regions. The Negishi procedure avoids this problem by iteratively adjusting the regional welfare weights so that the marginal value of income is consistent across regions at equilibrium (Negishi, 1960; Stanton et al., 2014).

Operationally, the model first solves the global welfare maximization problem using an initial set of regional weights. After each solution, the shadow prices associated with the trade-balance constraints are used to infer the relative present-value prices of traded goods, expressed relative to the numeraire. These prices are then used to evaluate each region's equilibrium command over global resources, including consumption and net trade positions. The resulting regional values are normalized so that the weights sum to one. The model is then solved again with the updated weights, and the procedure is repeated until the change in weights between successive iterations becomes sufficiently small. Thus, the weights are endogenous equilibrium objects: they reflect each region's income, consumption, trade position, and the prevailing intertemporal price system, rather than an externally imposed distributional preference. The purpose of this iterative procedure is to ensure that an additional unit of income has the same value in the global welfare objective regardless of the region in which it is received. This interpretation is particularly important in AD-MERGE 2.0 because regional mitigation costs, residual damages, and adaptation expenditures differ substantially across regions; the Negishi-weighted welfare formulation provides a consistent equilibrium basis for comparing these heterogeneous regional outcomes.

S1.1 Macroeconomic module

At the regional level, realized economic output is allocated among consumption, investment, energy-system expenditures, net exports of the numeraire good, and market damages. This balance can be written as

$$Y_{r,t} = C_{r,t} + I_{r,t} + EC_{r,t} + X_{r,t}^{\mathrm{nmr}} + MD_{r,t}, \tag{S4}$$

where $Y_{r,t}$ denotes realized output, $C_{r,t}$ is consumption, $I_{r,t}$ is investment, $EC_{r,t}$ represents energy-system costs, $X_{r,t}^{\mathrm{nmr}}$ denotes net exports of the numeraire good, and $MD_{r,t}$ represents market damages from climate change. This accounting structure links macroeconomic activity directly to the energy-system module, because changes in energy prices, technology choices, and climate-policy constraints affect the share of output required to satisfy energy demand.

Production is represented using a nested constant-elasticity-of-substitution structure. New economic output depends on new capital, labor, electricity, and non-electric energy:

$$YN_{r,t} = \left[a_{r,t}\left(KN_{r,t}^{\alpha_r} LN_{r,t}^{1-\alpha_r}\right)^{\gamma_r} + b_{r,t}\left(EN_{r,t}^{\beta_r} NN_{r,t}^{1-\beta_r}\right)^{\gamma_r}\right]^{1/\gamma_r}. \tag{S5}$$

Here, $YN_{r,t}$ denotes new output, $KN_{r,t}$ and $LN_{r,t}$ are new capital and labor, and $EN_{r,t}$ and $NN_{r,t}$ are new electric and non-electric energy inputs. The parameters α_r and β_r describe the value shares within the capital–labor and energy bundles, while γ_r governs substitution between the capital–labor bundle and the energy bundle. The productivity parameters $a_{r,t}$ and $b_{r,t}$ are calibrated to reproduce the reference socioeconomic pathway and autonomous energy-efficiency improvements.

Total realized output also reflects the contribution of past capital vintages. Output from previous periods does not disappear immediately but declines as existing capital depreciates:

$$Y_{r,t} = YN_{r,t} + (1-\delta_r)^{\Delta t} Y_{r,t-1}, \tag{S6}$$

where δ_r is the annual depreciation rate and Δt is the number of years represented by the model period. This vintage structure captures the inertia of the macroeconomic system: current production depends not only on new investments but also on earlier capital-formation decisions.

An important distinction is made between potential GDP and realized GDP. Potential GDP is used to calibrate productivity growth under reference conditions and reflects the socioeconomic pathway that would prevail under constant energy-price assumptions. Realized GDP is endogenous and can deviate from this reference pathway because energy-system costs, mitigation requirements, climate damages, and adaptation expenditures all compete with consumption and investment. This distinction is central for interpreting climate-policy costs: mitigation and damages do not simply occur on top of an exogenous GDP pathway, but interact with macroeconomic production and resource allocation within the model.

