# ECONOMIC DEVELOPMENT AND EMISSION CONTROL OVER THE LONG TERM: THE ICLIPS AGGREGATED ECONOMIC MODEL

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**Abstract.** In integrated assessments of climate change, greenhouse-gas emissions and climate change impacts provide the linkages between the world economy and the climate system. Key climatic processes operate at the scales of centuries. This requires highly aggregated models for portraying the dynamics of the economic system. An extended Ramsey-type optimal growth model is presented as the appropriate tool to be integrated with a reduced-form climate model in the ICLIPS integrated assessment. The eleven-region model of the world economy involves exogenous population and endogenous investment dynamics with productivity progress based on a technological diffusion model. World regions are linked via intertemporal trade flows of the composite consumption/investment good, capital mobility, and emission permit trading. Coupled with the ICLIPS Climate Model, the Aggregated Economic Model can determine corridors of permitted long-term carbon emission paths or, as primarily discussed in this paper, specific cost-effective emission trajectories. The sensitivity of mitigation costs to externally specified climate change/impact constraints and to to assumptions about non-$CO_2$ greenhouse-gas emissions flexibility is also discussed.

**Keywords:** climate stabilization target, integrated assessment, long-term economic model, tolerable windows approach

**Abbreviations:** AEM – Aggregated Economic Model; IAM – integrated assessment model; ICLIPS – Integrated Assessment of Climate Protection Strategies; GHG – greenhouse gas

## 1. Overview and Objectives

One of the main challenges faced by developers of Integrated Assessment Models (IAMs) addressing the climate change problem is to find the proper compromise between the spatial and temporal scales and resolutions of the models they need to integrate. The nature of climatic change (global, long-term problem with diverse sources and a multitude of impacts) requires a global model with some regional detail that covers dynamic processes of socioeconomic development and environmental change over at least a century. This leaves little choice for economists in selecting their tools: highly aggregated and drastically simplified models are needed to capture the key factors and processes that determine future emissions of greenhouse-gases (GHGs) and the social costs of their control. The DICE/RICE family of models (see Nordhaus, 1992, 1994; Nordhaus and Boyer, 2000), MERGE (Manne et al. 1995) or MiniCAM (Edmonds et al., 1996) demonstrate different ways to tackle this problem.

As explained and illustrated in earlier papers in this Special Issue, the mandate for the project on Integrated Assessment of Climate Protection Strategies (ICLIPS) is to develop an IAM suitable to conduct inverse assessments of long-term climate

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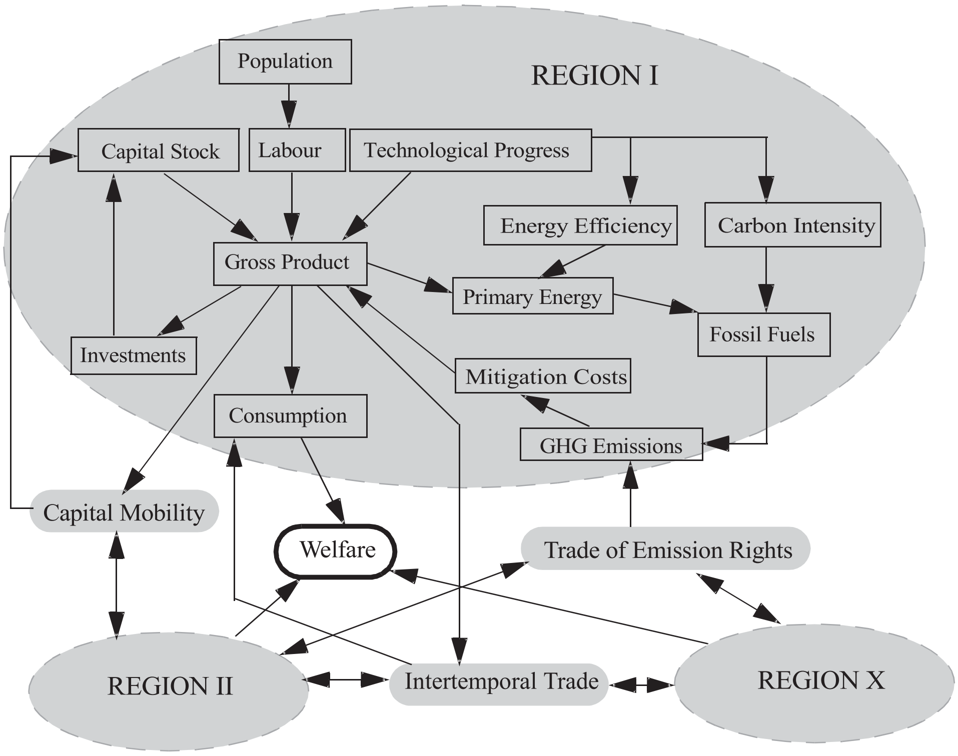


*Figure 1.* Structure of the ICLIPS Aggregated Economic Model (AEM)

stabilization strategies. Accordingly, the Aggregated Economic Model (AEM) adopted in the ICLIPS framework is built on a classic formulation of optimal growth models (Ramsey, 1928; Solow, 1970). This makes it a relative of the DICE/RICE family. The AEM elucidates endogenously the (transitional) investment and capital accumulation cycle. The actors' behavior and decisions are taken to be optimal and based on perfect foresight. Intertemporal optimization and perfect foresight are assumed to characterize the behavior of global actors with purpose and long-term perspective. In particular, decisions about the distribution of available income in investments and consumption are governed by this foresight. Figure 1 gives an overview of the model.

Based on exogenous assumptions about population dynamics and technological development, the AEM determines the economic development of each region. The key control variable is the rate of investment. In addition, the dynamics of growth is influenced by interregional linkages (trade and mobility of capital).

The adoption of the optimal growth model in climate policy analysis introduces additional components that influence growth dynamics. They include climate protection measures (i.e., emission reduction targets) and climate policy instruments (i.e., trade in emission permits). The actual costs of climate protection depend on the user-defined scheme of burden sharing and on the regional dynamic mitigation cost functions.

Similarly to all other IAMs, the ICLIPS AEM takes on the risky business of looking into the distant future. However, it is by no means a forecasting model. It is driven by a large number of assumptions included in model parameters or exogenous scenario variables. Nevertheless, the model provides consistent images of the future and useful insights for climate policy.

## 2. The Structure of the Aggregated Economic Model

This section presents an overview of the AEM structure and explains the model equations in a succinct form. Throughout this presentation, we use the following indices:

| | | |
|---|---|---|
| i, h | - | regions |
| j | - | greenhouse gases |
| k | - | traded goods (1 = composite good; 2 = emission permits) |
| t, $\tau$ | - | time index |
| r | - | iteration index. |

Social welfare represents the target criterion in setting and assessing the path of optimal growth. The economic growth model assumes utility-maximizing actors and includes a welfare optimizing "Global Planner". Welfare ($W$) is measured as the utility of per capita consumption ($c$):

$$W = \Sigma_t \Sigma_i (nw_i * POP_{it} * e^{-\rho t} * log(c_{it})) \tag{1}$$

The logarithmic utility function implies that an incremental unit of income in regions and for generations with low income produces a greater contribution to their welfare than for their more affluent counterparts. The discount factor, that includes the pure rate of time preference $\rho$, determines the extent to which current consumption is traded off against future consumption. *POP* is the population size and *nw* is a weighting factor in aggregating regional welfare values in a global welfare function (see Section 3 and Appendix).

The main component of the growth model is the macroeconomic production function. It represents the physical volume of production (measured in US$) as a function of the physical volume of production factors, capital and labor (capital is also measured in monetary units adjusted to price influences). The production function thus reflects the technological characteristics of aggregated production processes.

In the ICLIPS AEM, a Cobb-Douglas function is used. It assumes a constant elasticity of substitution of production factors and constant returns to scale, i.e., $\alpha$+$\beta$=1:

$$Y_{it} = A_{it} * K_{it}{}^{\alpha_{it}} * POP_{it}{}^{\beta_{it}}\ , \qquad i = 1, \ldots, n;\ t = 1, \ldots, T. \tag{2}$$

*Y* is the output, *K* is capital POP represents labor, $\alpha$ is the output-capital elasticity, $\beta$ the output-labor elasticity and *A* represents total factor productivity (TFP). Although this suggests that theoretically the production factors capital and labor can be substituted indefinitely, these processes do have economic limits as a result of declining marginal productivities.

