Interaction in Climate Games
The Case of Emissions Trading

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Abstract: Climate games deal with the interaction among multiple actors on global, regional and local levels of climate policy, increasing or decreasing emissions of greenhouse gases. Emissions trading is an instrument of the Kyoto Protocol to achieve emission reductions in regions and business sectors where they are least costly. Emission paths and emission trading flows are analysed within a dynamic multi-agent game, with reaction functions depending on individual threshold prices, the level of allowed emission reductions and the possibility to shift to a low-emission production. Data-based computer simulation depicts the interaction between emission reductions and prices.

1 Climate games and emissions trading

A major task in international climate negotiations is to find agreed emission limits and trajectories that prevent dangerous climate change, in accordance with Art. 2 of the UN Framework Convention on Climate Change (UNFCCC). [Philibert/Pershing (2001), Ott etal. (2004)]. One of the key issues is to find a fair allocation of emission permits respecting these limits.[Leimbach (2003)] Even though developing countries are less responsible for climate change, they would be affected much stronger and would be less capable to take countermeasures. To deal with these asymmetries, industrialized countries with high per-capita emissions agreed in the Kyoto Protocol to cut them down.

One of the questions is to define levels and indicators for dangerous climate change that can be translated into emission trajectories. An established mechanism is the tolerable windows approach which defines guardrails for temperature change which in a reverse manner selects emission paths compatible with the guardrails.[Bruckner etal. (1999), Petschel-Held etal. (1999)]. A more general mathematical approach is viability theory which applies regulators to keep a dynamic system within viable constraints [Aubin/Saint-Pierre (2004)]. An associated problem is to find mechanisms to allocate emission limits and permits from global levels down to regional, national and local levels, including individual firms and consumers.

Actors are important in several ways as they can choose targets as well as actions. Target setting is the result of evaluation processes which take into consideration the selection or exclusion of certain sets of system states or trajectories, based on value functions. Actions are chosen according to given rules (rule-based behavior) or in order to achieve given target sets. In many cases the optimum of a defined value function is sought. Both approaches are combined in adaptive iteration towards reaction functions which depend on actions taken by other actors.

Climate games deal with the decisionmaking and interaction among multiple actors on global, regional and local levels of climate policy. Game theory provides the terminology and a theoretical framework to analyze interpedendent decisionmaking, negotiations and coalition formation in climate policy [Svirezhev etal. (1999), Finus (2001), Kemfert (2001), Grundig etal. (2001)]. For a large number of actors and criteria, and complex dynamic interactions other methods are appropriate, such as multi-criteria decisionmaking, dynamic games and agent-based modelling.[Brassel etal. (2000), Pickl (2001), Krabs/Pickl (2003), Weber etal. (2003)]. Expert interviews, stakeholder dialogues and experimental gaming provide additional methodologies to link climate modelling with the socio-economic world, currently a key issue in integrated assessment.[Moss (2002)].

Decisionmaking in climate games is complicated by the number of actors and multiple levels involved which interfer with each other. Multi-actor and multilevel decisionmaking can be analyzed with a top-down approach from global decisionmaking bodies, which define global targets for emission reductions, based on scientific assessment and evaluations of what is tolerable or dangerous climate change. Decisions are implemented on global levels as well as national and sub-levels. In a bottom-up approach, local actors such as citizens, consumers and companies pursue their individual interests, having an impact on higher levels, e.g. by electing municipal and national governments or by selecting products with more or less environmental impact. In reality both approaches interfer with each other across levels.

Market mechanisms are assumed to provide an efficient and cost-effective allocation. Emission trading is designed as a market instrument to achieve emission reductions in regions and business sectors where they are least costly. Some of the models in this field combine general equilibrium models with the selection of policy instruments (see the survey in [Springer (2003)]. The underlying micro-macro link is a challenge for the theory of emissions trading as well as for its implementation.

