Appendix A Regional aggregation

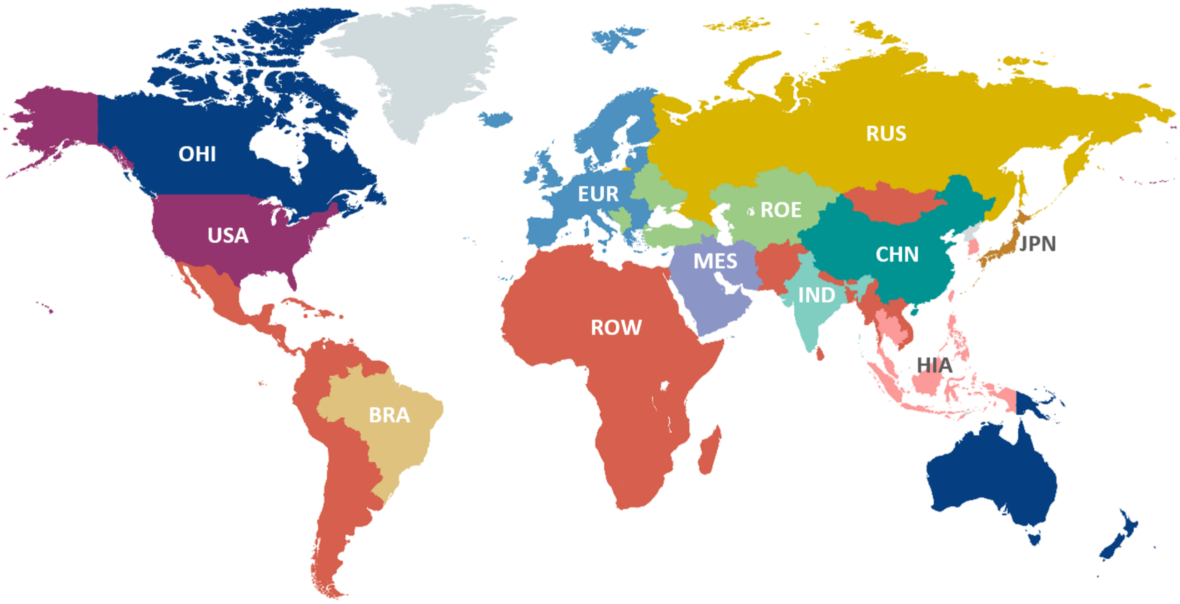

Figure 1: Regional aggregation of the STACO model (Dellink et al., 2015)