S2 Energy module

The energy module represents the bottom-up technology system that supplies electricity, non-electric energy, and hydrogen to the macroeconomic module. Following the MERGE structure, energy demand is linked endogenously to economic production, while energy-related emissions are determined from fuel use and the technology mix. In AD-MERGE 2.0, the module includes conventional electricity technologies, variable renewable energy, storage, hydrogen production, fossil and renewable non-electric energy carriers, carbon capture and storage, and carbon dioxide removal options.

The total energy cost, $EC_{r,t}$, represents the cost of meeting regional energy demand in region r and period t. It includes conventional electricity supply costs, wind and solar generation costs, grid integration and transmission markups for variable renewables, short-term storage costs, hydrogen production and transport costs, non-electric energy production costs, fuel costs, energy and carbon taxes, costs of relaxing carbon constraints, regional contributions to afforestation, DACCS costs, non-CO_2 GHG abatement costs, interregional trade costs, and energy-intensive sector adjustment costs. Thus, $EC_{r,t}$ enters the macroeconomic module as a competing claim on regional output, together with consumption, investment, market damages, and net exports of the numeraire good.

Energy supply is represented by the production of energy carriers from available technologies:

$$S_{e,r,t} = \sum_{k \in \mathcal{K}_e} \eta_{k,e,r,t} X_{k,r,t} + M_{e,r,t} - X^{\text{exp}}_{e,r,t}, \tag{S7}$$

where $S_{e,r,t}$ is the available supply of energy carrier e, $X_{k,r,t}$ is the activity level of technology k, $\eta_{k,e,r,t}$ is the output coefficient or conversion efficiency, $M_{e,r,t}$ denotes imports, and $X^{\text{exp}}_{e,r,t}$ denotes exports. The set $\mathcal{K}_e$ includes all technologies producing carrier e.

Energy demand must be satisfied in each region and period:

$$S_{e,r,t} \geq D_{e,r,t}, \tag{S8}$$

where $D_{e,r,t}$ denotes demand for energy carrier e.

Resource extraction is constrained by available reserves and resource potentials. Exhaustible resources are represented by cost categories that approximate increasing marginal extraction costs (see Fig. 3). Lower-cost categories are used first when economically attractive, whereas higher-cost categories become available as demand rises or as lower-cost reserves are depleted. Cumulative extraction cannot exceed the available resource base:

$$\sum_{\tau \leq t} Q_{f,r,\tau} \leq \bar{R}_{f,r,t}, \tag{S9}$$

where $Q_{f,r,t}$ is the extraction of exhaustible resource f, and $\bar{R}_{f,r,t}$ is the available reserve or resource potential. Remaining reserves evolve as:

$$R_{f,r,t+1} = R_{f,r,t} - Q_{f,r,t} + RA_{f,r,t}, \tag{S10}$$

where $R_{f,r,t}$ is the remaining reserve and $RA_{f,r,t}$ represents newly discovered or newly available resources. Together, Equations (S7)–(S10) summarize the role of the energy module: it selects technology activity levels that satisfy regional energy demand, respect resource and technology constraints, and determine the energy-system cost passed to the macroeconomic module.

S3 Climate module

The climate module in AD-MERGE 2.0 builds on the reduced-form climate structure also introduced in Manne et al. (1995) and (Marcucci and Turton, 2012). The module links anthropogenic greenhouse gas (GHG) emissions to atmospheric concentrations, radiative forcing, potential temperature change, and actual temperature change. In earlier MERGE implementations, several climate-module parameters were based on the IPCC Third Assessment Report, Working Group I (IPCC, 2001); in AD-MERGE 2.0, these parameters are updated using the latest IPCC AR6 WG1 assessment. In AD-MERGE 2.0, the main physical parameters are updated using the latest IPCC Sixth Assessment Report, Working Group I (AR6 WG1), particularly Chapter 7 and its Supplementary Material (Forster et al., 2021a,b). These updates include GHG radiative forcing relationships, radiative efficiencies, atmospheric lifetimes, and global warming potentials.

