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STACO Technical Document 3: Model description and calibration of STACO-3

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STACO Technical Document 3:
Model description and calibration of STACO-3

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Contributions to the development of the STACO model

The STACO project was first initiated in 2002 by Dr. E.C. van Ierland, Wageningen University, the Netherlands, and Dr. M. Finus, now at the University of Bath, UK. The project is maintained by the Environmental Economics and Natural Resources Group of Wageningen University; more information on the STACO project can be found at www.enr.wur.nl/uk/staco.

We thank all current and former members of the STACO team for the many years of collaboration and stimulating discussions on this topic. Especially, thanks to Niels Olieman and Elena Sáiz for coding large parts of the original STACO model; the elegant lines in our code are unmistakably theirs.
Finally, thanks to Sergey Paltsev of MIT for providing detailed baseline projections from EPPA model runs.

1 Introduction

The STACO project investigates the formation and stability of international climate agreements. The basic structure of the STACO models consists of interacting regions that (i) choose to join an international climate agreement or not; and (ii) choose their optimal climate policy given the coalition formed. The regions are characterised by their abatement cost and damage cost functions and are linked via global climate change and the possibility to establish an international agreement for greenhouse gas abatement.

This technical paper describes the revised STACO model, STACO-3, and its calibration in detail. Section 2 deals with the general setup of the model and provides the model equations. The calibration of the model parameters is discussed in Section 3. Section 4 illustrates what this calibration implies for the Business as Usual projection and the stable equilibria that result in the model without transfers. Section 5 contains some final remarks.

1.1 Revision history of the STACO model

The original STACO model, STACO-1, was developed by the Environmental Economics and Natural Resources Group of Wageningen University in collaboration with Michael Finus (University of Bath, United Kingdom, formerly Hagen University, Germany). The calibration of STACO-1 is described in detail in Dellink et al. (2004), and the full model is introduced in Finus, van Ierland and Dellink (2006). This model version was also used as the basis for several other studies with model specifications that were adapted to the topic of the respective article: Finus, Altamirano-Cabrera and van Ierland (2005), Altamirano-Cabrera and Dellink (2006) Weikard, Finus and Altamirano-Cabrera (2006), Altamirano-Cabrera, Finus and Dellink (2008), Dellink, Finus and Olieman (2008).

Nagashima, Dellink, Van Ierland and Weikard (2009) introduced an updated version of STACO, STACO-2. The most important update was the introduction of efficient pathways for emission reductions, by reformulating the essentially static STACO-1 version as a Ramsey type growth model. Technical details of STACO-2 are explained in Dellink et al. (2009). STACO-2 was used, with specific adaptations, in Nagashima and Dellink (2008), Weikard, Dellink and Van Ierland (2010), Dellink (2011), Dellink and Finus (2012), Dellink et al. (2013) and Weikard and Dellink (2014).

Here we describe the third generation of STACO, STACO-3, in detail. This model version has been used with minor modifications in Nagashima, Weikard, De Bruin and Dellink (2011).

As with STACO-2, many revisions were made to the model code and calibration. The major revisions with respect to STACO-2 are:

- ✓ extension to the Kyoto basket of greenhouse gases (rather than CO_2 only);
- ✓ regional discount rates based on the Ramsey rule with a fixed pure rate of time preference;
- ✓ revised regional aggregation;
- ✓ update of the simplified carbon cycle;
- ✓ updated calibration of marginal abatement costs, updated paths of population, GDP and emissions;
- ✓ flexible number of years and model horizon;
- ✓ flexible number of players (if appropriate data file is available).

The STACO model is coded in Matlab.

2 Set-up of the game in the updated model STACO-3.1

STACO 3 considers a two-stage, non-cooperative game of coalition formation. Countries or regions (hereafter referred to as regions) are denoted by $i = 1,\ldots,N$. The first stage consists of the membership decision where regions decide whether or not to join a coalition. Regions who decide not to join, non-signatories, remain singleton players. Signatories, those who decided to join, form a unique coalition. At the second stage, regions adopt their abatement strategies over the planning horizon *T*. The strategies are based on the following payoff function:

$$\max\ \pi_i(q_1,\ldots,q_T) = \sum_{t=1}^{T}\left\{(1+r_{it})^{-t}\cdot(b_{it}(q_t)-c_{it}(q_{it}))\right\} \qquad \forall i\in \boldsymbol{N} \qquad (2.1)$$

with $q_t \equiv \sum_{i=1}^{N} q_{it}$ and $r_{it} \equiv \rho + \eta\cdot\dot{y}_{it}$. In Eq. (2.1) the model horizon when accounting for the benefits is infinity (see Eq. (AI.5) in the Appendix); r_{it} is the discount rate following the Ramsey rule, where ρ represents the pure rate of time preference, η the consumption elasticity of marginal utility and $\dot{y}_{it}$ the growth of consumption per capita. q_t is the abatement matrix for period t , b_{it} is a concave benefit function of past and current global abatement and

c_{it} is a strictly convex abatement cost function of regional current abatement given per region and per time period. The infinite horizon for benefits from abatement ensures a proper reflection of the long-term aspects of climate change while the planning horizon (the duration of the international agreement) is limited. In the model, signatories reach an agreement in 2010 (t=0) and set their abatement paths until 2110 (T=100). The climate module underlying our benefit function and the full set of model equations are reported in Appendix I.