The objective of the AEM is to describe the processes of economic development over time (e.g., gross national product, per capita income) rather than their constant or steady state growth rates. This approach is based on the combination of the endogenous capital accumulation cycle and a technological diffusion model (cf. Ciscar and Soria, 2000).

The capital accumulation cycle (with investments *I* and depreciation rate $\delta$) is based on investment decisions that, for any point in time, compare current reduction of consumption to a later increase of consumption resulting from expansion of the basis of production:

$$K_{it} = (1 - \delta_{it}) * K_{i,t-1} + I_{i,t-1} \;, \qquad i = 1, \ldots, n; \; t = 1, \ldots, T. \tag{3}$$

Technological progress is represented by a simple diffusion equation, presupposing the convergence of total factor productivity change rates (*tfpr)* under the assumption that production technologies will be exchanged between developed and less developed regions. A diffusion parameter *(tdf)* determines the speed of this adjustment:

$$A_{it} = (1 + tfpr_{it}) * A_{i,t-1} \;, \qquad i = 1, \ldots, n; \; t = 1, \ldots, T \;, \tag{4}$$

$$tfpr_{it} = tdf_i * (tfpr_{max,t-1} - tfpr_{i,t-1}) \;, \qquad i = 1, \ldots, n; \; t = 1, \ldots, T \;, \tag{5}$$

where $tfpr_{max}$ is the exogenously specified growth rate of TFP in the most advanced region.

The AEM is a multiregional global model. Although this makes data collection and scenario specification considerably more difficult, it provides a better description of the dynamics relevant to climate change. The model can cope with the disparate present conditions and future development paths of different regions. It can also depict essential elements of growth dynamics that result from interactions among regions. Finally, regional differences in mitigation potentials and conflicting interests in climate policy can also be studied.

Three fundamental types of interregional relations are distinguished in our AEM: intertemporal trade, mobility of capital, and trade in emission rights.

Taking the form of direct foreign investments, the mobility of capital is a fundamental element of the growth dynamics. International capital transfers are motivated by differences in regional rates of return to capital. This accelerates economic development in the capital importing regions while the source regions also benefit from higher returns. Transfers of capital (*CA*) between regions are balanced in each period:

$$\Sigma_i CA_{it} = 0 \;, \qquad t = 1, \ldots, T. \tag{6}$$

Trade in capital, unlike other forms of trade, generates net foreign assets (*NFA*) and establishes a claim for interest (*RR*) by the exporter:

$$NFA_{it} = (1 + RR_{t-1}) * NFA_{i,t-1} + CA_{it} \ , \quad i = 1, \ldots, n; \ t = 1, \ldots, T \quad (7)$$

with

$$RR_t = \Sigma_i((\alpha_{it} * Y_{it})/K_{it} - \delta_{it})/n \ , \qquad t = 1, \ldots, T. \quad (8)$$

It is difficult for economic theory to explain why, in spite of higher return rates in developing regions, the flow of capital to these regions is relatively small. The usual explanation is that investors in developing regions have to pay an implied risk premium. Recent attempts to explain this phenomenon start from a non-equilibrium model that takes errors in estimating return rates into account in explaining international mobility of capital (Ianchovichina et al., 1999). In our model, capital mobility is approximately adjusted to real trade flows by keeping interest rates only at the level of internationally averaged return rates on capital and simultaneously limiting the volume of capital flows and net foreign assets to a certain percentage of total gross product (*fmax, fmin, expo, impo*). This yields:

$$NFA_{it} \leq fmax * Y_{it} \ , \qquad i = 1, \ldots, n; \ t = 1, \ldots, T \, ; \quad (9a)$$

$$-NFA_{it} \leq fmin * Y_{it} \ , \qquad i = 1, \ldots, n; \ t = 1, \ldots, T. \quad (9b)$$

Terminal conditions of the model prescribe that all foreign assets are withdrawn and thus all obligations from capital transfers are fulfilled by the end of the time horizon:

$$NFA_{iT} = 0 \ , \qquad i = 1, \ldots, n. \quad (10)$$

The following current account restrictions affect both capital mobility and trade flows (*NTX*):

$$CA_{it} + NTX_{ikt} \leq expo * Y_{it} \ , \quad i = 1, \ldots, n; \ k = 1; \ t = 1, \ldots, T \, ; \quad (11a)$$

$$-CA_{it} - NTX_{ikt} \leq impo * Y_{it} \ , \quad i = 1, \ldots, n; \ k = 1; \ t = 1, \ldots, T. \quad (11b)$$

In the model setting described in Section 5.2 (policy scenario 1), there is a joint binding rate of around 50% for the constraints (9) and 70% for the constraints (11), with constraint (11b) as most restrictive in quantity (nearly 50%) as well as in quality (highest marginal values).

In a sectorally aggregated model producing one homogenous composite good, commodity trade takes place only if temporal flexibility (temporary trade deficit) is permitted and when paying for emission permits. Exports and imports of emission permits and the composite good are balanced in each period:

$$\Sigma_i NTX_{ikt} = 0 \ , \qquad k = 1, 2; \ t = 1, \ldots, T. \quad (12)$$

Each region exports to and imports from a common pool. This formulation yields transparency and numerical efficiency.

Emissions trading is an essential feature of the model. The exchange of "physical" units of emission rights (measured for instance in gigatons (Gt) of carbon) has to be distinguished from the payment for it (in units of the composite good). These exchange processes do not necessarily occur in the same period.

Emission trading in AEM is based on the concept of differentiated burden sharing (as agreed in the Kyoto Protocol). This is implemented through the initial allocation of emission rights rather than by setting regional reduction targets. The regions' share in the pool of total emission rights is specified while the absolute level of allocated emission rights is determined endogenously.* Based on the initial allocation of emission rights and unlimited permit trading, emissions can be reduced in regions with the lowest marginal abatement costs. This arrangement maximizes emissions reductions for a given cost or minimizes the costs for a given reduction target.

The initial distribution of emission rights exerts a decisive influence on the price of the emission rights and on the extent of permit trade. The criteria to use in distributing emission rights are fiercely debated on economic, political, and ethical grounds (see, e.g., Rose et al, 1998; Ringius et al., 1998). Many analysts argue that in the long term an equal per capita distribution seems to be the fairest solution. In the short term, however, this distribution principle would give developing countries a great advantage (they could sell a large part of their emission rights). In the world of political reality, there is little chance of such a burden-sharing scheme being accepted in the near future.

A combined distribution principle has perhaps a greater chance of actually being implemented. We assume an allocation routine in which an initial grandfathering (status quo) distribution of emission rights gradually turns into a per capita distribution (whereby it must be noted that such a distribution is relatively unfavorable to rapidly expanding regions such as China and Southeast Asia). With *SH* and *PSH* as one region's shares in the pool of global emission rights and in global population, respectively, and with *LQ* as the period during which the transition to equal per capita distribution is completed, we get:

$$SH_{it} = PSH_{it} \, , \qquad i = 1, \ldots, n; \; t = LQ, \ldots, T \tag{13}$$

$$SH_{it} = ((LQ - t) * SH_{i,0} + (t - 1) * PSH_{it})/(LQ - 1) \, , \qquad i = 1, \ldots, n; \; t = 1, \ldots, LQ - 1. \tag{14}$$

Another important choice to be made is whether to use a static or a dynamically-adjusted basis in the per capita distribution. The former allocates emission rights according to the population distribution in a particular year while the latter observes

* The intended long-term analysis goes far beyond the time horizon of the Kyoto Protocol. Short-term adaptation and mitigation measures are not considered in detail. Hence, we do not attempt to base the analysis on the specific reduction targets of the Kyoto Protocol.

changes in population distribution. The former option could provide a stimulus to an active demographic policy.

A further point in climate policy discussions concerns the limitation of trade in emission rights. This would increase mitigation costs in general. The intention is to limit the trade in so-called “hot air” or “tropical air” (emission rights that cannot be utilized economically) and to induce technological change by obliging the industrial nations to undertake emission reduction efforts domestically. The export of emission rights can be restricted most efficiently in relation to the amount of originally allocated emission rights. If *xperm* represents the respective share parameter, and *GLR* is the global pool of emission rights, we get:

$$NTX_{ikt} \leq xperm * SH_{it} * GLR_t \ , \quad i = 1, \ldots, n; \ k = 2; \ t = 1, \ldots, T. \quad (15)$$

Restrictions on emission rights import are related to actual emissions (with *mperm* as cap):

$$- NTX_{ikt} \leq mperm * EM_{ijt} \ , \qquad i = 1, \ldots, n; \ j = \text{‘}CO2\text{’}; \ k = 2; \ t = 1, \ldots, T. \quad (16)$$

When emissions reductions are required, and restrictions (15) and (16) hold, regions would buy emission permits as long as the purchase price is lower than their marginal abatement costs. Similarly, other regions sell their emission permits while their mitigation costs remain below the permit price. By assuming unlimited trading and no transaction costs, marginal costs of abatement will be equalized globally.