Appendix B Emissions, GDP and population projections

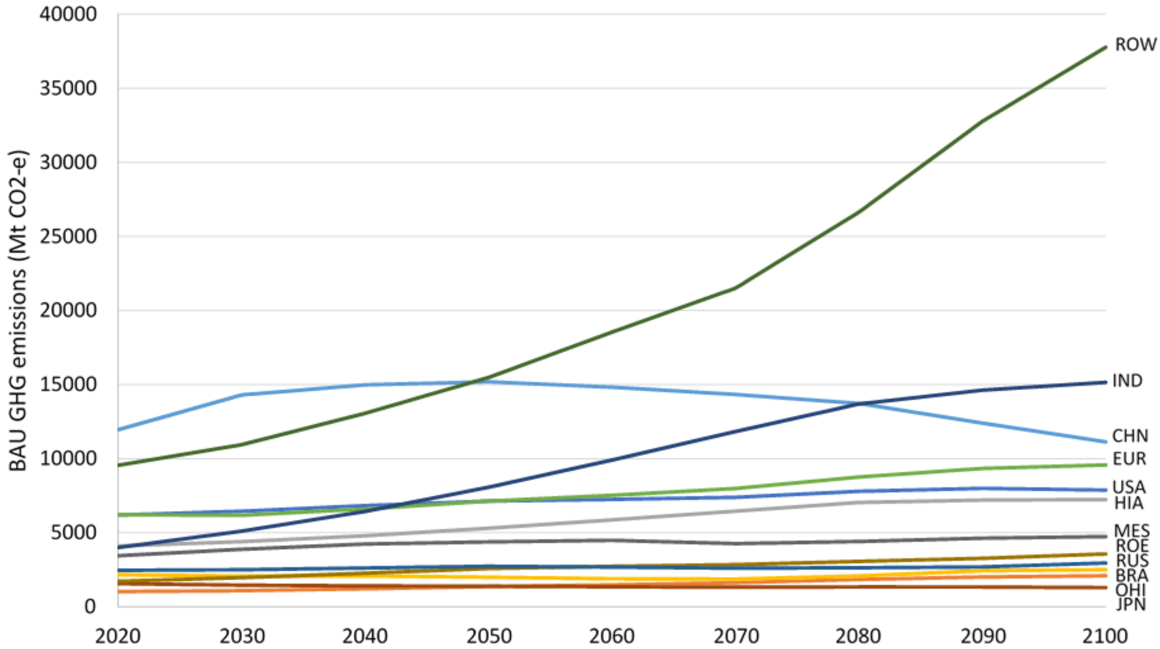

Figure 2: BAU emissions paths per region (own calibration based on SSP2 data (IIASA, 2018))

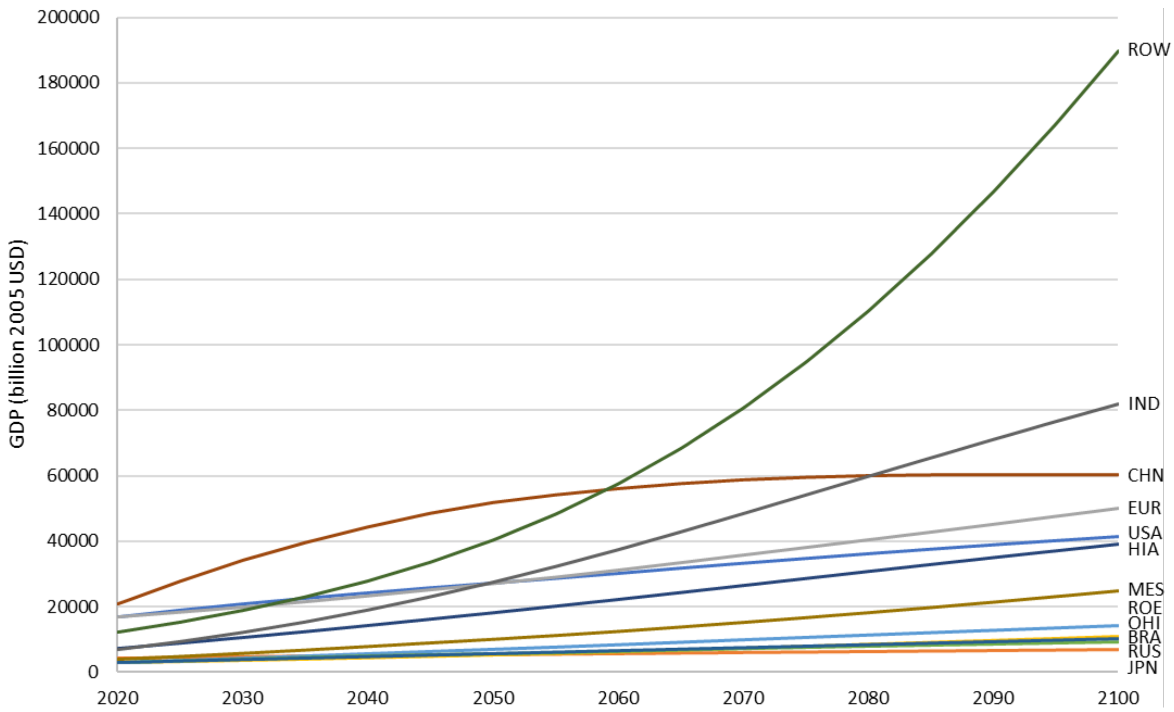

Figure 3: GDP projections per region (own calibration based on SSP2 data (IIASA, 2018))