The model represents carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and two aggregated groups of fluorinated GHGs, short-lived fluorinated GHGs (SLF) and long-lived fluorinated GHGs (LLF). Emissions, atmospheric concentrations, and temperature are calibrated to historical data up to the 2015 base year. After 2015, energy-related emissions are determined endogenously by the energy-system module, while selected non-energy emissions follow exogenous scenario assumptions. These emissions are then translated into atmospheric concentrations, radiative forcing, and temperature change through the climate module. The complete numerical parameterization and GAMS implementation are provided in the supplementary code archive.

S3.1 Greenhouse gas emissions

Energy-related CO_2 emissions are determined endogenously from regional fossil fuel use and technology deployment. Regional energy-related emissions are aggregated to obtain global CO_2 and CH_4 emissions. Non-energy emissions, including non-energy CO_2 and other GHG emissions, are specified exogenously following the SSP-consistent calibration pathway used in the model. Total GHG emissions are also reported in carbon-equivalent terms using 100-year global warming potentials (GWP). The GWP values are updated using IPCC AR6 WGI Chapter 7 and its Supplementary Material (Forster et al., 2021a,b). These values are used for aggregation and reporting, while the climate module separately tracks the atmospheric stock and radiative forcing contribution of each GHG.

S3.2 Carbon cycle

The atmospheric evolution of CO_2 is represented using a multi-reservoir impulse-response approximation. This formulation follows the MERGE carbon-cycle structure, which is based on the reduced-form representation of the ocean-atmosphere carbon cycle developed by Maier-Reimer and Hasselmann (1987). The impulse response to a CO_2 emission pulse is expressed as a weighted sum of exponential decay terms:

$$G(\tau) = \sum_{j=1}^{5} a_j \exp\left(-\frac{\tau}{T_j}\right), \tag{S11}$$

where $G(\tau)$ is the fraction of an emitted CO_2 pulse remaining in the atmosphere after time τ. Parameter a_j is the fraction of emissions assigned to reservoir j. These reservoir fractions satisfy $\sum_{j=1}^{5} a_j = 1$, so that the emitted CO_2 pulse is fully allocated across the atmospheric reservoirs. T_j is the corresponding adjustment time scale. The long-lived reservoir has an effectively infinite time scale. The coefficients a_j allocate an emitted CO_2 pulse across five reservoirs, while T_j gives the characteristic decay time, in years, for each reservoir. In this parameterization, $a_1 = 0.142$ is associated with $T_1 = \infty$, implying that 14.2% of an emitted pulse is assigned to a very long-lived reservoir. The remaining shares are assigned to reservoirs with finite decay times: $a_2 = 0.241$ with $T_2 = 313.8$ years, $a_3 = 0.323$ with $T_3 = 79.8$ years, $a_4 = 0.206$ with $T_4 = 18.8$ years, and $a_5 = 0.088$ with $T_5 = 1.7$ years Maier-Reimer and Hasselmann (1987). Since the a_j coefficients sum to one, the emitted pulse is fully distributed across the reservoirs.

This formulation captures the multi-timescale nature of the carbon cycle. A relatively small fraction of CO_2 is removed rapidly through the short-lived reservoir, while a substantial fraction persists for decades to centuries through the reservoirs with longer values of T_j. Consequently, atmospheric CO_2 concentration in each model period reflects both current emissions and the remaining fractions of past emissions.

In the discrete implementation, CO_2 emissions are allocated across five reservoirs:

$$S_{j,t+1} = (1 - \delta_j)^{\Delta t} S_{j,t} + a_j \bar{E}_{\mathrm{CO_2},t}, \tag{S12}$$

where $S_{j,t}$ is the atmospheric CO_2 stock in reservoir j at time t, δ_j is the annual decay rate determined by a distributed lag process. Δt is the number of years in the model period, and $\bar{E}_{\mathrm{CO_2},t}$ is the period-average CO_2 emission flow. Total atmospheric CO_2 is then:

$$S_{\mathrm{CO_2},t} = S^{\mathrm{pre}}_{\mathrm{CO_2}} + \sum_{j=1}^{5} S_{j,t}, \tag{S13}$$

where $S^{\mathrm{pre}}_{\mathrm{CO_2}}$ is the pre-industrial stock component assumed not to decay within the model horizon. The base-year atmospheric CO_2 stock is calibrated to historical data through 2015.