The regional costs of emission reductions are represented by dynamic mitigation cost functions. In integrated assessment models, mitigation cost functions represent the link between the magnitude of emission reductions relative to a reference path and the resulting economic costs. Traditional mitigation cost functions are quasi-static functions that are actually valid only for a single point in time. The parameters in traditional mitigation cost functions (see Nordhaus, 1994) are constant (at least for long periods), i.e., the cost of subsequent emission reductions is the same regardless of preceding reduction efforts. Research by Grübler and Messner (1998) explore explicit mitigation cost functions that alleviate these shortcomings by considering cumulative (learning) processes. In addition to the customary progressive cost dynamics (cost parameter *b2>1* in Equation (19) below), technological learning leads to relative cost reductions, i.e., the larger the volume of reduction already undertaken, the cheaper further reduction becomes. This relationship is implemented in AEM by linking the mitigation costs to the cumulative amount of reduction.

The mitigation cost function implemented in our model hides basic relationships of the energy system (see Section 4). It consists of four equations and applies to $CO_2$ only. Climate protection measures absorb a part of the produced gross product which is then no longer available for investments or for private and public consumption. The income loss, expressed in terms of gross domestic product

(GDP) loss, in any given period is the difference in potential cumulative loss of regional gross product (*GPLO*) between two consecutive periods of time (see also Gritsevskii and Schrattenholzer, 2002):

$$NY_{it} = Y_{it} - (GPLO_{it} - GPLO_{i,t-1}) \ , \qquad i = 1, \ldots, n; \ t = 1, \ldots, T \ , \quad (17)$$

where *NY* represents the gross product net of climate protection cost.

The potential cumulative loss in GDP in year t is given by the sum of gross product calculated for the years 1 to t, weighted by the mitigation costs (*DCR*) for the year t:

$$GPLO_{it} = \Sigma_{\tau \leq t} Y_{i\tau} * DCR_{ijt}, \quad i = 1, \ldots, n; \ j = \text{‘CO2’}; \ t = 1, \ldots, T. \quad (18)$$

The equation for determining *DCR* formally corresponds to a traditional mitigation cost function, with enhanced regional and temporal resolution. However, the independent variable is not the emission reduction (related to the reference emission path *BEM*) in year t, but the cumulative amount of emission reduction $\mu$:

$$DCR_{ijt} = b1_{ijt} * {\mu_{ijt}}^{b2_{ijt}}, \quad i = 1, \ldots, n; \ j = \text{‘CO2’}; \ t = 1, \ldots, T \ , \quad (19)$$

where

$$\mu_{ijt} = \Sigma_{\tau \leq t}(BEM_{ij\tau} - EM_{ij\tau}) / \Sigma_{\tau \leq t} BEM_{ij\tau} \ , \qquad i = 1, \ldots, n; \ j = \text{‘CO2’}; \ t = 1, \ldots, T \ . \quad (20)$$

*EM* represents the actual emissions, and *BEM* is the reference emission. The cost function parameters $b1$ and $b2$ are time-dependent and regionally differentiated. Reference emissions are computed ex ante as the product of carbon intensity, energy intensity, and total output in a restricted model setting containing equations (1)-(12), (24) and (25).

The emission variable *EM* is derived from the equations of the mitigation cost function. Due to a climate protection objective (or an impact threshold), emissions are expected to diverge from the baseline (reference path). Two equations describe additional constraints. The first one requires emissions not to exceed the amount of allocated plus imported emission permits:

$$EM_{ijt} \leq SH_{it} * GLR_t - NTX_{ikt} \ , \qquad i = 1, \ldots, n; \ j = \text{‘CO2’}; \ k = 2; \ t = 1, \ldots, T. \quad (21)$$

The second constraint keeps the sum of regional emissions below the global emission limit:

$$\Sigma_i EM_{ijt} \leq GLR_t \ , \qquad i = 1, \ldots, n; \ j = \text{‘CO2’}; \ t = 1, \ldots, T. \quad (22)$$

Due to the effect of discounting, the weight of incomes in the more distant future is declining in the present-value welfare measure. Simultaneously, mitigation costs significantly decrease over time due to autonomous efficiency improvements (i.e. $b1_t < b1_{t-1}$). The latter may dominate the cost-reducing effect of learning-by-doing and could imply drastic reductions in later periods at nearly no costs even without earlier mitigation. In order to restrict extreme model behavior, the emission reduction rate is limited to *err*:

$$1 - EM_{ijt}/EM_{ij,t-1} \leq err \ , \quad i = 1, \dots, n; \ j = 1, \dots, m; \ t = 1, \dots, T. \quad (23)$$

The income computed in Equation (17) is reduced by net exports and increased by net imports (negative *CA* and *NTX*). We close our model with the following balance equation that determines the consumption level C:

$$C_{it} = NY_{it} - I_{it} - CA_{it} - NTX_{ikt} \ , \quad i = 1, \dots, n; \ k = 1; \ t = 1, \dots, T. \quad (24)$$

Per capita consumption is derived by:

$$c_{it} = C_{it}/POP_{it} \ , \qquad i = 1, \dots, n; \ t = 1, \dots, T. \quad (25)$$

Finally, at the interface between the climate and the economy model, the following equation determines the trajectory of total emissions (*E*):

$$E_{jt} = \Sigma_i EM_{ijt} + LUEM_{jt} \ , \qquad j = 1, \dots, m; \ t = 1, \dots, T \ , \quad (26)$$

where *LUEM* accounts for emissions from land-use change, either exogenously specified or provided by the ICLIPS land-use change module.

$SO_2$ emissions are strongly correlated with industrial $CO_2$ emissions, but also subject to an autonomous desulfurization process by rate *sulfred*:

$$EM_{ijt} = EM_{i,'co2',t} * EM_{i,j,0}/EM_{i,'co2',0} * (1 - sulfred)^t \ , \\ i = 1, \dots, n; \ j = \text{‘}SO2\text{’}; \ t = 1, \dots, T. \quad (27)$$

## 3. Intertemporal Equilibrium Solution

Economic growth models belong to the group of optimization models whose solution algorithms presuppose the formulation of a single target criterion (which may well be synthetic). A Pareto-optimal solution is normally obtained by choosing a global (weighted) objective function embracing welfare gains in all regions. In models with multiple actors, however, development options of the individual actors and their trading strategies cannot be determined independently from one another.

The AEM assumes that states co-operate in trading and climate policy, but follow national interests in income distribution. One implication is that all regions have to eliminate their accumulated trade deficits in the long term. All interregional trade flows and transfers have to be balanced to simultaneously satisfy national/regional budget constraints. This budget balancing is a non-trivial problem because essential price information (e.g., the price of emission permits) are a priori unknown on the one hand, and import and export take place at different times (and thus at different prices), on the other. Omitting these trade balance deficits would contradict real economic processes and ignore an essential element of future economic dynamics.

Two approaches are implemented in the AEM to resolve this problem. The first one applies the method of sequential joint maximization (Dixon, 1975; Manne and Rutherford, 1994). It consists of adapting welfare weights that measure the regional contributions to the global objective function in such a way that budget constraints are always satisfied in the equilibrium solution. The existence of such an equilibrium solution has been proven by Negishi (1972). The adjustment of the welfare weights (also called Negishi weights) on the basis of intertemporal trade balance deficits takes place iteratively between two complete optimization runs. The technical details of this procedure are described in the Appendix.

The second approach is used in our model to deal with interregional interactions related to capital mobility. The stock of foreign assets is updated on the basis of capital flows. The interest accruing to this amount is immediately calculated according to the globally averaged rate of return to capital. When the terminal condition (all foreign assets will be removed in the final period) is included, the above procedure of eliminating trade deficits causes all budget constraints to be fulfilled.