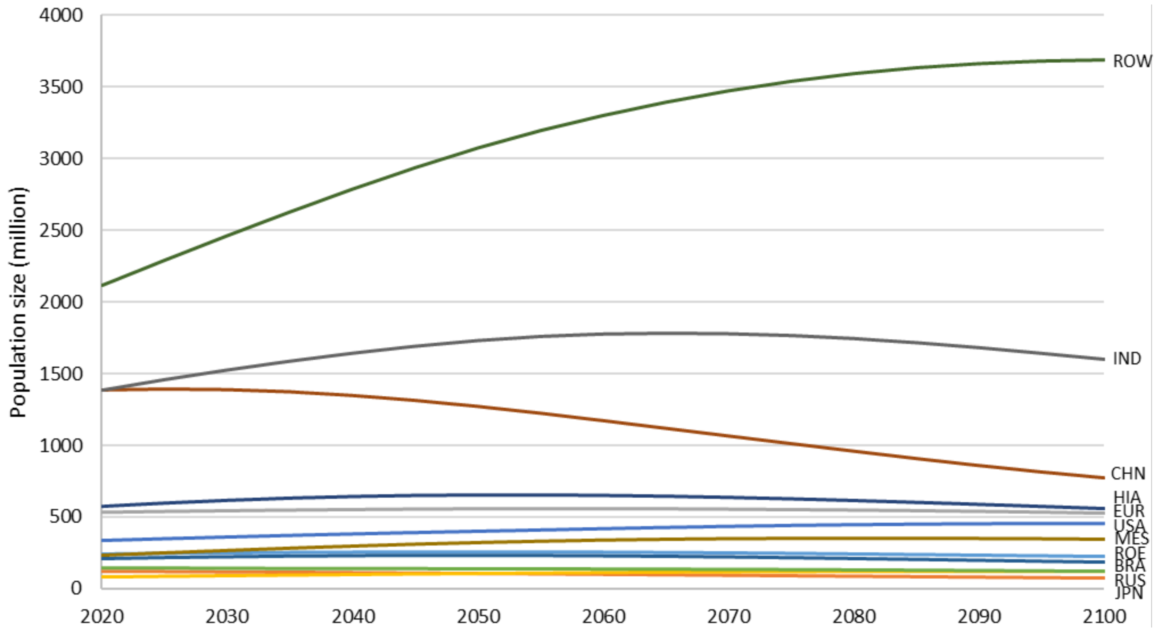

Figure 4: Population projections per region (own calibration based on SSP2 data (IIASA, 2018))

Appendix C Calibration of the benefits of abatement

The general simulation model's benefits estimates are largely based on the STACO 3 model's climate and benefits calibrations. Regional damages of emissions and benefits of abatement are linked to global BAU-emissions via a linearized climate module, which translates emissions into GHG concentrations, temperature change and ultimately into global damages. Abatement benefits are defined as forgone damages, i.e. the difference in damages between emissions after collective abatement and the global BAU emissions baseline. Regional benefits are calculated by scaling global benefits by a regional benefit share parameter and the region's respective annual GDP projection.

The linearity of the emissions-damages interaction is given by the combination of the climate dynamics' functional forms. Specifically, temperature change is commonly presented as a logarithmic function of concentrations (via an intermediate radiative forcing step) and damages as a quadratic function of temperature change. In combination, these functional forms yield a quasi-linear function for concentrations and damages, which is why the STACO model uses a linear approximation for these non-linear dynamics (Dellink et al., 2004; Dellink et al., 2015). The linearity of the benefits functions constitutes a convenient feature of the model as it ensures dominant strategies for all players of the standard game of coalition formation. In the model, atmospheric GHG concentrations M_t (ppmv CO2-e) are thus a linear function of concentrations in the previous period and global emissions after abatement $Q_t = \sum q_{it}$ (Gt CO2-e):

$$M_t(M_{t-1}, Q_t) = (1 - \delta_M) \cdot M_{t-1} + \gamma_M \cdot \sum_{i=1}^{N} \{\bar{e}_{it} - q_{it}\}; \quad M_0 = \overline{M_{2019}} \tag{1}$$