We assume that signatories and singletons play a Nash game with regard to their abatement strategies. Non-signatories choose their abatement level by maximising their own payoff, taking the other regions' abatement level as given. Signatories choose abatement levels that jointly maximise the sum of their payoffs, taking the abatement levels of non-signatories as given. We call 'All Singletons' the case where no regions or just one region signs the agreement. On the other hand, the 'Grand Coalition', is the case when a global agreement is reached and all regions sign the agreement, leading to the highest global abatement level, i.e. the global optimal abatement level. Between non-cooperation and full cooperation we have a large number of possible partial coalitions. With twelve regions we have $2^{12} - 12 = 4084$ possible coalitions. A coalition $S \subseteq \{1,...,N\}$ can be said to be stable when it is both *internally* and *externally* stable, i.e. when no one wants to leave or join the coalition. When none of the signatories has an incentive to withdraw from the coalition, as a lower payoff would be obtained due to this change in strategy, the coalition is said to be internally stable. When none of the non-signatories have an incentive to participate in the coalition, as a lower payoff is expected by joining the agreement, it is said that the coalition is externally stable. The agreement is assumed to be an 'open membership agreement' (Finus et al., 2005) since non-signatories can freely join the coalition whenever they want (without the authorization of other signatories).

3 Calibration of the updated model STACO-3.1

3.1 General calibration aspects

The base year for the calibration of the model is 2010. The model horizon is solved in 5-year steps until 2110, although this can be changed in the Matlab code.

The regional aggregation has been based on the MIT-EPPA model as described in Paltsev et al. (2005) and Paltsev (2010), and differs somewhat from STACO2:

Table 3.1. Regional aggregation in the STACO3

Names	*STACO3*	*STACO2*	*EPPA5*
USA	USA	USA	USA
Japan	JPN	JPN	JPN
EU27 & EFTA	EUR	EU / EET	EUR
Other High Income	OHI	OOECD	CAN, ANZ
Rest of Europe	ROE	FSU / ROW	ROE
Russia	RUS	FSU	RUS
High Income Asia	HIA	DAE	ASI
China	CHN	CHN	CHN
India	IND	IND	IND
Rest of the World	ROW	ROW	AFR, LAM, MEX, REA
Middle East	MES	EEX	MES
Brazil	BRA	BRA	BRA

3.2 Calibration of the socioeconomic drivers

Population and GDP are calibrated such that, in absence of costs or benefits from mitigation action, they follow the baseline projections of EPPA5. Emission projections are linked to GDP levels using time- and region-specific emission coefficients.

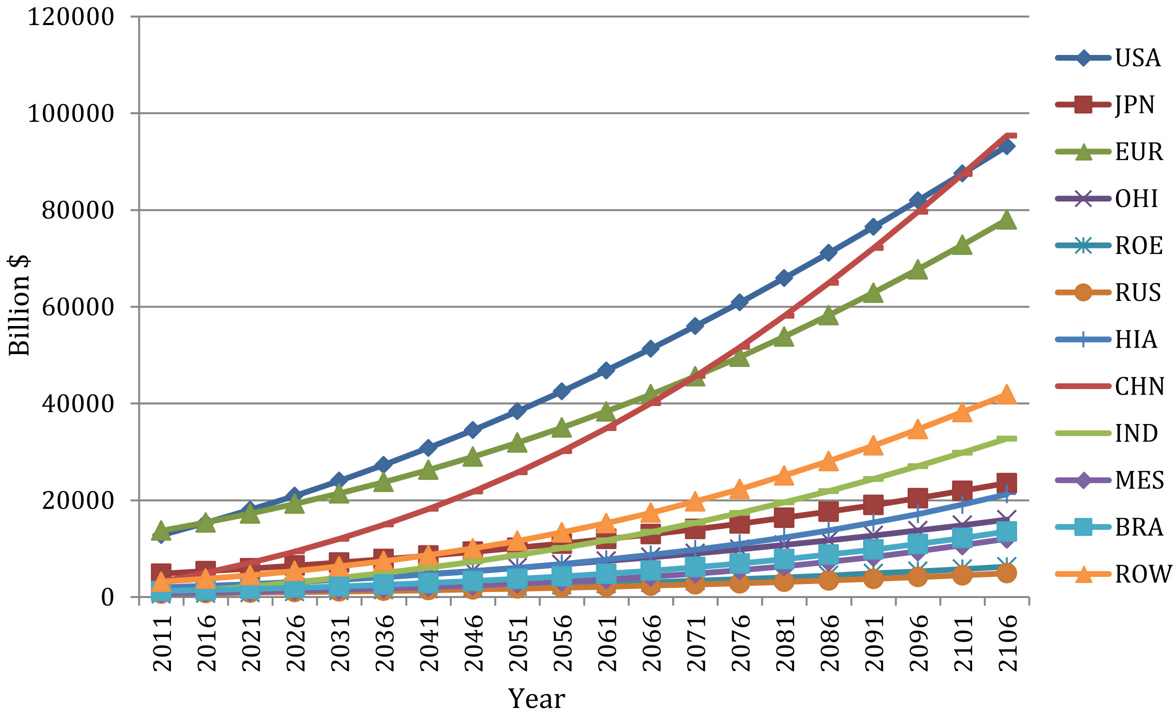

Figure 3.2 The baseline projections of undiscounted regional GDP paths

3.3 Calibration of the climate module

Greenhouse gas emission projections are linked to GDP levels using time- and region-specific emission coefficients.