In this paper, emission paths and emissions trading are analysed in a game of multiple actors which act according to value functions, taking into account net benefits of economic growth as well as marginal damages of climate change, costs for emission reduction and the selling and buying of emission permits [see Scheffran/Leimbach (2003)]. This expands the author's modelling framework developed to analyze dynamic games in climate policy.[Scheffran/Pickl (2000), Ipsen et al. (2001), Scheffran (2002ab)]

2 The model framework for emissions trading

The task of climate policy is to keep total emissions $G(t) = \sum_{i=1}^{n} G_i(t)$ of $i = 1, ..., n$ actors in a time period t below a total allowed limit $G^*(t)$. and to translate it into admissible targets $G_i^*(t)$ for each actor. Regulations are designed to generate emission reductions $R_i(t) = r_i(t)\bar{G}_i(t)$ from an emission baseline $\bar{G}_i(t)$ for actor i such that actual emissions $G_i(t) = \bar{G}_i(t) - R_i(t) = \bar{G}_i(t)(1-r_i(t)) \leq G_i^*(t)$ stay within the limits. $r_i(t)$ is the percentage of reductions from the baseline. Emission reductions are associated with reduction costs, either by loss of production, consumption and thus benefits, or by investing into restructuring towards low-emission and high-cost technologies.

One option is to impose G_i^* as legal limits and leave it to actors i to obey these limits by whatever means, paying a fine if the limit is violated. More gradual is emission tax, i.e. actors pay an amount proportionate to emissions. A market approach is emissions trading, based on defined emission permits G_i^* and allocation plans for a group of actors to satisfy the collective limit. Each actor can buy or sell permits to increase or reduce emissions at a market price that results from the interplay of supply and demand, depending on the benefits and costs of emission reductions. While some actors acquire emission permits on the market if this is beneficial, others sell them.

In the following we develop the modelling framework to analyze the decision-making and interaction processes on emission reductions. Each actor can invest into production and consumption of economic goods, causing emissions and damages, and buy or sell emission permits. The value functions of actors are affected by the following terms:

- The benefits generated from production and consumption of economic output Q, measured by a utility function $U(Q)$
- Investments (costs and efforts) $C(G)$ associated with emissions G to generate economic output
- The damages and dangers in terms of utility losses $D(G)$ induced by emissions causing climate change
- The costs and income Π for buying or selling emission permits, in excess of allowed emissions G^*

Expressing all terms in units of utility gains and losses results in the value function $V = U - C - D - \Pi$. In the following, the four value terms are defined as non-linear functions:

$$\begin{aligned} Q &= q \cdot G^{\alpha}, \quad U = u^q \cdot Q^{\nu} = u^g G^{\mu} \\ C^G &= c^g \cdot G^{\beta}, \quad C^R = c^r \cdot R^{\gamma}, \quad D = d \cdot G^{\delta} \end{aligned}$$

Here we distinguish between the production costs C^G for generating emissions and the mitigation costs C^R for emission reductions. The factors q, c^g, c^r, d, u^q, u^g represent the respective output on the left-hand side for the first unit of input on the right hand side. Note that for $R < 0$ (emission increase) the abatement costs C^R are zero ($c^r = 0$). The parameters $u^g = u^q q^{\nu}$ and $\mu = \alpha\nu$ combine production and emissions in the utility function.

In emissions trading schemes, deviations $G - G^*$ from allowed emissions are taken into account with a term $\Pi = \pi \cdot (G - G^*)$ where π is the price per emission unit. Then for $i = 1, ..., n$ actors we have a non-linear value function of emissions G_i and emission reductions R_i, assuming exponents are equal for all actors:

$$V_i = U_i - C_i - D_i - \Pi_i = u_i^g \cdot G_i^\mu - c_i^g \cdot G_i^\beta - c_i^r \cdot R_i^\gamma - d_i \cdot G^\delta - \pi(G_i - G_i^*). \quad (1)$$

Note that damage is a function of total emissions $G = \sum_j G_j$. Introducing t as an index for a given time period and using $G_i(t) = \bar{G}_i(t)(1 - r_i(t))$ as reduced from baseline emissions in this period, we seek those percentage emission reductions $r_i(t) \leq 1$ that maximize the value function V_i (negative $r_i < 0$ represent emission increases). Thus we resolve $\partial V_i / \partial r_i \geq 0$ which leads to

$$(-\mu u_i^g \cdot G_i^{\mu-1} + \beta c_i^g \cdot G_i^{\beta-1} - \gamma c_i^r \cdot R_i^{\gamma-1} + \delta d_i \cdot G^{\delta-1} + \pi) \cdot \bar{G}_i - \pi_i'(G_i - G_i^*) \geq 0 \quad (2)$$

with $\pi_i' = \partial \pi / \partial r_i$. It is not possible to resolve this general non-linear equation for r_i but in special cases (see section 4).