δ_M is a calibration parameter that can be interpreted as the decay of GHG concentrations over time, and γ_M represents a transfer coefficient from emissions to concentrations. Table 1 lists the different parameter values of the model, which were estimated using ordinary least squares regression (OLS) to fit the baseline data of the STACO model (Dellink et al. 2015). The starting value $M_0 = 500$ ppm is equivalent to the atmospheric concentration of GHG in 2019 as reported in the annual greenhouse gas index (AGGI) by the US National Oceanic and Atmospheric Administration's (NOAA) Global Monitoring Laboratory (NOAA, 2020).

Table 1: *Benefits model parameters, Dellink et al. (2015)*

Parameter	Value
δ_M	0.0014
γ_M	0.1297
δ_T	0.0313
γ_T	0.0001
γ_D	0.4920

Concentrations M_t are then converted into temperature change ΔT_t (°C as compared to 1900) via the following linearized function:

$$\Delta T_t(\Delta T_{t-1}, M_t) = (1 - \delta_T) \cdot \Delta T_{t-1} + \gamma_T \cdot M_t; \quad \Delta T_0 = \overline{\Delta T_{2019}} \tag{2}$$

δ_T is a calibration parameter which can be interpreted as heat dissipation and γ_T is a transfer coefficient from concentrations to temperature change. ΔT_0 is the atmospheric temperature change in 2019 compared to 1900, which the NOAA reported to be 1.03°C (WMO, 2020).

Global damages d_t are a linearized function of temperature change ΔT_t, which are converted into regional damage shares d_{it} using share parameters θ_i based on Finus et al. (2006):

$$d_{it}(\Delta T_t) = \theta_i \cdot (\gamma_D \cdot \Delta T_t) \cdot \bar{Y}_{it} \tag{3}$$

γ_D is a scale parameter of global damages as used in STACO 3 and based on Tol (2009) whose value is included in Table 1. $\bar{Y}_{it}$ are the regional GDP values of the respective years. The different regional benefit share parameters are presented in Table 2.

Regional benefits are then described as the difference between region-specific damages with and without abatement, discounted over time. As the abatements of any particular year produce a stream of benefits over the abatement year as well as the subsequent years, presumably to infinity, the benefits function is a concave expression of discounted benefits accruing to past and current global abatement that extend beyond the agreement term:

$$B_{it}(Q_t) = \sum_{s=t}^{\infty} \{(d_{is}(Q_t = 0) - d_{is}(Q_t)) \cdot (1 + r)^{-t}\} \tag{4}$$

We use a discount rate r of 2.5 percent, which lies in the middle of the range commonly used as near-term discount rates in the recent literature (Rennert et al., 2022). For simplification purposes, our model is based on a single, constant discount rate rather than region and time-specific ones as used in STACO 3.

To derive a static benefits function, we assume constant abatement paths for the duration of the agreement and no abatement after 2100. Setting the global abatement path to one unit (Mt CO2-e) of abatement per year yields regional net present values of the different regional benefit streams, which were then converted into equivalent annual annuities (EEAs) to be uniform across the abatement horizon. The static regional benefits function can then be expressed as follows, with B_i as an annual benefit:

$$B_i(Q) = b_i \cdot Q \tag{5}$$

where $Q = \sum q_i$ and b_i is a region-specific benefit parameter and the slope of each region's marginal abatement benefit curve. An overview of the regional benefit parameters is included in Table 2. As no data was available on BAU emissions or GDP beyond 2100, benefit estimates after this year are based on the assumption of constant global emissions and regional GDP, using the values from the last available data year. Rather than accounting for an infinite stream of benefits, the model includes benefits until the year 2200, given that later benefits become marginal due to discounting.