The climate module is deliberately kept extremely simple, and is only meant to provide a link between emissions and climate change damages. We follow Nordhaus (1994) and Germain and Van Steenberghe (2003) and approximate the climate system by a system of three equations (for concentrations, radiative forcing and atmospheric temperature increase, respectively) and ignore the non-linear feedbacks between the atmosphere and the oceans.

The simple climate module exploits the fact that temperature change is often represented as a log function of concentrations (through an intermediate step with radiative forcing), and damages as a quadratic function of temperature change. As e.g. Dellink et al. (2004) show, combining both functional forms leads to a virtually linear function for the relevant range of concentration levels. Thus, a linearised carbon module can adequately approximate the full nonlinear system, but not the intermediate steps; hence radiative forcing is not explicitly represented. The linearization is a vital aspect of STACO, as it ensures dominant strategies for all players. The intermediate calculations of greenhouse gas concentrations and temperature change should, however, be interpreted with sufficient care, knowing that these are estimated purely with this link in mind.

Concentrations of greenhouse gases are thus a linearised function of concentrations in the previous period plus current global emissions after abatement:

$$M_t\left(M_{t-1}, q_t\right) = \left(1-\delta_M\right) \cdot M_{t-1} + \gamma_M \cdot \sum_{i=1}^{N} \left\{\overline{e}_{it} - q_{it}\right\} \;;\; M_0 = \overline{M_{2010}} \qquad (3.1)$$

Next, temperature change is calculated using the same linearised function form:

$$\Delta T_t(\Delta T_{t-1}, M_t) = (1-\delta_T) \cdot \Delta T_{t-1} + \gamma_T \cdot M_t \;;\; \Delta T_0 = \overline{\Delta T_{2010}} \qquad (3.2)$$

The key parameters in this linearised model, δ_M, γ_M, δ_T and γ_T, were estimated using OLS to best fit the baseline projections provided by Paltsev for the EPPA model (Paltsev et al., 2005; Paltsev, 2010). Appendix II lists all parameter values used in STACO 3.

3.4 Calibration of the benefits of abatement

An important characteristic of the STACO model is that it distinguishes between calibration of global damages and regional damage shares. While this is clearly an oversimplification of the impacts of climate change, it is not restrictive given our assumption of linear benefits and it allows users to directly calibrate the marginal global benefits from abatement. The benefit function is describe as follows:

$$b_{it}(q_t) = \sum_{s=t}^{\infty} \left\{ \left(d_{is}(q_t = 0) - d_{is}(q_t) \right) \cdot \prod_{z=t+1}^{s} \left(1 + r_{iz}\right)^{-1} \right\} \tag{3.3}$$

where d_{it} is the damage function represented by the following linearised equation (see previous section):

$$d_{it}(\Delta T_t) = \theta_i \cdot (\gamma_D \cdot \Delta T_t) \cdot \overline{Y_{it}} \tag{3.4}$$

in which θ_i is the regional benefit share (See Table 3.3), ΔT_t is temperature, $\overline{Y_{it}}$ is production and γ_D is the global damage parameter. γ_D is determined by estimates of the global cost of carbon made by Tol (2009). The discount rate follows the Ramsey rule and is calibrated to the UK Treasury's Green Book (2003) for discounting, assuming a 1.5% per cent pure rate of time preference and a consumption elasticity of marginal utility of 1. Combining Eqs.3.3 and 3.4, global benefits can be expressed as the present value (in period *t*) of the future stream of avoided damages induced by abatement in period *t.*

Table 3.3 Regional shares of benefits

	Default calibration in STACO1&2	*Alternative calibration in STACO1&2*		*Calibration in STACO3*
Regions	θ_i	θ_i	*Regions*	θ_i
USA	0.2263	0.1238	USA	0.2263
JPN	0.1725	0.1138	JPN	0.1725
EU15	0.2360	0.0640	EUR	0.2491
OOE	0.0345	0.0165	OHI	0.0345
EET	0.0130	0.0130	ROE	0.0271
FSU	0.0670	0.0350	RUS	0.0403
EEX	0.0300	0.0304	HIA	0.0300
CHN	0.062	0.0620	CHN	0.0620
IND	0.0500	0.1709	IND	0.0500
DAE	0.0249	0.0855	MES	0.0249
BRA	0.0153	0.0525	BRA	0.0153
ROW	0.0680	0.2330	ROW	0.0680
World	$(\sum \theta_i = 1)$	$(\sum \theta_i = 1)$	World	$(\sum \theta_i = 1)$

3.5 Calibration of the costs of abatement

STACO3 abatement cost estimates are based on Morris et al. (2008). We duly note the caveats that Morris et al. provide in interpreting these data as marginal abatement cost (MAC) curves, nonetheless our assessment is that this is the best available information for calibrating these costs. We draw this conclusion among other reasons, because most of our calibration efforts (including emissions and GDP) mimic the EPPA5 model on which Morris et al. (2008) is also based. Figure 3.4 provides an overview of the resulting MAC curves.