3 The price mechanism

Resolving equation 2 for the threshold price leads to:

$$\pi \geq \mu u_i^g \cdot G_i^{\mu-1} + \beta c_i^g \cdot G_i^{\beta-1} - \gamma c_i^r \cdot R_i^{\gamma-1} - \delta d_i \cdot G^{\delta-1} + \pi_i'(1 - \frac{G_i^*}{\bar{G}_i}) \equiv \pi_i^*. \quad (3)$$

This threshold price increases with productivity u_i^g and decreases with damage per emission unit d_i and costs c_i^g, c_i^r. If marketprice exceeds this threshold ($\pi >$

π_i^*) it is profitable for actor i to sell emission permits, below this threshold it is profitable to buy emission permits. The actual permit price adjusts to this demand-supply interaction. For each actor the difference $\pi_i^* - \pi > 0$ is an incentive to buy permits while $\pi - \pi_i^* > 0$ is an incentive to sell them. Thus, this difference can be used to define individual demand and supply functions around the own threshold price π_i^* for actors $i = 1, ..., n$:

- Demand $\Delta G_i^+ = a_i^+(\pi_i^* - \pi) \geq 0$ (for $\pi \leq \pi_i^*$)

- Supply $-\Delta G_i^- = a_i^-(\pi - \pi_i^*) \leq 0$ (for $\pi \geq \pi_i^*$)

Parameters a_i^+ and a_i^- indicate the “reactivity” of demand and supply to the price difference which in the following we assume to be equal for actor i ($a_i^+ = a_i^- \equiv a_i$). Summing up all demands and supplies leads to the well-known linear demand and supply functions. Then market balance (supply=demand) leads to

$$\sum_i \Delta G_i = \sum_i a_i(\pi_i^* - \pi) = 0.$$

Thus, for homogenous reactions $a_i = a$ for all actors $i = 1, ..., n$, the market price is the average of all marginal value gains

$$\pi = \frac{\sum_i a_i \pi_i^*}{\sum_i a_i} = \sum_i \frac{\pi_i^*}{n} \tag{4}$$

which does not depend on individual reactivity but on productivity, marginal costs and damages of all actors.

4 Interaction for linear-quadratic value functions

For analytical purposes we now treat linear-quadratic functions of G_i. In particular, it is assumed that both utility and costs of production are linear functions in emissions while mitigation costs and damages are quadratic functions. Skipping the upper index in c_i^r and using $u_i = u_i^g - c_i^g$ as utility gain (net growth) per emission unit, we obtain for constant allowance

$$V_i = u_i G_i - d_i G^2 - c_i R_i^2 - \pi(G_i - G_i^*) \quad (5)$$

Further emission reductions increase value for

$$\frac{\partial V_i}{\partial r_i} = (-u_i + 2d_i G - 2c_i r_i \bar{G}_i + \pi)\bar{G}_i - \pi_i'(\bar{G}_i(1 - r_i) - G_i^*) \geq 0. \quad (6)$$

This leads to the threshold condition for optimal emission reductions

$$r_i \leq \frac{(\pi - u_i + 2d_i[\bar{G}_i + \sum_{j\neq i} \bar{G}_j(1 - r_j) - \pi_i'(1 - G_i^*/\bar{G}_i)}{2\bar{G}_i(d_i + c_i) - \pi_i'} = r_i^*. \quad (7)$$

Below this threshold actor i would continue reduction to increase value, above this threshold diminish reduction, thus from both sides would approach the optimum r_i^*. The reduction threshold increases linearly with emission price π and decreases with the amount of own emissions $\bar{G}_i$ and unit reduction costs c_i. It also decreases with emission reductions r_j of other actors j, because marginal damage is lower in a world with lower emissions.