For non-CO_2 GHGs, atmospheric concentrations are represented using a single-reservoir decay process. For each non-CO_2 GHG, the discrete form representation is:

$$\tilde{S}_{g,t+1} = (1 - \delta_g)^{\Delta t} \tilde{S}_{g,t} + \bar{E}_{g,t}, \qquad g \neq \mathrm{CO_2}, \tag{S14}$$

where $S_{g,t}$ is the atmospheric concentration or stock of GHG g and $\tilde{S}_{g,t}$ is the atmospheric stock above the equilibrium level, δ_g is the annual decay rate, and $\bar{E}_{g,t}$ is the period-average emissions. The atmospheric lifetimes and related decay parameters for all GHG emissions follow IPCC AR6 WGI Chapter 7 Supplementary Material (Forster et al., 2021b).

S3.3 Radiative forcing

Radiative forcing is calculated from the atmospheric stocks of GHGs. The GHG radiative forcing formulation follows the IPCC AR6 WGI treatment of well-mixed greenhouse gases, particularly Chapter 7 Supplementary Material, Table 7.SM.1 (Forster et al., 2021b). For CO_2, radiative forcing follows the logarithmic relationship:

$$\Delta F_{\mathrm{CO_2},t} = \phi_{\mathrm{CO_2}} \ln\left(\frac{S_{\mathrm{CO_2},t}}{S_{\mathrm{CO_2},2015}}\right), \tag{S15}$$

where $\Delta F_{\mathrm{CO_2},t}$ is CO_2 radiative forcing, $\phi_{\mathrm{CO_2}}$ is the CO_2 forcing coefficient, and $S_{\mathrm{CO_2},2015}$ is the base year atmospheric CO_2 stock.

For CH_4 and N_2O, AD-MERGE 2.0 retains the nonlinear concentration-based forcing structure used while updating the forcing-related parameters using IPCC AR6 WGI. The formulation accounts for the nonlinear dependence of forcing on atmospheric concentrations and for the overlap between CH_4 and N_2O absorption bands:

$$\Delta F_{g,t} = \phi_g \left[(m_g S_{g,t})^\eta - (m_g S_{g,2015})^\eta \right] - \Omega_g \left(S_{\mathrm{CH_4},t}, S_{\mathrm{N_2O},t} \right), \qquad g \in \{\mathrm{CH_4}, \mathrm{N_2O}\}, \tag{S16}$$

where ϕ_g is the GHG-specific forcing coefficient, m_g is a stock-conversion multiplier, η is the forcing exponent, and Ω_g represents the interaction between CH_4 and N_2O forcing. The corresponding radiative efficiencies and forcing-related parameters are taken from IPCC AR6 WGI Chapter 7 and its Supplementary Material (Forster et al., 2021a,b).

For fluorinated GHGs, radiative forcing is represented as approximately linear in the deviation from the reference atmospheric stock:

$$\Delta F_{g,t} = \phi_g \left(S_{g,t} - S_{g,2015} \right), \qquad g \in \{\mathrm{SLF}, \mathrm{LLF}\}. \tag{S17}$$

This linear approximation follows the IPCC AR6 WGI treatment for many minor well-mixed GHGs, for which forcing is calculated from radiative efficiencies and changes in atmospheric abundance. The radiative efficiencies for fluorinated GHGs are taken from IPCC AR6 WGI Chapter 7 Supplementary Material, particularly the tables reporting lifetimes, radiative efficiencies, and emission metrics (Forster et al., 2021b).