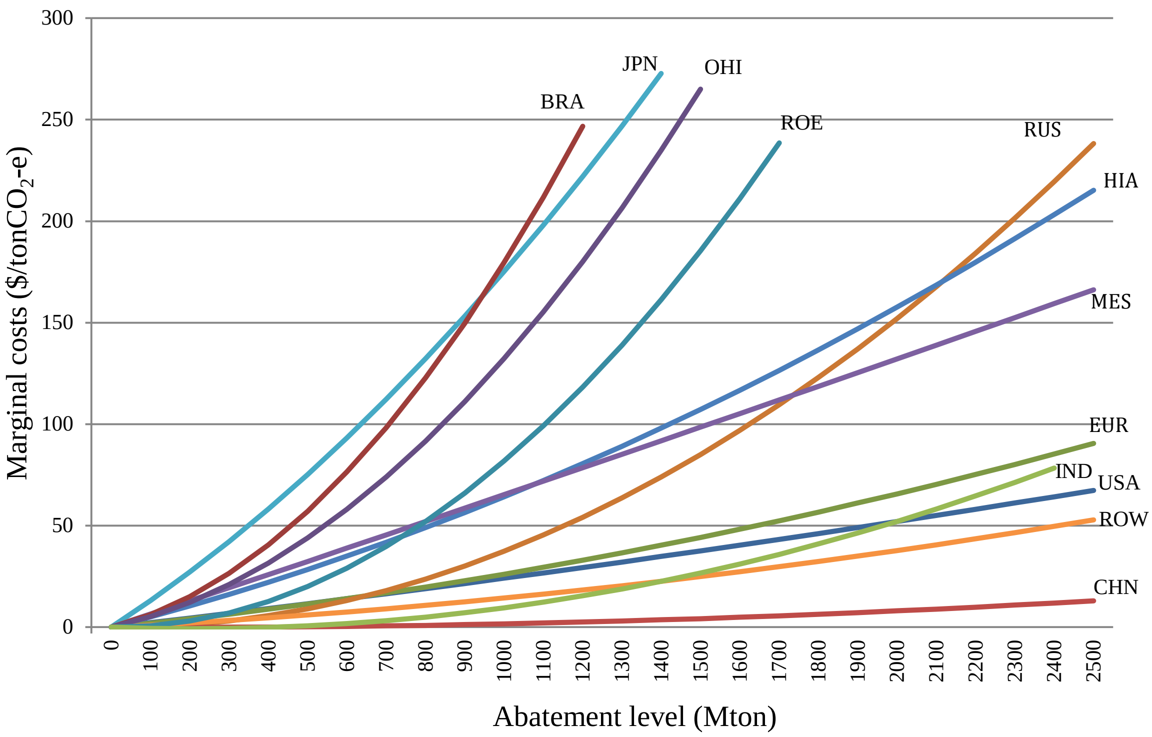

Figure 3.4. Marginal abatement cost curves in 2011 in the STACO model

Equation 3.3 describes the regional abatement cost function and is based on a cubic function with regional parameters α_i and β_i.

$$c_{it}(q_{it}) = \frac{1}{3} \cdot \alpha_i \cdot (1-\varsigma_i)^t \cdot q_{it}^3 + \frac{1}{2} \cdot \beta_i \cdot (1-\varsigma_i)^t \cdot q_{it}^2 \qquad (3.5)$$

where ς_i is the technological progress parameter. The regional parameters α_i and β_i are estimated based on EPPA data. Table 3.4 displays the values of these parameters.

Table 3.4 Regional parameter values

Regions	Parameter of abatement cost α	β
USA	1.89e-6	0.0224
JPN	49.42e-6	0.1266
EUR	6.76e-6	0.0195
OHI	89.12e-6	0.0439
ROE	83.97e-6	-0.0017
RUS	38.78e-6	-0.0012
HIA	14.67e-6	0.0499
CHN	2.43e-6	-0.0008
IND	16.85e-6	-0.0071
MES	0.81e-6	0.0648
BRA	131.61e-6	0.0497
ROW	4.57e-6	0.0098

4 Results of STACO 3.1

In this section the results for (i) the All Singletons coalition structure, (ii) the Grand Coalition and (iii) all stable coalitions (if any) are analysed.

4.1 All Singletons coalition structure

The results of the non-cooperative game, where all players act as singletons, are shown in Table 4.1. In this case marginal abatement cost equal marginal benefits for each region.

The abatement level is determined by the regional marginal benefits and marginal costs resulting in different abatement level from region to region. Even in the All Singletons scenario, the USA and the EU have an incentive to make considerable abatement efforts, as they have a high share of global benefits. Regions with a low share of global benefits and high abatement cost, such as HIA and BRA, have less incentive to reduce their emissions.