## 4. Data Base and Empirical Foundations

The AEM can be run in two modes: reference mode and policy mode. In reference mode, several equations are suppressed (e.g., mitigation cost functions, distribution of and trade in emission rights) and the economic model is allowed to determine the optimal development paths based on different scenarios of main exogenous driving forces (population dynamics, technological change) and parameters (e.g., diffusion parameter, depreciation rates, discount rates). In order to simplify the subsequent discussion (in terms of input data and results), we present one reference scenario that also serves as the basis for the policy scenarios. In order to ensure consistency across different model components, some parameter in AEM are predetermined by the scenario underlying the mitigation cost function. This is essential due to the fact that by means of the mitigation cost functions the AEM integrates insights of the energy sector which are needed in order to get some reasonable estimates of the costs of emission reduction (see below). The model distinguishes 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.

A large part of the input data for the model (population, carbon intensities, energy efficiency improvements, initial values for gross domestic product and capital stock) is based on the IIASA Reference Scenario F (Gritsevskii and Schrattenholzer, 2002). This scenario is similar to the A2 scenario of the World Energy Council (see Nakicenovic, 1998) and resembles the IPCC SRES A2 scenario (Nakicenovic et al., 2000). Reference Scenario F largely extrapolates current economic, technological and environmental trends. It is a growth-oriented, emission-intensive scenario that forms a suitable basis of comparison for the analysis of alternative policy scenarios. It assumes a population of 10.1 billion in the year 2050. High rates of economic growth lead to a five-fold increase in the global gross product by the year 2050 compared to 1990 and to an 18-fold increase by the year 2100 (compared to a factor of 12 in the IPCC IS92a scenario). The technological changes are moderate (roughly 1% annual reduction in energy intensity globally) and the fossil resource pool is confined to those currently exploitable plus already identified reserves. Coal continues to play a dominant role in providing energy throughout the next century. The proportion of the non-fossil energy sources increases to around 50% by 2100.

The Reference Scenario F imposes a significant impact on the environment. In addition to climate change, these environmental impacts include effects associated with increased $SO_2$ emissions: health impacts, acidification of soils and lakes, forests damage, etc. It is not assumed that future societies will tolerate such impacts. Nevertheless, this scenario presents a useful reference case for our analyses.

The model's empirical foundation includes the parameter estimation and calibration of the Cobb-Douglas production function, the regional depreciation rates of the capital stock, and the mitigation cost function. Parameters for the latter are derived from a statistical evaluation of many computed scenarios using the coupled MACRO-MESSAGE model and the IIASA scenario database (Gritsevskii and Schrattenholzer, 2002; Schrattenholzer and Schäfer, 1996). As a result, each single parameter of the mitigation cost function aggregates interdependencies from resource extraction to the provision of energy end-use services. The parameters integrate the utilization of domestic resources, energy imports/exports and related monetary flows, investment requirements, the types of production or conversion technologies selected as well as interfuel and energy-capital substitution processes. Hence, each unit of carbon emission reduction in the model is linked to specific changes in the energy system.

The Cobb-Douglas production function requires the calibration of two parameters: the total factor productivity (TFP) and the elasticity parameter $\alpha$. We have taken elasticity values adopted in similar models, specifically the values used in the MERGE model (Manne et al., 1995) for the base year 1990. From then on, however, temporal variation is assumed in the regionally differentiated parameters. By 2050, the TFP parameters for all regions converge at around 0.25.

The development of TFP is predetermined in a phase of calculations preceding the actual model calculations and is thus exogenous. The rates of change in TFP are determined on the basis of a technological diffusion model. This model assumes that, through the transfer of technology and knowledge, in the long term all regions reach a level of productivity equal to that of the most advanced regions. This diffusion and convergence process, however, occurs at different rates in different regions. Thus, EEU or FSU have higher diffusion rates than, e.g., AFR or MEA. The concrete parameter values are in turn adjusted so that the resulting economic development in the reference run depicts the development of the IIASA reference scenario F.

The starting point for the calculation of the physical capital stock is derived from data on investments from national accounting (World Bank, 1999). For many countries, additional sufficiently long time series (divided into five categories: machines and equipments, means of transport, business premises, dwellings, other buildings) are provided by the Penn World Tables 5.6a (see Summers and Heston, 1991). A linear model with two predictors (material welfare, expressed as a logarithm of the per capita gross national product, and time as the year of investment) is fitted to these data in order to estimate investments in the individual categories also for countries for which only aggregated data on investments are available. By using the differentiated depreciation rates from the Penn World Tables, the net capital stock in each of these categories is finally calculated as the residual value of cumulative investments at constant replacement prices on the basis of degressive (geometric) depreciation. The evolution of aggregated depreciation rates is derived from the historic time series of capital stock determined this way. For the long-term scenario horizon, however, it appears to be more realistic to assume convergence rather than a long-lasting continuation of past trends. Under the hypothesis that, particularly in developing countries, short-lived categories of investment goods (e.g., machines and means of transport) are increasingly used, we assume a long-term stabilization of the depreciation rates at 9%.

## 5. Model Application for Cost-effectiveness Analysis

The main application of the ICLIPS IAM is to explore corridors of long-term carbon emissions under user-specified levels of acceptable climate change impacts and mitigation costs. Such applications are presented in the twin papers on integrated assessment of long-term climate policies in this Special Issue (Toth et al., 2002a, 2002b). Here we present only one prominent path within the corridors - the cost-effective emission path. We present detailed results that complement the corridor results associated with any user-specified targets. Our focus is on the mitigation costs and on the question how the burden of emissions reduction may be shared between the world regions in the long run. We explore cost sensitivities and compare our cost-effective paths and other results to those of similar models. First we present the reference run, then we turn to the results of the policy runs.

### 5.1. Reference run

In the reference run, baseline welfare and emission paths are established by assuming that no climate policy is needed. The path of uncontrolled emission of GHGs implies reference welfare values that are merely hypothetical, because they do not consider damages caused by the induced climate change. The differences in welfare between control runs and the reference run, however, can be taken to compare the social costs of different climate policy interventions to reach the same climate/impact target.

According to the results of the reference run, the regions can be assigned to one of four groups with regard to long-term economic development:

1. moderate growth on a high level: NAM, PAO, WEU;
2. accelerated growth: EEU, FSU, PAS;
3. medium growth: CPA, MEA, LAM;
4. delayed growth: AFR, SAS.

Figure 2 shows the development of incomes in 5 of the 11 world regions measured in constant 1985 US dollar (this unit also applies to monetary figures presented graphically below). The differences in welfare between western industrial nations and other regions of the world increase initially. By the end of the $21^{st}$ century, the dynamics of development in the less developed regions begin to catch up at increasing speed. This pattern of development is largely determined by exogenous assumptions and founded only to a small extent endogenously.

GHG emissions increase in almost all regions. Increases are drastic in CPA and SAS (Figure 3). Apart from LAM, PAO, and WEU, reductions in energy intensity and carbon intensity cannot compensate increasing emissions due to population and economic growth. In addition, according to the underlying baseline scenario, the proportion of coal used in energy production increases again in the mid-21st century, causing the decline in carbon intensity to cease in many cases. This is shown clearly by the renewed rise of emissions in CPA after 2050, and as an

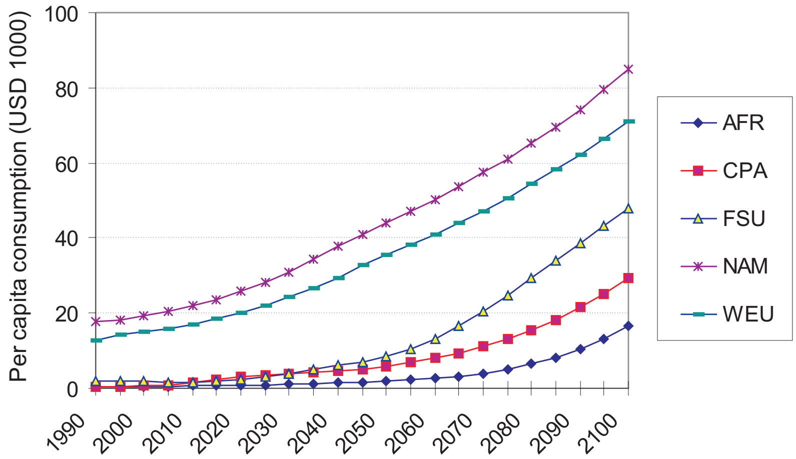


*Figure 2.* Economic development in the reference run

outcome of the economic upsurge in SAS, MEA, or AFR. The combined effect is an accelerated increase in global emissions up to around 25 GtC in the year 2100.