Resolving the threshold condition leads to a threshold price

$$\pi \geq u_i + 2c_i r_i \bar{G}_i - 2d_i G + \pi_i'((1 - r_i) - G_i^*/\bar{G}_i) = \pi_i^*$$

If price is above this threshold, further emission reductions increase value. Below it, emission reductions decrease value und would be avoided by actor i.

Neglecting π_i' in a first approximation, according to the analysis in the previous chapter the market price of emissions is the average of the threshold prices of all actors (with $a \equiv a_i$ for $i = 1, ..., n$)

$$\pi = \frac{\sum_i \pi_i^*}{n} = \frac{\sum_i u_i + 2c_i r_i \bar{G}_i - 2d_i G}{n}. \tag{8}$$

which depends on benefits, costs and damages per emission unit of all actors. With the partial derivative of the approximate price function $\pi_i' = 2\bar{G}_i(c_i + d)/n$ (with $d = \sum_j d_j$) we obtain the price-adjusted optimal reduction for actors $i = 1, ..., n$

$$r_i^* = \frac{\sum_{j \neq i} \pi_j^* + u_i - 2d\bar{G}_i - n(u_i - 2d_i(\bar{G}_i + G_{-i})) + 2(G_i^* - \bar{G}_i)(c_i + d)}{2\bar{G}_i[(n-1)(d_i + c_i) - d_{-i}]} \tag{9}$$

where $G_{-i} = \sum_{j \neq i} \bar{G}_j(1 - r_j)$ and $d_{-i} = \sum_{j \neq i} d_j$. The reaction curves $r_i^*(r_{-i})$ represent targets for emission reduction of actor i as a function of emission reduction vectors $r_{-i} = (r_1, ..., r_{i-1}, r_{i+1}, ..., r_n)$ of all other actors, except r_i. The slopes of the reaction curves are given by

$$\frac{\partial r_i^*}{\partial r_j} = \frac{2\bar{G}_j(c_j + d_{-i} - nd_i)}{2\bar{G}_i[(n-1)(d_i + c_i) - d_{-i}]}.$$

The signs of these conjectural variations determine whether emission reduction of actor j induces reduction or increase for actor i. The numerator and denominator are both positive for $\frac{d_{-i}}{n-1} - c_i \leq d_i \leq \frac{d_{-i}+c_j}{n}$. For moderate marginal damages for actor i and marginal reduction costs c_i and c_j this condition could be satisfied which implies that reductions by one actor j induce reductions by actor i. If however the marginal damages are either excessively high or low, then the slope becomes negative and actors behave asymmetrically. For emission increases of actor j, the reaction curve changes fundamentally because marginal reduction costs are zero ($c_j = 0$). Then the sign of the numerator is only a function of the marginal damages.

Actors who seek to adapt to their respective optimal reductions r_i^* can be represented by an iterative adjustment procedure (tatonnement)

$$\Delta r_i(t) = r_i(t+1) - r_i(t) = \alpha_i^r (r_i^*(t) - r_i(t)) \quad (i = 1, ..., n).$$

In this set of dynamic difference equations, the reactivity parameter α_i^r determines the speed of adaptation. For $\alpha_i^r = 1$, actor i would jump in a single time step to the optimal reduction which however moves as a result of actions of other actors. Whether a stable Nash equilibrium exists depends on the combination of marginal benefits, costs and damages of all actors.

5 Model specifications

After explaining the basic model, we now treat some model specifications to deal with some particular aspects relevant in model applications.

1. So far the threshold prices π_i^* of all actors have the same relevance for the market price π, how "small" an actor may be. This can be modi-

fied by giving more weight to bigger or more powerful actors (e.g. those with higher emissions or GDP). In particular, setting price reactivity proportionate to emission baselines, $a_i = a\bar{G}_i$, we obtain the market price $\pi = \sum_i \pi_i^* \bar{G}_i/\bar{G}$, weighted with the emission fractions $\bar{G}_i/\bar{G}$ of total emissions. The partial derivative easily modifies to $\partial\pi_i/\partial r_i = \sum_j (\partial\pi_i^*/\partial r_i)(\bar{G}_i/\bar{G})$.