Table 4.1 All Singletons structure

Regions	Annual abatement (% of BAU emissions) 2011	2110	Net present value (NPV) of payoffs (Billion US$) over 100 years	Marginal abatement costs in 2011 ($/tonCO2)	Marginal benefits in 2011 ($/tonCO2)
USA	6.16	33.00	3507.55	10.07	10.07
JPN	6.30	34.07	4309.52	11.39	11.39
EUR	12.66	45.69	5173.23	14.60	14.60
OHI	1.92	14.20	463.33	1.25	1.25
ROE	7.93	12.33	362.42	0.98	0.98
RUS	11.50	20.69	836.58	2.25	2.25
HIA	0.97	7.03	464.00	1.26	1.26
CHN	6.77	28.63	283.53	0.89	0.89
IND	14.85	25.19	182.14	0.53	0.53
MES	1.45	8.76	337.73	0.93	0.93
BRA	0.60	3.37	244.52	0.66	0.66
ROW	3.80	15.12	816.73	2.31	2.31
Global	6.88	23.51	16981.28	-----	-----

4.2 Grand Coalition structure (without transfers)

Table 4.2 displays the results for the Grand Coalition scenario. In this case the marginal abatement costs equal the sum of marginal benefits among all regions at the level of 47 US$/ton in 2011. In the Grand Coalition the total gains from abatement are 58 trillion US$, which represents an increase of more than 40 trillion compared to the All Singleton case. Even when a higher global payoff is achieved in the Grand Coalition scenario, CHN is worse off. In Table 4.2, the incentives to change membership are also given. These represent the gains of leaving a coalition given that the other regions all remain in the coalition. Regions with positive incentives (i.e. a positive value in the last column) will benefit from leaving the Grand Coalition while those with negative incentives will prefer to remain in the coalition.

Figure 4.2 depicts the path of net benefits over time, these are the net benefits from past and current abatement that arise in period t and represent a cash flow. The figure shows that the benefits to all regions, with the exception of China, increase over time. The benefits for China, in contrast, decrease over time, reflecting that China has to undertake an enormous amount of abatement for the benefit of the world, while reaping only little benefits domestically. Not only are they worse off than when leaving the Grand Coalition, they are in this setting even worse off than in absence of climate change (they can of course, not prevent climate change, so in case they would not act at all, they would even be worse off as they would still suffer damages.

Table 4.2 Grand Coalition structure

Regions	Annual abatement (% of BAU emissions) 2011	2110	Net present value (NPV) of payoffs (Billion US$) over 100 years	Marginal abatement costs in 2011 ($/tonCO2)	Incentives to change membership (NPV Billion$)
USA	25.87	100.00	12795.98	47.12	575.43
JPN	23.88	100.00	18569.78	47.12	-1428.82
EUR	32.13	100.00	21508.83	47.12	-1782.91
OHI	37.08	100.00	1429.88	47.12	563.84
ROE	50.64	72.49	911.18	47.12	651.75
RUS	50.13	100.00	2292.19	47.12	1269.40
HIA	29.85	92.48	609.19	47.12	1350.40
CHN	39.64	100.00	-1353.45	47.12	2382.70
IND	58.38	95.41	21.21	47.12	713.55
MES	73.04	100.00	367.20	47.12	1065.60
BRA	20.23	38.33	393.91	47.12	668.99
ROW	40.94	66.91	1027.70	47.12	2238.65
Global	37.73	89.43	58573.6	------	-------