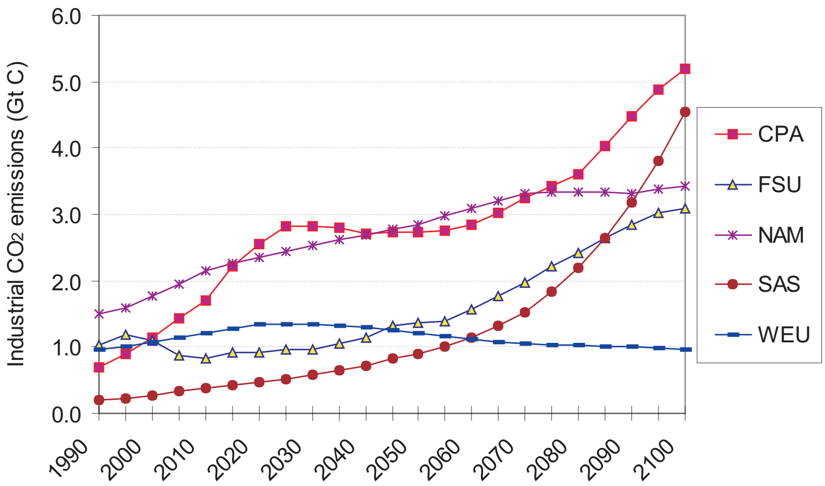


*Figure 3.* Industrial $CO_2$ emissions in the reference run

The rise in global $CO_2$ emission is accompanied by a proportional rise in the aerosol-forming $SO_2$ emissions (which therefore have a cooling effect). The assumption of a strong correlation between $SO_2$ and $CO_2$ is supported by the underlying IIASA base scenario F and justified again by the increasing share of coal. The AEM assumes an autonomous desulfurization rate of 0.5% annually.

The climate change induced by this reference scenario is computed by coupling with the ICLIPS Climate Model. This requires additional assumptions about the emissions of other greenhouse gases. Emissions of ozone-depleting gases are prescribed according to the Montreal Protocol and its amendments in all cases. Two scenarios are distinguished for emissions of the other non-$CO_2$ greenhouse gases. In the first scenario, the values of 1990 are kept constant while in the second case emissions of non-$CO_2$ GHGs follow the IPCC IS92a scenario. A temperature curve with a slightly higher increase results from the increase in non-$CO_2$ emissions. For the year 2100, Scenario 1 calculates a temperature increase of around 1.8 °C relative to pre-industrial values, by the year 2200 the increase is around 3.8 °C. (The climate sensitivity parameter anchored in the climate model at 2.5 °C under doubled $CO_2$ equivalent GHG concentration represents the "best estimate" of the Intergovernmental Panel on Climate Change (IPCC, 1996)). As a result of the increase in non-$CO_2$ emissions in Scenario 2, the correspondingly higher values in 2100 and 2200 are 2.1 and 4.2 °C, respectively.

## 5.2. Policy runs for a climate window

### 5.2.1. *Key assumptions*

Taking the reference run described in the previous section as a starting point, policy scenarios in the framework of cost-effectiveness calculations are analyzed with the ICLIPS Integrated Climate-Economy Model. A policy scenario is defined by the formulation of climate change/impact targets. In cost-effectiveness analyses, we search for the least-cost emission path to reach a pre-determined climate change target while achieving the greatest possible welfare. The policy target we explore stems from the German Environmental Council on Global Change (WBGU, 1995)(Figure 4).

The Council reviews the range of variability of the global mean temperature in the late Quarternary, the geological period that shaped our present environment, and finds the minimum of 10.4 °C in the Wuerm ice age and the maximum of 16.1 °C in the Eamian. The Council argues that a considerable departure from this range would imply major changes in the composition and function of today's ecosystems but proposes to extend the range by 0.5 °C at both ends to arrive at a tolerable window for global mean temperature ranging from 9.9 to 16.6 °C. Moreover, based on arguments about adaptive capacity of various climate-sensitive sectors, the Council maintains that the rate of change in the global mean temperature should not exceed 0.2 °C/decade. Taken together, these constraints define the WBGU climate window.

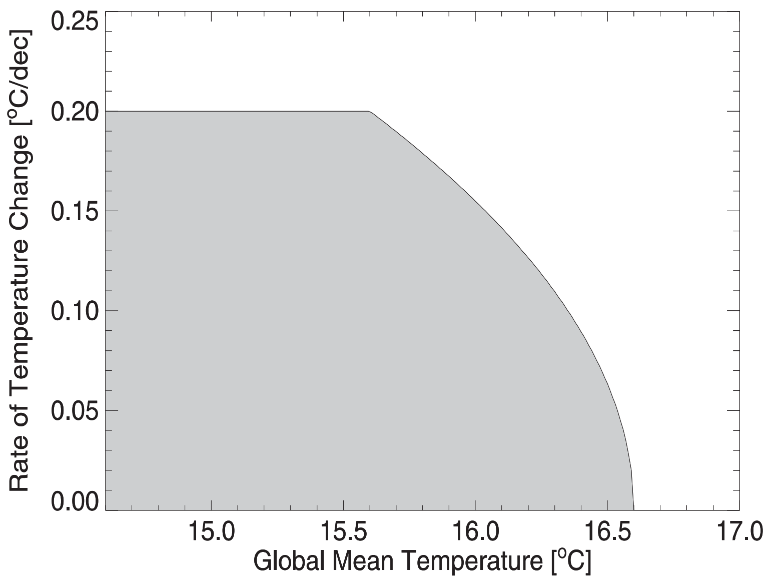


*Figure 4.* The WBGU climate window

Although its origins go back to 1995, the Council's proposal regarding the long-term stabilization target remains influential in the policy debate, at least in Germany. It is one of the few normative targets published by a top-level advisory board to any government. The objective of our analysis is to demonstrate how the ICLIPS IAM can explore the implications of normative targets proposed by the policy community. The analysis and results should not be interpreted as a science-based proposal by the authors or by the rest of the ICLIPS team. In fact, many observers maintain that, despite the geo-historical arguments, the WBGU target is somewhat arbitrary. It is important to note that the ICLIPS project encompasses Climate Impact Response Functions (Füssel et al., 2002) of various impact sectors in order to help explore and make the choice of stabilization targets based on what are perceived to be unacceptable impacts of climate change. Incidentally, the WBGU climate window is similar in nature and magnitude to the long-term climate change constraint (maximum 2 °C increase in global mean temperature) proposed by the European Union before the Kyoto Conference of the Parties to the UNFCCC and comparable to the various sea-level rise limits suggested by the Alliance of Small Island States.

The analysis is based on the scenarios presented in the previous section. They differ in their assumptions about non-$CO_2$ emissions as follows:

– Scenario 1: constant $CH_4$ and $N_2O$ emissions
– Scenario 2: $CH_4$ and $N_2O$ emissions according to IS92a (mostly increasing).

The policy scenarios consider emission permit trade among the Annex-I regions from 2000 on. Non-Annex-I countries take part in international emission trade only from 2010 on. Similarly to capital transfer and intertemporal trade, the *ad valorem* trade in emission permit is limited to 10% of the respective current gross regional product. Furthermore, there is no limitation on the physical amount of emission rights that may be exported, while the share of reduction obligations that may be covered by emission permit imports is limited to 50%. Other important assumptions in the model include a pure rate of time preference of 3% (same as in the reference run), and the completion of the transition to an equal per capita distribution of emission rights by 2050 (based on 2025 population).

### 5.2.2. *Results*

In reviewing the results below, it is important to keep in mind that the two scenarios deliver complementary information. To be exact, they represent a single policy scenario with differing underlying assumptions, with important implications for comparing the mitigation costs of the two scenarios. These costs are significantly higher for Scenario 2 because of the higher baseline emissions of non-$CO_2$ GHGs. Correspondingly, the implicitly avoided damages are higher. A discussion of the two scenarios helps to clarify the dependence of mitigation costs on exogenous modeling assumptions.