2. We distinguish two different ways of emission reductions where ρ_i defines the share for one or the other, allowing to explore different reduction scenarios:

   - Emission reductions $\rho_i R_i$ associated with production or consumption losses. Marginal net benefits are replaced by $u_i \rho_i$.
   - Emission reductions $(1-\rho_i)R_i$ by reducing emissions per production unit, e.g. by investing into more efficient, low-emission technologies. Marginal abatement costs are replaced by $c_i(1-\rho_i)^2$.

   The other two value terms (damage D_i, emissions trading Π_i) still depend on complete emission reductions $r_i = \rho_i r_i + (1-\rho_i)r_i$.

3. Marginal net benefits u_i are not treated as constant but vary with the baseline emissions $\bar{G}_i$. We assume that for higher emissions marginal benefits decline according to $u_i/\bar{G}_i^\omega$ with exponents $0 \leq \omega \leq 1$, which implies higher marginal benefits at lower emissions.

4. Besides the condition $v_i^r = \partial V_i/\partial r_i \geq 0$ we also take into account the condition $V_i \geq 0$ to be satisfied. This defines boundaries for emission

reductions and emission prices within which net value losses can be avoided. This leads to a threshold price for zero value $V_i = 0$

$$\pi_i^0 \equiv \frac{u_i \bar{G}_i (1-r_i) - d_i (\sum_j \bar{G}_j (1-r_j))^2 - c_i r_i^2 \bar{G}_i^2}{\bar{G}_i (1-r_i) - G_i^*}.$$

Positive value is assured for $\pi < \pi_i^0$ and $G_i(1-r_i) > G_i^*$ or for $\pi > \pi_i^0$ otherwise. Resolving for r_i leads to a quadratic equation of emission reductions to keep net economic growth $V_i > 0$. The actions of actors depend on both thresholds and their combination, leading to four different types of behavior ($V_i > 0$ and $v_i^r > 0$; $V_i > 0$ and $v_i^r < 0$; $V_i < 0$ and $v_i^r > 0$; $V_i < 0$ and $v_i^r < 0$).

5. An essential question is how to allocate global reduction permits G^* to the individual actors $i = 1, ..., n$, depending on global targets $G^*(t)$ and baseline emissions $\bar{G}_i(t)$. Two different mechanisms are taken here into consideration:

   - Allocation of permits is proportionate to population N_i, $G_i^* = G^* \frac{N_i}{N}$, where N is the world population.

   - Allocation of permits is proportionate to the amount currently emitted $G_i^* = \kappa \cdot \bar{G}_i$. where $\kappa = G^* / \sum_i \bar{G}_i$. Thus, larger emitters who demand more emissions have the right for a bigger share but also would have to take a greater share of reduction.

6 Computer simulation of emissions trading

In the following we simulate the dynamic interaction in emissions trading, based on the outlined model and stylized data used in the ICLIPS model [Leimbach (2003), Leimbach/Toth (2003)], expanding the approach developed in [Scheffran/Leimbach (2003)] from a single-step optimization to a multi-step dynamic system. To compute the threshold and permit prices as well as optimal emission reductions we apply the Gross Domestic Product (GDP) and emissions data of the year 2005, as used in the ICLIPS reference scenario. For the linear-quadratic value function defined in equation 5 net economic growth (production minus costs) is assumed to be 3%. The damage and the mitigation cost functions are calibrated on the data point assuming that 5% incremental reduction leads to 2% loss of damage or economic growth.

The figures show results from simulations of the linear-quadratic approach (equation 5), where the final prices and optimal reductions are based on the iterative adjustment procedure outlined in section 4. For each time step $t = 1, ..., 25$, starting with a given emission baseline $\bar{G}_i(t)$ and allowed emissions $G_i^*(t)$, we let the interactive iteration run with an iteration index $l = 1, ..., L$ to determine reductions $r_i^l(t)$ gradually moving towards the optimal reductions $r_i^*(t)$ of all actors. The results $r_i(t) = r_i^L(t)$ from the iteration are used as input into the next time period $t + 1$, to determine the increased or reduced emission baseline $\bar{G}_i(t+1) = \bar{G}_i(t)(1 - r_i(t)) = G_i(t)$ to calculate emission price and optimal reductions for the next period. Allowed emissions $G_i^*(t)$ are based on the equity principle to gradually achieve equal emissions per capita in 25 years in all regions (using population of 2005 as fixed), certainly a tough requirement.