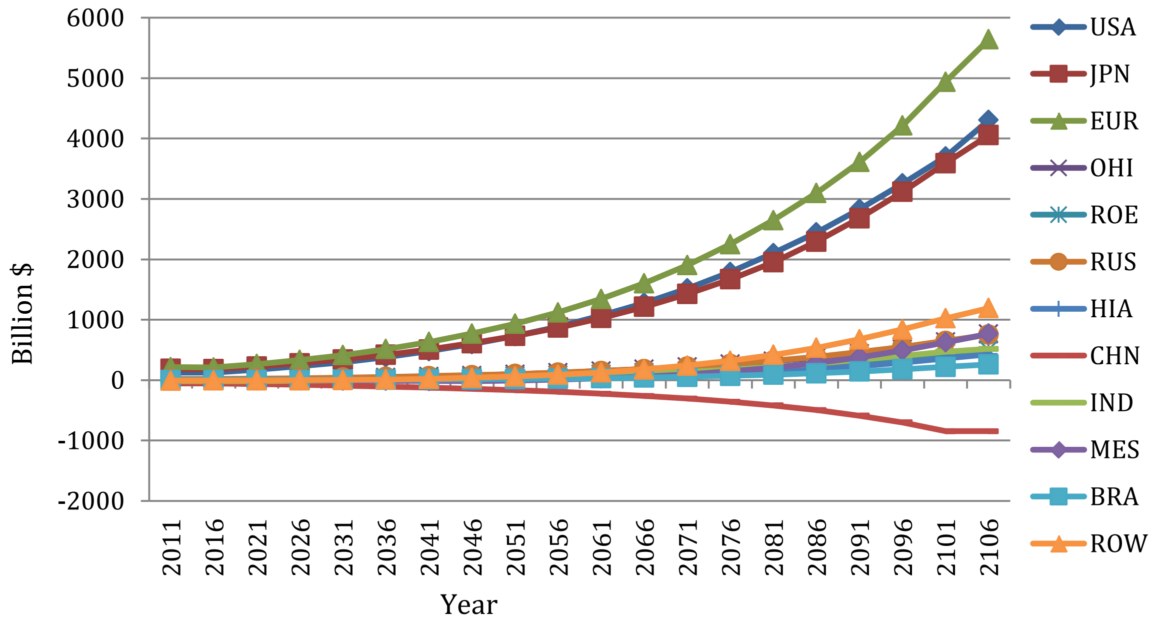

Figure 4.2. Undiscounted annual regional net benefits in Grand Coalition

In the All Singletons case total global emissions reach almost 80GtC by 2110. In the Grand Coalition case, global emissions are limited to approximately 25GtC by 2110.

4.3 Stable Coalitions

The STACO model computes regional payoffs for all possible coalitions. There are 12 regions in the model, resulting in a total of 4084 possible coalitions. Each of these coalitions are tested for external and internal stability. A coalition that exhibits both internal and external stability is considered to be stable. Our model finds one stable coalition when no transfers are made, namely the coalition between Japan and Europe. The results of this coalition are given in Table 4.3. Table 4.4 shows the results of the best-performing stable coalition (i.e. with highest global payoff) with optimal transfers (see Weikard, 2008, and Nagashima et al., 2009).

Table 4.3 The stable coalition in the baseline scenario (without transfers): {JPN, EUR}

Regions	Annual abatement in 2011 (% of BAU)	NPV of Payoffs (bln$) over 100 years	NPV of Transfers (bln$)	Incentive to change membership (bln$)	Marginal benefits in 2011 ($/tonCO2)	Marginal abatement costs in 2011 ($/tonCO2)
USA	6.16	3894.37	0.00	-509.63	10.07	10.07
JPN	*13.84*	*4548.04*	*0.00*	*-238.52*	*11.39*	*25.99*
EUR	*20.35*	*5188.17*	*0.00*	*-14.94*	*14.60*	*25.99*
OHI	1.92	510.73	0.00	-175.04	1.25	1.25
ROE	7.93	399.64	0.00	-202.56	0.98	0.98
RUS	11.50	923.55	0.00	-394.17	2.25	2.25
HIA	0.97	511.71	0.00	-356.14	1.26	1.26
CHN	6.77	315.45	0.00	-768.96	0.89	0.89
IND	14.85	200.90	0.00	-230.79	0.53	0.53
MES	1.45	372.43	0.00	-356.74	0.93	0.93
BRA	0.60	269.62	0.00	-196.08	0.66	0.66
ROW	3.80	903.43	0.00	-709.16	2.31	2.31

Table 4.4 The best-performing stable coalition with optimal transfers: {USA, EUR, ROE, CHN, IND, BRA, ROW}

Regions	Annual abatement in 2011 (% of BAU)	NPV of Payoffs (bln$) over 100 years	NPV of Transfers (bln$)	Incentive to change membership (bln$)	Marginal benefits in 2011 ($/tonCO2)	Marginal abatement costs in 2011 ($/tonCO2)
USA	*17.27*	*8479.20*	*-784.36*	*-30.40*	*10.07*	*30.04*
JPN	6.30	13154.21	0.00	-677.33	11.39	11.39
EUR	*22.82*	*12264.65*	*-2637.37*	*-43.98*	*14.60*	*30.04*
OHI	1.92	1405.77	0.00	-32.41	1.25	1.25
ROE	*40.58*	*1046.24*	*348.94*	*-3.75*	*0.98*	*30.04*
RUS	11.50	2560.33	0.00	-94.49	2.25	2.25
HIA	0.97	1410.11	0.00	-38.05	1.26	1.26
CHN	*31.94*	*648.15*	*1245.29*	*-2.32*	*0.89*	*30.04*
IND	*48.09*	*484.26*	*370.89*	*-1.74*	*0.53*	*30.04*
MES	1.45	1025.49	0.00	-24.33	0.93	0.93
BRA	*14.99*	*714.03*	*364.44*	*-2.56*	*0.66*	*30.04*
ROW	*30.21*	*2135.24*	*1092.18*	*-7.66*	*2.31*	*30.04*

Note: Best-performing indicated the highest global payoff.