Figure 5 shows income losses (in %) relative to the reference scenario. Income losses are measured as per capita consumption losses. In Scenario 1, the losses remain largely below 2%. Regions with losses above or near the 1% mark are CPA, EEU, FSU, NAM, and MEA, in other words regions with high per capita emissions and/or with an economic sector strongly based on fossil energy resources. There are also regions (e.g., AFR, SAS) increasing per capita consumption relative to the reference scenario. It becomes much more expensive to satisfy the climate constraint under Scenario 2. Some regions (CPA, FSU, PAS) fall below their reference income values by more than 5% . The enormous differences between Scenario 1 and 2 are surprising as well as the interregional differences, which are already visible in Scenario 1, but become striking under Scenario 2. Figure 6 demonstrates that there are also huge differences over time. While (according to Figure 6) in Scenario 1 higher income losses are expected in the second half of the century, in Scenario 2 substantial losses already occur in the first half of the century. This applies in particular to CPA and NAM. Gains in SAS and AFR as well as losses in MEA and PAS arise similarly in the second half of the century. In order to find the reasons for these results, we need to have a look at the associated "optimal" emission trajectories and trade flows of emission rights.

The "optimal" emission strategies determined by the model for selected regions are presented in Figures 7 and 8. In Scenario 1, many developing regions can follow their baseline emission paths for several decades, some of them well into the second half of the 21st century. Industrial regions need to begin reducing emissions significantly much earlier. However, the transition phase (2000-2030) to form an energy-saving and less carbon-intensive economy is relatively long, mitigation costs will therefore be moderate. Under Scenario 2, stricter $CO_2$ emission reduc-

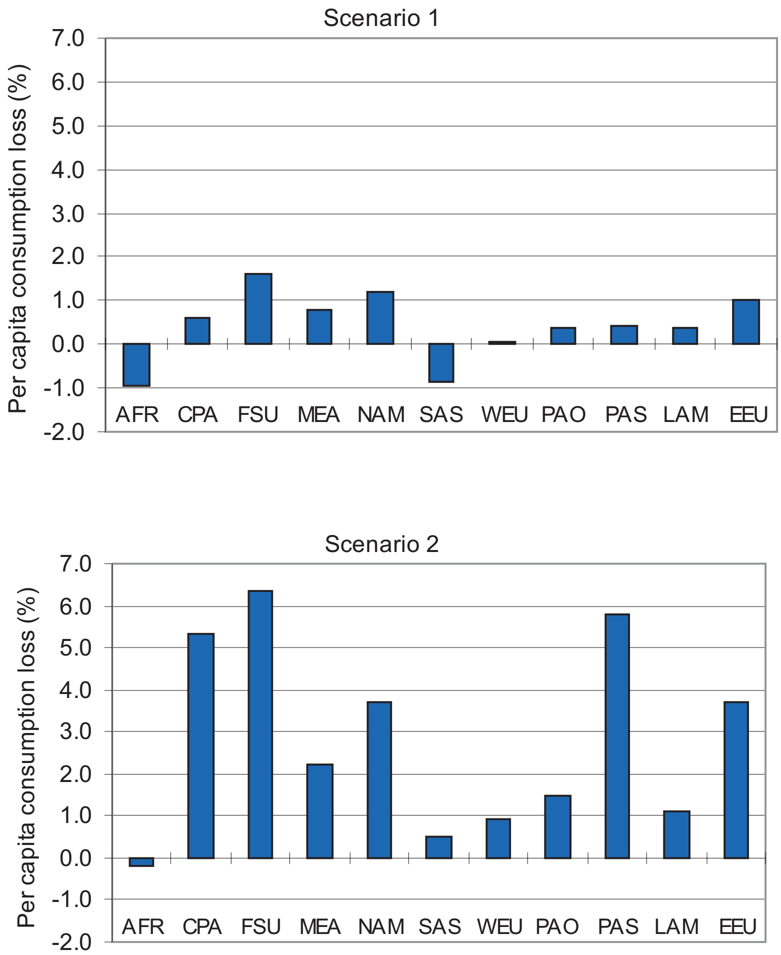


*Figure 5.* Average loss of per capita consumption between 1995 and 2100

tions are necessary, and costs increase. This additional control of $CO_2$ is required to compensate the increasing radiative forcing caused by rising non-$CO_2$ emissions. These global reduction requirements are manifested in appreciably altered regional emission paths relative to Scenario 1. In all Annex-I regions, emission reduction has to begin much earlier and proceed considerably faster. Developing regions need to participate in emission reduction earlier. The case of China (region CPA) is particularly interesting. China has to reduce its emissions drastically starting as early as 2020. The local minimum in China's emission curve in 2035 is a result of the climate window. The specified rate of temperature change constraint is likely to become binding soon. As major emitters, China and NAM need to undertake very

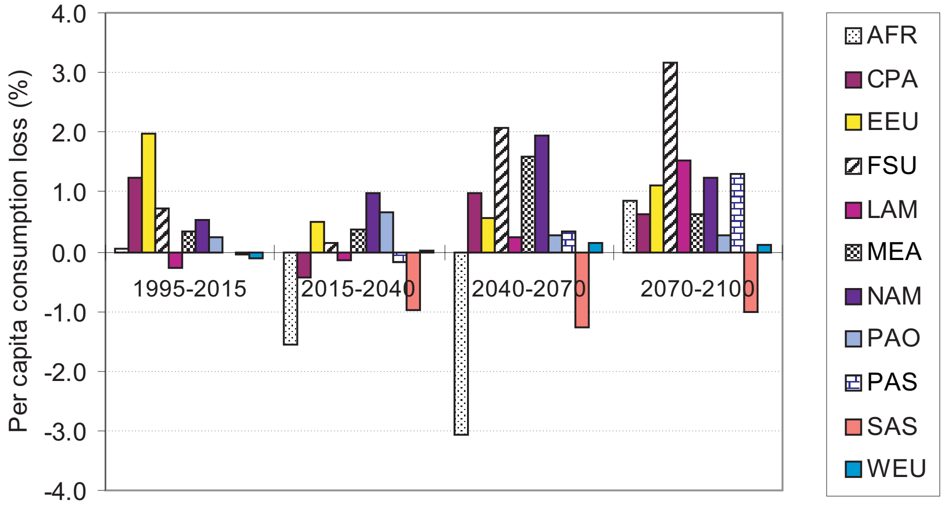


*Figure 6.* Average loss of per capita consumption in Scenario 1 for different periods

large reductions in order to keep the climate system within the specified global climate window.

While the climate window determines the overall emission reduction pattern, regional differences in the emission trajectories are heavily influenced by the allocation of emission rights. Although the transition period between the initial status quo allocation and the final per capita allocation seems to be quite long, high per capita emitters (e.g., NAM) and fast developing regions (e.g., CPA, PAS, EEU) run quickly into shortage of emission rights. This shortage can either be resolved by enhanced domestic reduction efforts or massive imports of emission rights. Both might become costly.

The emission permit trade flows are presented in Figures 9 and 10. The general structure of the permit trade is robust. The main exporters are SAS, AFR, partly LAM, and initially also FSU. The leading importers are CPA, NAM, and to a lesser extent MEA, PAS, and WEU. In Scenario 1, FSU changes from being an exporter in the first decades of the 21st century to an importer in later decades. In Scenario 1 with virtually unlimited emission trade (the 50% import barrier has little restrictive effect), the extent of trade flows is very high. The volume of permit trade is lower in Scenario 2, but it involves a considerably higher proportion of actual emissions. The fast increase in early decades is particularly striking.

Permit trade makes it possible to achieve climate protection targets on the one hand, and reduces the costs of emission reduction, on the other. The costs, measured as changes in per capita income relative to the reference scenario, nonetheless vary widely. Regions like AFR and SAS can even exceed their reference income. This is made possible either by the sale of emission rights which cannot immedi-

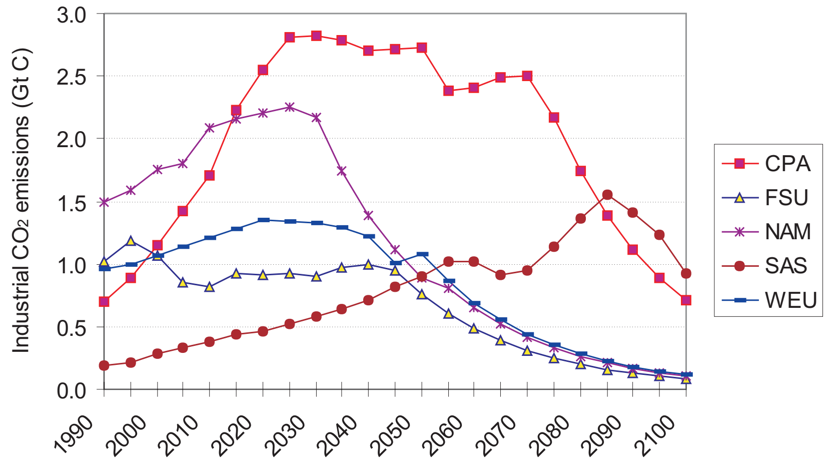


*Figure 7.* Industrial $CO_2$ emissions of selected regions in Scenario 1.