Table 2: *Regional shares of global benefits (Dellink et al., 2015) and regional benefit parameters (own calibration)*

Region	θ_i	b_i
USA	0.2263	48.886
JPN	0.1725	6.415
EUR	0.2491	62.022
OHI	0.0345	1.824
ROE	0.0271	1.890
RUS	0.0403	1.923
HIA	0.0300	5.649
CHN	0.0620	21.176
IND	0.0500	18.633
MES	0.0249	2.877
BRA	0.0153	0.784
ROW	0.0680	53.398
World	$\sum \theta_i = 1$	

Appendix D Calibration of the costs of abatement

The model's abatement cost estimates are based on the abatement cost curves used in the STACO 3 model, which, in turn, are based on Morris et al. (2012) and the EPPA5 model (Dellink et al., 2015). The STACO model's cost estimates are described by cubic functions with two regional cost parameters α_i and β_i, as well as a region-specific technological progress parameter ς_i:

$$C_{it}(q_{it}) = (1-\varsigma_i)^t \left(\frac{1}{3} \cdot \alpha_i \cdot q_{it}^3 + \frac{1}{2} \cdot \beta_i \cdot q_{it}^2 \right). \tag{6}$$

Thus, abatement costs in region i fall at a constant rate ς_i over time. We simplify the region-specific abatement cost functions by approximating the second term by a quadratic one via OLS in the domain $[0, \overline{e_i}]$, where $\overline{e_i}$ denotes each region's mean BAU-emissions over the time horizon 2020 to 2100. Figure 5 provides a graphical example of the cubic and the approximated quadratic abatement cost curves for the USA. The approximated quadratic cost functions can generally be expressed as

$$C_{it}(q_{it}) = (1-\varsigma_i)^t \left(\frac{1}{2} \cdot \xi_i \cdot q_{it}^2 \right), \tag{7}$$

where c_i is a region-specific cost parameter representing the slope of each region's linear marginal abatement cost curve in 2020.[1]

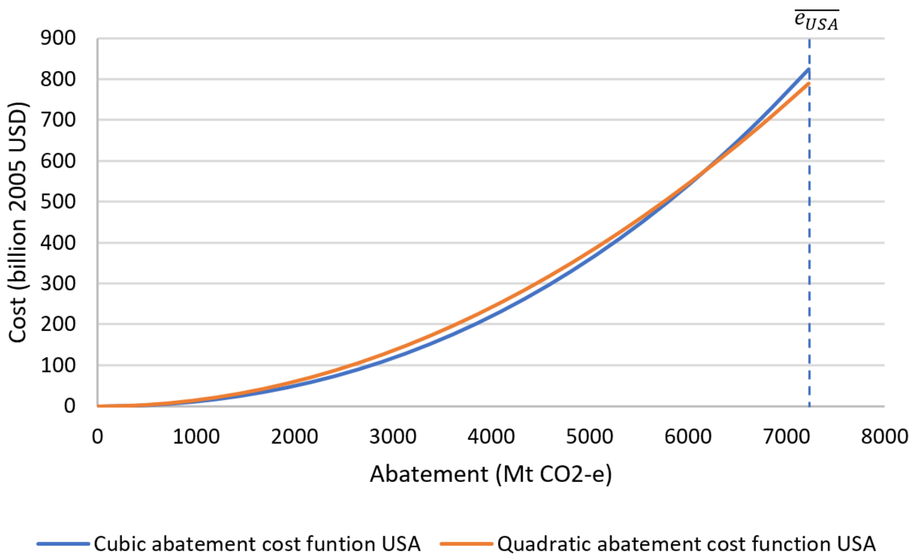

Figure 5: Quadratic approximation of a cubic abatement cost function for 2020

[1]We do not add a linear term to the quadratic cost function, as the regressions yield negative coefficients for this term, i.e., negative marginal abatement costs for low abatement levels. Although these could be interpreted as local ancillary benefits, we choose to mimic the interpretation of the cubic model which monotonously increases in the positive domain.