The results are depicted in the following figures where the following acronyms are used for the 11 regions: AFR Sub-Saharan Africa; CPA China, Mongolia, Vietnam, Cambodia, Laos; EEU Eastern Europe; FSU Former Soviet Union; LAM Latin America and the Caribbean; MEA Middle East and North Africa; NAM North America; PAO Pacific OECD (Japan, Australia, New Zealand); PAS Other Pacific Asia; SAS South Asia (mainly India); WEU Western Europe.

Depicted are emissions per capita and values for each region as well as total emissions and emission price. By using the parameter ρ we distinguish two different mixes of emission reductions. In the first case (Figure 1), represented by $\rho = 0.75$, one quarter of emission reductions is realized through restructuring and modernization of production while the rest results from production losses. The second case is the opposite (Figure 2), three quarters of emission reductions is realized through modernization ($\rho = 0.25$).

The results are quite different. In case 1, only two regions significantly buy permits and thus increase emissions per capita (WEU and Pacific OECD) which are also the regions with the highest value gains. The other regions either keep emissions almost constant or sell emission permits (first of all Russia) and thus reduce emissions per capita. This includies North-America which starts with highest per capita emissions and reaches value losses during the process. Finally for all regions values go up, due to avoided damage and diminishing mitigation costs at lower emission levels. Total emissions slightly go down (from about 8 to 7 Gigaton Carbon) while the permit price goes up from about 60 to

80 Dollars per ton of carbon. In case 2, basically no region significantly increases emissions, leading to an overall reduction of about 50% in 25 years, while permit price increases from about 25 to 40 Dollars/tonC. However, due to high mitigation costs the values of all regions start in the negative range and move up to zero values.

The analysis shows the significance of finding the proper mix between the two options of reducing emissions. Shutting down production facilites is a way of reducing emissions if they are replaced by lower-emission technologies at moderately higher costs. The results should not be overstated in this reduced model since both the equal emissions per capita assumption and the square functions in damage and mitigation cost overdraw the effect. Further analysis can take this into consideration by modifying our approach with more appropriate assumptions.