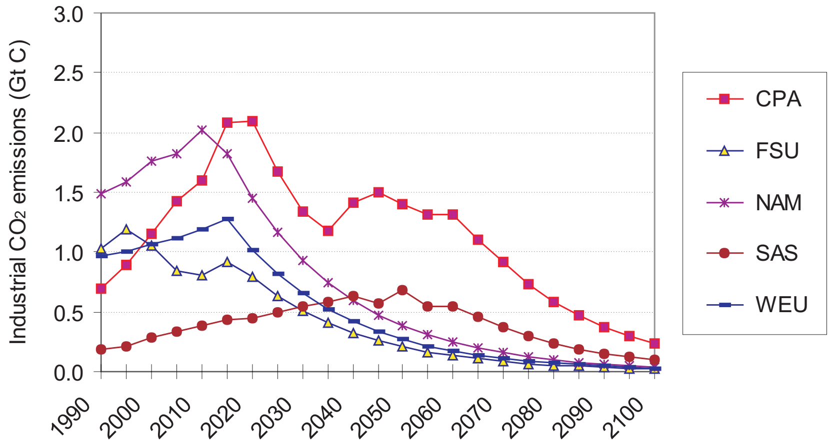


*Figure 8.* Industrial $CO_2$ emissions of selected regions in Scenario 2.

ately be used in an equally productive way, or by creating trade balance deficits (and thus increasing disposable domestic product) in expectation of later opportunities to sell emission rights. In Scenario 2, exporters of emission rights can additionally profit from the very high permit prices: 120$/tC on average, compared to 15$/tC in Scenario 1. Among others, the differing permit prices explain the big differences between Scenario 1 and 2 as well as between different regions. Emission rights exporting regions can use the income from trade to embark on a

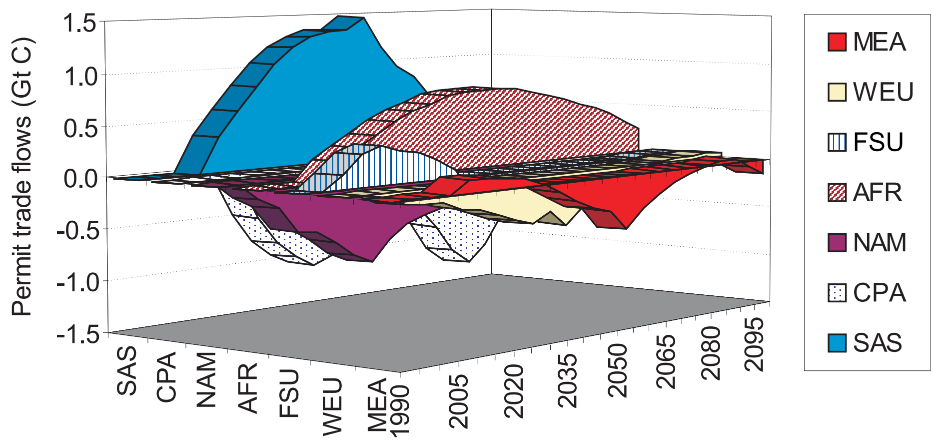


*Figure 9.* Emission permit trade flows in Scenario 1.

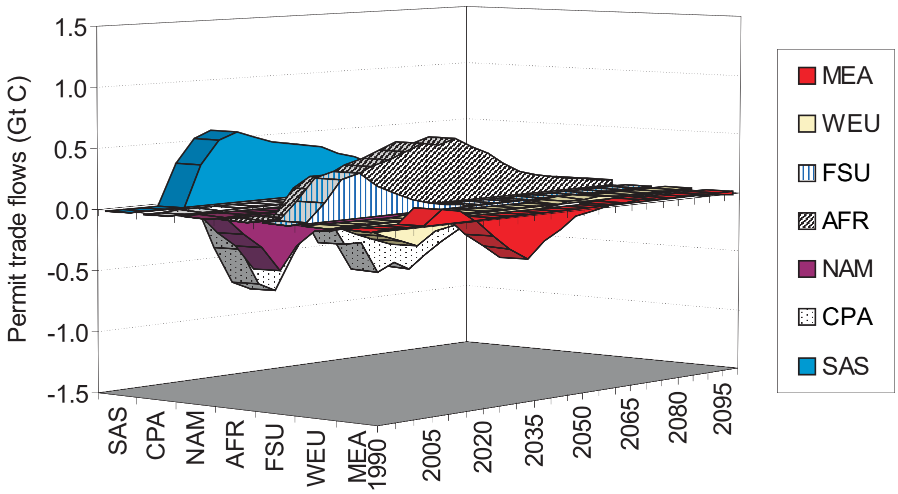


*Figure 10.* Emission permit trade flows in Scenario 2.

faster growth path in the long term. In contrast, the importers are hampered by negative trade effects. For China (one of the largest likely "losers"), an additional factor is that climate protection requirements occur in a phase of dynamic growth and thus have a stronger restrictive effect.

One should keep in mind that many of the results can only be interpreted in a right way when recognizing the intertemporal optimization behavior of the model and the underlying model assumptions. Thus the question, why LAM benefits in the next 20 years in Scenario 1 and why FSU does not (see Figure 6), can be explained as follows: LAM benefits over the first 20 years because it increases its disposable income by composite good and capital imports well aware of the fact that long-term emission rights export possibilities will emerge to compensate trade balance deficits. For FSU this possibilities exist only in the short run and emission rights exports in the beginning will be used in order to build up a surplus in the intertemporal trade balance (instead of increasing the disposable income). This surplus in the trade balance helps FSU to contain its losses over the long term. This gains additional importance due to the fact that in the reference case FSU grows faster than LAM, hence it is more severely affected by the policy scenarios.

### 5.3. Comparison of ICLIPS with the WRE Analysis

In order to help locate our model and results on the current landscape of IAMs, we compare our results with those of the well-known Wigley-Richels-Edmonds (WRE) analysis (Wigley et al., 1996) and the associated MERGE analysis (Manne and Richels, 1997). The WRE analysis is based on the IPCC IS92a emission scenario that is similar to the baseline scenario of the present analysis for the relevant periods. WRE use inverse calculations in order to generate emission paths for attaining prescribed $CO_2$ concentration levels, while not allowing emissions to change too abruptly. We reproduce this analysis with the concentration targets of 350, 450, 550, 650, and 750 ppm. While the WRE analysis requires the concentration trajectory to attain the stabilization level in 2150, our analysis restricts the concentration path to the prescribed level over the entire time horizon. This is similar to the WRE analysis in which, according to Figure 1 of Wigley et al. (1996, p.240), none of the concentration paths exceeds the concentration target, except for the 350 ppm case. The present analysis assumes the target level of 350 ppm to be approached in 2200. Our initial concentration level is 354 ppm as it is in the WRE analysis as well. While in Wigley et al. (1996) the requirement of avoiding abrupt changes in emissions is not explicitly specified, in our analysis the emission reduction rate is constrained by cost considerations (cost-effectiveness) and supplemented by a maximum emission reduction rate of 20% in any five-year period.

Figure 11 shows the resulting emission trajectories for this and the WRE analysis. While the qualitative pattern is similar, differences in detail occur. Due to the assumption of keeping emissions constant from 2110 onwards, the ICLIPS analysis requires a sharper decline of emissions in the second half of this century in all cases except the 350 ppm case, but this is compensated by slightly higher emissions in the mid-term. As to the 350 ppm case, the opposite behavior can be observed. The 350 ppm concentration target requires an immediate deviation from the baseline, otherwise costs explode and emission reduction limits are exceeded.