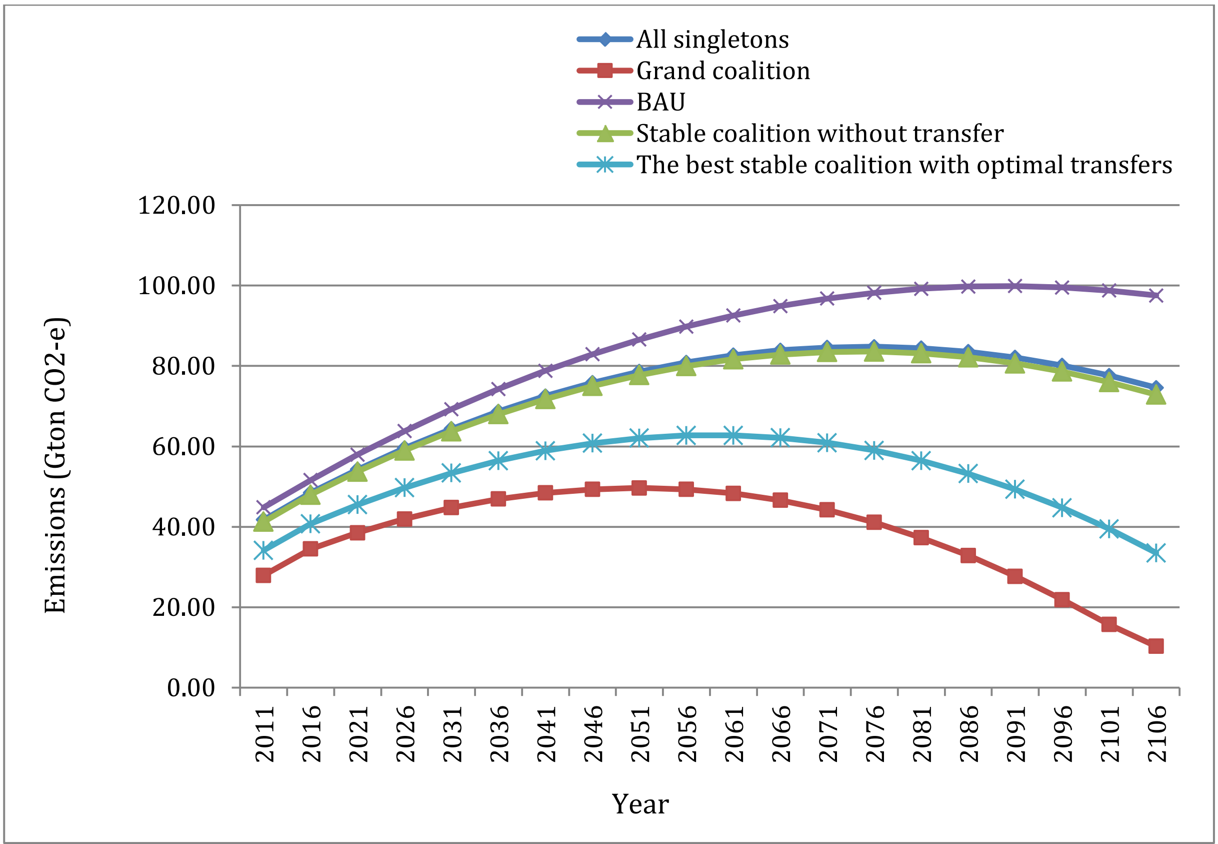

Figure 4.3 Emission paths for BAU, All singletons, Grand coalition, and stable coalitions without transfers {JPN, EUR}, and with optimal transfers {USA, EUR, ROE, CHN, IND, BRA, ROW}

5 Final Remarks

This document introduces the structure and functional specification of the STACO-3 model, and serves as background documentation for publications that use the STACO model. An updated overview of STACO-related publications can be found on www.enr.wur.nl/uk/staco.

Appendix I. STACO model equations

In the following, t refers to time ($t = 1,...,T$), i refers to regions ($i = 1,...,N$).

Variables

π_i = Payoff

q_{it} = Abatement

M_t = Concentrations of GHGs

ΔT_t = Temperature

d_{it} = Damages

b_{it} = Benefits of abatement

c_{it} = Abatement costs

Payoff function of region i (Objective function)

$$\pi_i(q_{1,...,}q_T) = \sum_{t=1}^{T} \{(1+r_{it})^{-t} \cdot (b_{it}(q_t) - c_{it}(q_{it}))\} \qquad \forall i \qquad \text{(AI.1)}$$

with $q_t \equiv \sum_{i=1}^{N} q_{it}$ and $r_{it} \equiv \rho + \eta \cdot \dot{y}_{it}$

Concentrations of greenhouse gases

$$M_t\left(M_{t-1}, q_t\right) = \left(1-\delta_M\right) \cdot M_{t-1} + \gamma_M \cdot \sum_{i=1}^{N} \left\{\overline{e}_{it} - q_{it}\right\} \;;\; M_0 = \overline{M_{2010}} \qquad \text{(AI.2)}$$

Temperature change

$$\Delta T_t(\Delta T_{t-1}, M_t) = (1-\delta_T) \cdot \Delta T_{t-1} + \gamma_T \cdot M_t \;;\; \Delta T_0 = \overline{\Delta T_{2010}} \qquad \text{(AI.3)}$$

Damages

$$d_{it}(\Delta T_t) = \theta_i \cdot (\gamma_D \cdot \Delta T_t) \cdot \overline{Y_{it}} \tag{AI.4}$$

Benefits of abatement

$$b_{it}(q_t) = \sum_{s=t}^{\infty} \left\{ \left(d_{is}(q_t = 0) - d_{is}(q_t) \right) \cdot \prod_{z=t+1}^{s} \left(1 + r_{iz}\right)^{-1} \right\} \tag{AI.5}$$