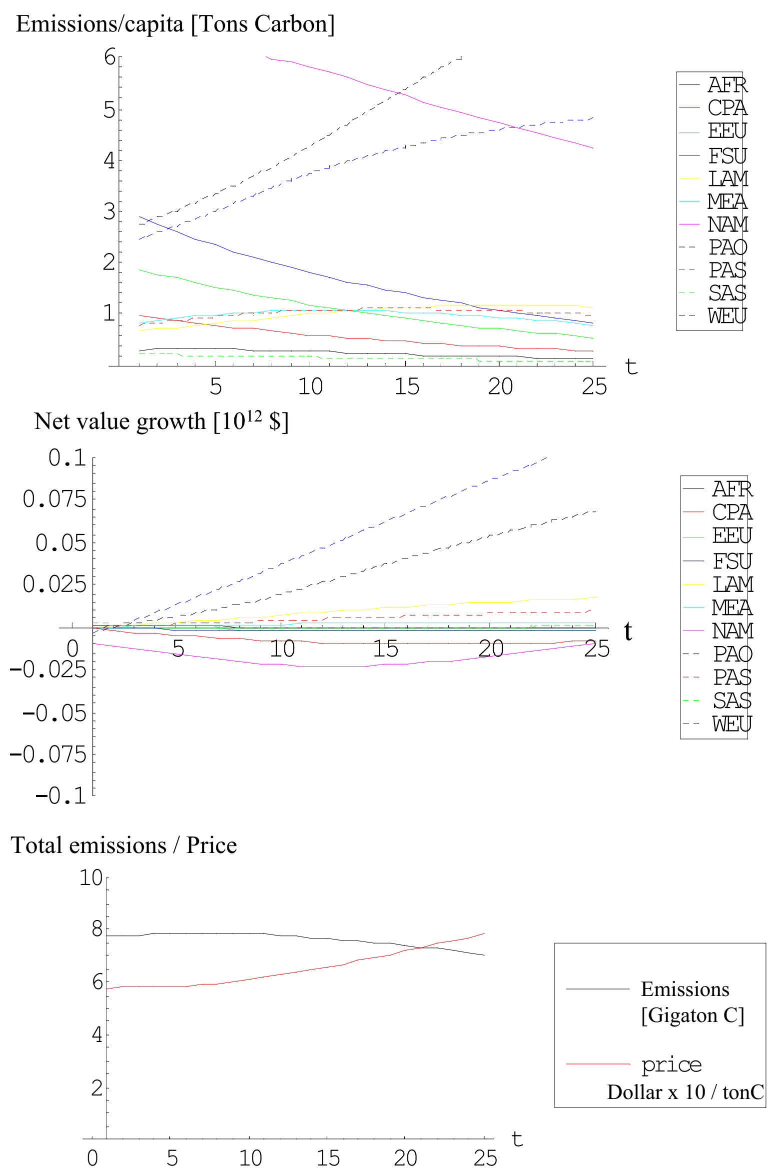

Figure 1: Computer simulation of emission tradings among 11 world regions for $\rho = 0.75$. Depicted are emissions per capita and net value growth for each region as well as total emissions and emission price.

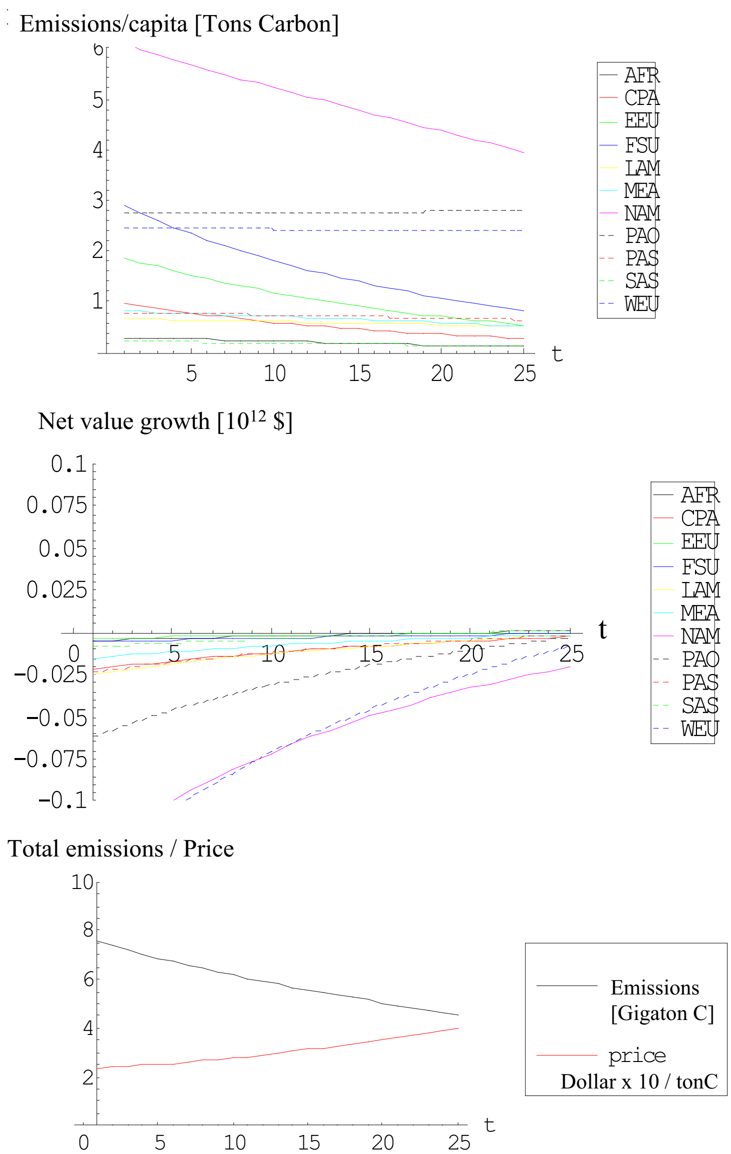

Figure 2: Computer simlation of emission tradings among 11 world regions for $\rho = 0.25$.

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