To construct a static version of the model, we replace the technological progress term in eq. 7 by a parameter $\bar{\varsigma}_i$ that reflects a constant 'average' technology. The parameter $\bar{\varsigma}_i$ is calibrated such that regional abatement in the static model matches the average abatement over the time horizon 2020 to 2100. We also adjust $\bar{\varsigma}_i$ for the start year of our model, 2020, to capture the technological change since 2011, the start year of the STACO 3 model. This yields the following static abatement cost function:

$$C_i(q_i) = \frac{\bar{\varsigma}_i}{2} \cdot \xi_i \cdot q_i^2 = \frac{1}{2} \cdot c_i \cdot q_i^2. \tag{8}$$

An overview of the different cost parameters and mean BAU-emissions levels is provided in Table 3.

Table 3: *Regional cost parameter values and mean baseline emissions*

Region	α_i	β_i	ξ_i	$\bar{\varsigma}_i$	Mean annual BAU emissions $\overline{e_i}$ (Mt CO2-e)
USA	1.89e-6	0.0224	0.0300	0.798	7,229
JPN	49.42e-6	0.1266	0.1648	0.798	1,391
EUR	6.76e-6	0.0195	0.0485	0.798	7,711
OHI	89.12e-6	0.0439	0.1199	0.798	1,536
ROE	83.97e-6	-0.0017	0.1234	0.798	2,683
RUS	38.78e-6	-0.0012	0.0561	0.798	2,659
HIA	14.67e-6	0.0499	0.0974	0.798	5,834
CHN	2.43e-6	-0.0008	0.0177	0.452	13,654
IND	16.85e-6	-0.0071	0.0854	0.452	9,880
MES	0.81e-6	0.0648	0.0667	0.798	4,278
BRA	131.61e-6	0.0497	0.2060	0.652	2,137
ROW	4.57e-6	0.0098	0.0624	0.798	20,709

Source: α_i, β_i from Dellink et al. (2015); $\xi_i, \bar{\varsigma}_i, \bar{e}_i$ own calibration.

References

Dellink, R. B., J. C. Altamirano-Cabrera, M. Finus, E. C. van Ierland, A. Ruijs, and H. P. Weikard (2004). Technical background paper of the STACO model (version 1.0).

Dellink, R. B., K. C. de Bruin, M. Nagashima, E. C. van Ierland, Y. Urbina-Alonso, H. P. Weikard, and S. Yu (2015). STACO technical document 3: Model description and calibration of STACO 3.

Finus, M., E. v. Ierland, and R. Dellink (2006). Stability of climate coalitions in a cartel formation game. *Economics of Governance 7*(3), 271–291.

IIASA (2018). Shared socioeconomic pathways database - version 2.0. https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#v2. Accessed: 2020-12-28.

Morris, J., S. Paltsev, and J. Reilly (2012). Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: results from the eppa model. *Environmental Modeling & Assessment 17*(4), 325–336.

NOAA (2020). Noaa's annual greenhouse gas index. https://www.esrl.noaa.gov/gmd/aggi/.

Rennert, K., B. C. Prest, W. A. Pizer, R. G. Newell, D. Anthoff, C. Kingdon, L. Rennels, R. Cooke, A. E. Raftery, H. Ševčíková, et al. (2022). The social cost of carbon: advances in long-term probabilistic projections of population, gdp, emissions, and discount rates. *Brookings Papers on Economic Activity 2021*(2), 223–305.

Tol, R. S. (2009). The economic effects of climate change. *Journal of Economic Perspectives 23*(2), 29–51.

WMO (2020). State of the global climate 2020. https://storymaps.arcgis.com/stories/6942683c7ed54e51b433bbc0c50fbdea.