Abatement costs

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

Appendix II. Model parameters for the base specification

Symbol	Description	Value	Source
ρ	Pure rate of time preference	0.015	UK Treasury (2003)
η	Marginal elasticity of consumption	1	UK Treasury (2003)
δ_{M}	Calibration parameter of concentrations equation	0.0016	Own calculation based on EPPA model
γ_{M}	Transfer coefficient from emissions to concentrations	0.128	Own calculation based on EPPA model
$\overline{e_{it}}$	Business As Usual (BAU) greenhouse gases (GHGs) emissions by region	Time-specific	Own calculation based on EPPA model
$\overline{M_{2010}}$	Atmospheric concentrations of GHGs in 2010	479 ppm	EPPA model
δ_{T}	Calibration parameter of temperature equation	0.239	Own calculation based on EPPA model
γ_{T}	Transfer coefficient from concentrations to temperature change	0.053	Own calculation based on EPPA model
$\overline{\Delta T_{2010}}$	Atmospheric temperature change compared to 1900 in 2010	0.805 °C	EPPA model
θ_i	Share of region i in global benefits	see Table 3.3	Finus et al. (2006)
γ_D	Scale parameter of damage and benefit function	0.492	Own calculation based on Tol (2009); global marginal benefits amount to 41$/t$CO_2$-e in 2010
$\overline{Y_{it}}$	Production by region and period	Time-specific	Own calculation based on EPPA model
α_i	Abatement cost parameter of region i	see Table 3.4	Own calculation based on Morris et al. (2008)
β_i	Abatement cost parameter of region i	see Table 3.4	Own calculation based on Morris et al. (2008)
ς_i	Technological progress parameter	Region-specific: 0.005 / 0.01 / 0.02	Own calculation, loosely calibrated to Morris et al. (2008)

References

Altamirano-Cabrera, J.-C. and M. Finus, 2006, "Permit Trading and Stability of International Climate Agreements", *Journal of Applied Economics* 9, 19-47.

Altamirano-Cabrera, J.C., M. Finus, and R.B. Dellink, 2008, "Do abatement quota lead to more successful climate coalitions?", *The Manchester School* 76, pp. 104-129.

Dellink, R.B., 2011, "Drivers of stability of climate coalitions in the STACO model", *Climate Change Economics* 2(2), 105-128.

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)", *mimeo,* Wageningen University.

Dellink, R., T. Dekker and J. Ketterer, 2013, "The fatter the tail, the fatter the climate agreement", *Environmental and Resource Economics* 56, 277-305.

Dellink, R.B. and M. Finus, 2012, "Uncertainty and climate treaties: does ignorance pay?", *Resource and Energy Economics,* 34, 565-584.

Dellink, R.B., M. Finus and N.J. Olieman, 2008, "The Stability Likelihood of an international climate agreement", *Environmental and Resource Economics* 39, pp. 357-377.

Dellink, R.B., M. Nagashima, E.C. van Ierland, E. Hendrix, E. Sáiz and H.P. Weikard, 2009, "STACO Technical Document 2: Model description and calibration of STACO-2.1", *Mansholt Graduate School Discussion Paper* 49, Wageningen.

Finus, M., J.-C. Altamirano-Cabrera, E.C. van Ierland, 2005, "The Effect of Membership Rules and Voting Schemes on the Success of International Climate Agreements", *Public Choice* 125, 95-127.

Finus, M., E.C. van Ierland and R.B. Dellink, 2006, "Stability of climate coalitions in a cartel formation game", *Economics of Governance* 7, pp. 271-291.

Nagashima, M. and R.B. Dellink, 2008, "Technology spillovers and stability of international climate coalitions", *International Environmental Agreements: Politics, Law and Economics* 8, pp. 343-365.

Nagashima, M., R.B. Dellink, E.C. van Ierland and H.P. Weikard, 2009, "Stability of international climate coalitions – a comparison of transfer schemes", *Ecological Economics* 68, pp. 1476-1487.

Nagashima, M., H.P. Weikard, K.C. de Bruin and R.B. Dellink, 2011, "International climate agreements under induced technological change", *Metroeconomica* 62(4), 612-634.

Nordhaus, W.D., 1994, *Managing the global commons: The economics of climate change,* Cambridge: The MIT Press.

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker, 2005, "The MIT Emissions Prediction and Policy Analysis (EPPA) model: version 4", *MIT joint program on the science and policy of global change report* 125. Cambridge: MIT.

Paltsev, S. (2010). Baseline projections for the EPPA-5 model. Personal communication.

UK Treasury, 2003, *The Green Book: appraisal and evaluation in central government*, London.

Weikard, H.P., 2008, "Cartel stability under an optimal sharing rule", *Manchester School* 77(5), 599-616.

Weikard, H.-P., M. Finus, and J.-C. Altamirano-Cabrera, 2006, "The Impact of Surplus Sharing on the Stability of International Climate Agreements", *Oxford Economic Papers* 58, 209-232.

Weikard, H.P. and R.B. Dellink, 2014, "Sticks and carrots for the design of international climate agreements with renegotiations", *Annals of Operations Research*, 220, 49-68.

Weikard, H.P., R.B. Dellink and E.C. van Ierland, 2010, "Renegotiations in the greenhouse", *Environmental and Resource Economics* 45, 573-596.