We turn to the mitigation costs. Manne and Richels (1997) calculate the costs for the emission reduction strategy associated with the 550 ppm WRE pathway. The

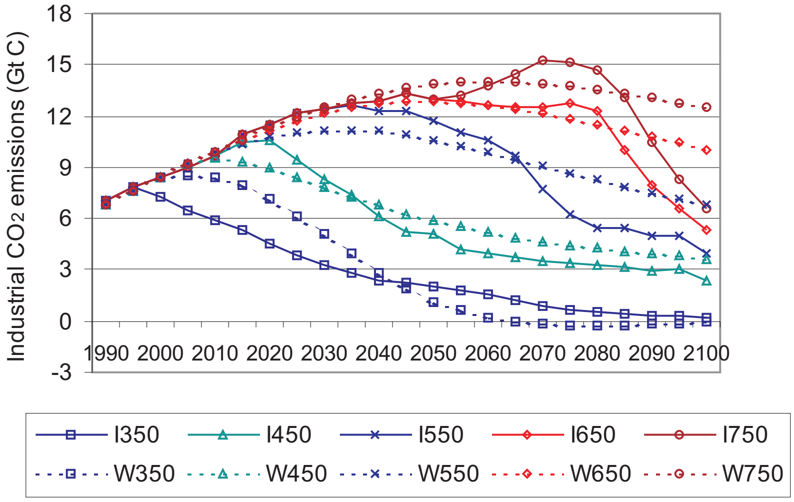


*Figure 11.* Alternative anthropogenic $CO_2$ emission paths. Note: I = ICLIPS, W = WRE model results. The numbers represent stabilization of GHG concentrations between 350 and 750 ppm $CO_2$-equivalent.

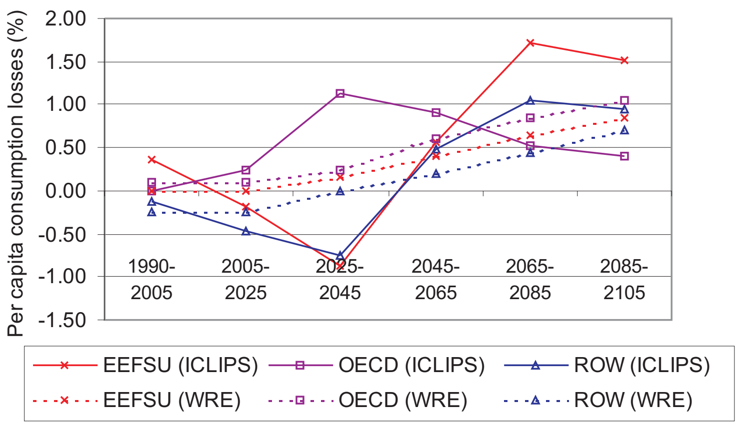


*Figure 12.* Annual per capita consumption losses.

cost analysis stems from the MERGE model. An emission rights allocation scheme similar to that of the present analysis is used. Considering where flexibility (i.e., the opportunity of emissions trading) Manne and Richels determine global costs to be accounted for about $750-800 billion. The corresponding value in our analysis is around $880 billion, with the OECD countries sharing more than $750 billion. While the absolute amount of mitigation costs is nearly the same, the temporal and especially the regional distributions differ significantly. This is demonstrated in Figure 12 by annual per capita consumption losses averaged over 20-year time periods. While these costs increase in the WRE analysis for all regions (EEFSU – Eastern Europe and former Soviet Union; ROW- Rest of the World) more or less monotonically*, our analysis shows increasing costs first for the OECD region and decreasing costs for the other two regions. This trend reverses in the mid of this century and especially EEFSU is confronted with higher per capita consumption losses. Our model is obviously more sensitive to the carbon constraint implied by the concentration target. The emissions trading effects and the implied intertemporal trade effects cause different cost trajectories with additional benefits for emission rights exporters. In the WRE analysis "where" flexibility not only reduces overall costs, but also diminishes regional cost differentials. This is somewhat surprising since the oil price, as endogenously determined by the MERGE model, is known to be sensitive to alternative pathways of stabilization. Nevertheless, a decreasing oil price due to declining international demand for crude oil in a carbon-constrained world could explain why in the medium term an oil exporting region like EEFSU will not benefit as much as shown in our analysis.

## 6. Concluding Remarks

This paper presents the AEM component of the ICLIPS IAM. The Ramsey-type optimal growth framework provides the conceptual foundations of the model. Its calibration is harmonized with two other components of the ICLIPS IAM system: the MESSAGE-MACRO model adopted by Gritsevskii and Schrattenholzer (2002) to establish regional dynamic $CO_2$ mitigation cost functions and the DART model by Klepper and Springer (2002) to explore medium-term sectoral and regional implications of long-term abatement paths. Additional features of the AEM structure and specification follow from its tight integration with the ICLIPS Climate Model. The unique feature of the economic model comes from its application in an inverse integrated assessment framework. The AEM model, its parameterization, and the underlying scenarios presented in this paper operate behind most case studies presented in this special issue.

While other papers in this special issue present emission corridors (the bundle of all permitted emission paths under externally specified climate and cost constraints), we focus on the least-cost paths within those corridors. Similarly to results of other IAMs, all quantitative results from the cost-effectiveness analysis involve a wide range of uncertainty. They should always be considered and interpreted together with the underlying model parameterization and scenario assumptions. The qualitative insights are nevertheless robust. For example, the higher costs indicated in NAM relative to WEU do not primarily result from higher specific mitigation

* The cost estimates of the WRE analysis are derived from Figure 8 in Manne and Richels, 1997, p.259.

costs (in NAM cheap reduction potential does exist), but rather from the relative difference between the allocated and required amounts of emission permits. Due to the high per capita emissions, this difference is much bigger in NAM, which therefore has to spend a part of national income to import emission permits. Finally, dynamically developing regions (like CPA) suffer relatively high welfare losses due to climate protection measures. The contrary is valid for regions with delayed growth dynamics. However, the magnitudes of welfare losses or gains do not change the basic economic growth characteristics.

Embedded in the ICLIPS IAM, the AEM can provide valuable information to evaluate selected emission paths within the corridor. While the climate constraint is not affected by the choice among the permitted paths, regional welfare implications and permit trade flows might drastically differ. This makes the cost-effectiveness analyses presented in this paper particularly interesting for policymakers in their efforts to strike a generally acceptable compromise between desirable long-term global climate protection targets and acceptable regional/national mitigation costs.

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## Appendix: Iterative procedure to find an equilibrium solution

Each iteration (index r) comprises the following 5 steps:

1. Solve the whole optimization problem with a given set of Negishi weights.

2. Calculate the present value prices of the composite good and the emission permit by using the shadow prices from Equations (12) and (26):

$$PVP_{kt} = \frac{TB'_t}{TB0'}\,, \qquad k = 1;\ t = 1, \ldots, T \tag{A1a}$$

$$PVP_{kt} = \frac{TE'_t}{TB0'} , \qquad k = 2;\ t = 1, \ldots, T , \tag{A1b}$$

with $PVP_1$ and $PVP_2$ as the present values of the composite good and the emission permit, respectively, *TB'* as the shadow price of the composite good derived from the dual variable of equation (12), *TE'* as the shadow price of $CO_2$ emissions derived as dual variable of Equation (26), and *TB0'* as the value of the dual variable of the trade balance (12) in the first period for which trade is considered. According to this formulation, the present value of the composite good in the first period is normalized to 1. By using present values, economic figures of different periods can be made comparable. The price of emission permits is equivalent to the carbon price derived from Equation (26).

3. Calculate the intertemporal trade deficit (*DEF*) for each region by multiplying the trade volume with the respective present value prices:

$$DEF_{ir} = \sum_k \sum_t PVP_{kt} \cdot NTX_{ikt} , \qquad i = 1, \ldots, n;\ r = 1, \ldots, q. \tag{A2}$$

4. Adjust the Negishi weights (*NW*) as a function of the intertemporal trade deficit and a weighing factor that represents the weight of each region's economy (measured as the sum of gross product and foreign trade summed up over the entire time span):

$$NW_{i,r+1} = NW_{ir} \cdot \left( 1 + \frac{DEF_{ir} \cdot (prm \cdot \ln(ord(r)) + 2 \cdot prm)}{\sum\limits_h weight_h + weight_i} \right) , \qquad i = 1, \ldots, n;\ r = 1, \ldots, q-1 \tag{A3}$$

with

$$weight_i = \sum_t \left( \sum_k PVP_{kt} \cdot NTX_{ikt} + PVP_{1t} \cdot C_{it} \right) , \ i = 1, \ldots, n. \tag{A4}$$

The equation of Negishi weights adjustment is founded heuristically. The parameter *prm* governs the speed of adjustment. As a rule of thumb, it holds that the closer the current solution to the equlibrium, the higher *prm* should be. *Ord(r)* represents the ordinal value of the set index r.

5. Transformation of the new Negishi weights into the interval (0,1):

$$nw_i = \frac{NW_{i,r+1}}{\sum\limits_h NW_{h,r+1}} , \qquad i = 1, \ldots, n. \tag{A5}$$