Total radiative forcing is calculated as:

$$\Delta F_t = \Delta F^{\mathrm{base}} + \Delta F_{\mathrm{CO_2},t} + \Delta F_{\mathrm{CH_4},t} + \Delta F_{\mathrm{N_2O},t} + \Delta F_{\mathrm{SLF},t} + \Delta F_{\mathrm{LLF},t} - \Delta F_t^{\mathrm{sul}}, \tag{S18}$$

where ΔF^{base} represents forcing components not explicitly modeled, and $\Delta F_t^{\mathrm{sul}}$ represents the cooling effect of sulfur aerosols. The sulfur cooling term follows the reduced-form MERGE climate-module structure, while GHG forcing parameters are updated using IPCC AR6 WGI.

S3.4 Potential and actual temperature change

Potential temperature change is the equilibrium temperature response associated with a given level of radiative forcing:

$$\Delta PT_t = \chi \Delta F_t, \tag{S19}$$

where ΔPT_t is potential temperature change and χ is the climate-sensitivity conversion parameter. This formulation follows the simple energy-balance structure used in MERGE-type models, in which equilibrium temperature response is proportional to radiative forcing.

The conversion parameter is linked to equilibrium climate sensitivity:

$$\chi = \frac{\Delta T_{2\times\mathrm{CO_2}}}{\phi_{\mathrm{CO_2}} \ln(2)}, \tag{S20}$$

where $\Delta T_{2\times\mathrm{CO_2}}$ denotes equilibrium climate sensitivity. In AD-MERGE 2.0, the central value is set to $3\,^\circ\mathrm{C}$, consistent with the IPCC AR6 WGI assessed best estimate (Forster et al., 2021a). Alternative low and high values are used in sensitivity analysis to capture uncertainty in the climate response.

Actual temperature change responds gradually to potential temperature because of ocean heat uptake and other thermal inertia processes. This lagged adjustment is represented as:

$$\Delta AT_{t+1} = (1-\lambda)^{\Delta t} \Delta AT_t + \left[1 - (1-\lambda)^{\Delta t} \right] . \frac{\Delta PT_t + \Delta PT_{t+1}}{2}, \tag{S21}$$

where ΔAT_t is the actual global mean temperature change, λ is the annual adjustment coefficient, and Δt is the number of years in the model period. This equation follows the MERGE reduced-form temperature response, where actual temperature approaches potential temperature gradually rather than instantaneously. Since the model uses decadal time steps, radiative forcing and the corresponding potential temperature are not assumed to remain constant within each period. The averaging term provides a simple trapezoidal approximation of the intra-period forcing level that drives the adjustment of actual temperature. Thus, actual temperature evolves partly from the previous-period temperature state and partly toward the average potential temperature implied by forcing during the current model interval.

References

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., and Zhang, H.: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., and Zhou, B., pp. 923–1054, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.009, 2021a.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., and Zhang, H.: Supplementary Material to Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021b.

IPCC: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001.

Maier-Reimer, E. and Hasselmann, K.: Transport and Storage of CO2 in the Ocean: An Inorganic Ocean-Circulation Carbon Cycle Model, Climate Dynamics, 2, 63–90, https://doi.org/10.1007/BF01054491, 1987.

Manne, A., Mendelsohn, R., and Richels, R.: MERGE: A model for evaluating regional and global effects of GHG reduction policies, Energy policy, 23, 17–34, https://doi.org/10.1016/0301-4215(95)90763-W, 1995.

Marcucci, A. and Turton, H.: The MERGE-ETL Model: Model Documentation, Tech. rep., Paul Scherrer Institute, Villigen, Switzerland, 2012.

Negishi, T.: Welfare economics and existence of an equilibrium for a competitive economy, Metroeconomica, 12, 92–97, https://doi.org/10.1111/j.1467-999X.1960.tb00275.x, 1960.

Stanton, E. A., Ackerman, F., and Stanton, E. A.: Negishi Welfare Weights in Integrated Assessment Models: The Mathematics of Global Inequality, p. 133–148, Anthem Environment and Sustainability,Anthem Frontiers of Global Political Economy, Anthem Press, https://doi.org/10.1007/s10584-010-9967-6, 2014.