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Reaching National Kyoto-Targets in Germany by Maintaining a Sustainable Development

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Abstract

Within this paper, we analyze the fulfillment of the Kyoto-emissions reduction commitment exemplary in Germany and its implication on long-term paths of all macro-variables. Germany, like all other industrial or Annex B countries, has to reduce its emissions by 2010 and after what we call a "Kyoto-forever-scenario". We exemplary investigate tradable permits as reduction measures in a national OverLapping Generations (OLG)-model, where we change the discounting technique by using generation adjusted discounting (GAD) in comparison to conventional OLG-models. We show that within our model-framework Germany is able to develop along growing paths of e.g. GDP in sharp contrast to conventional results of OLG-simulations. At the same time, nowadays living generations have to share higher burdens in terms of lower GDP, per capita consumption and employment which can be interpreted, firstly, as contemporary costs for reaching sustainable paths and, secondly, contributions for internalizing intertemporal external effects. However, all costs in terms of lower macro-variables for current living generations are overcompensated by higher future values of them. This effect can be interpreted as intertemporal application of full cost-bearance, or, in other words, the polluter pay principle which is oriented on the sustainability of GHG abatement.

Non technical abstract

This paper investigates the sustainability of the German economy when reaching the Kyoto emissions reduction target. We use a special intergenerational discounting technique which actually takes into account intergenerational peculiarities in an overlapping generations modeling framework which leads to completely different statements than using the same model with a conventional discounting method. By applying this discounting technique sustainable growth paths of all economic variables can be reached with respect to overall welfare units at the expense of currently living ones. Their contribution to the achievement of "sustainability" can be interpreted as an application of an intertemporal polluter pays principle, where (negative) intertemporal externalities are - to a large extent - avoided. This is not only fair from a normative viewpoint, but also efficient due to the internalization of today's occurring external costs with respect to climate change.

JEL-Classification: D58, D61, Q28, Q38, Q48.

Keywords: OLG-models, Discounting, Sustainability, Climate Change, Kyoto Targets.

1 Introduction

One of the milestones in international climate policy was the third conference of the Parties (COP-3) in Kyoto 1997. Leading industrialized countries committed themselves in Annex-B of the Kyoto-Protocol to reduce six GHG's on basis 1990 within the commitment period from 2008 to 2012 by at least 5.2%. Within our paper, we concentrate on the fulfillment of the Kyoto-commitments in specific industrialized countries, especially Germany. Therefore, we assume a so-called "Kyoto-forever-scenario",[1] which means that Germany has to reduce its GHG-emissions by 21% until the year 2150. We analyze national reduction measures, exemplary tradable permits, in an OLG-model, where we change the discounting technique in comparison to conventional OLG-models and illustrate that long-term paths of major macro-variables are developing in a complete different manner.

Our analysis abstracts from infinitely living Ramsey-type-agents and, therefore, from optimal growth theory. OLG-models depict empirical circumstances more realistically even though Manne (*Manne* 1999) as well as Stephan et al. (*Stephan et al.* 1998) conclude that there are no significant differences between both types of models. The discounting technique used in most of all models are typically very similar, i.e. each generation maximizes the present value of lifetime-utilities. Therefore, future utility units are discounted to the beginning of their respective lives. Welfare present values are calculated by discounting generation-specific utilities to the beginning of the planning horizon using the "social discount rate".[2] Generation-specific myopia equals the myopic attitude of a central planner who sums up all generation-specific present values. We refrain from this very strong assumption (see chapter 2), because the assumed discounting technique biases in favor of current living generations and discriminates against future ones and is, therefore, not "neutral" in an intergenerational framework. Tol *(Tol* 1999*)* as well as Bayer (*Bayer* 2000) analyzed different kinds of discounting measures and their impacts on climate change and economic reactions. They both found out that the discounting method has substantial impacts on long-term emission control and short run emission abatement.

Howarth (*Howarth* 1998) shows that welfare statements heavily depend on transfer assumptions between different generations. One result is that in a "utilitarian moral model" aggressive abatement measures can be legitimated. This is due to the renunciation of discounting utilities in the intertemporal welfare function. Howarth argues from an ethical point of view and assumes moral duties towards future living generations which have to be taken into account by current living ones. More aggressive abatement is thus being demanded by current generations than in the reference case where positive utility discounting is applied.

Distributional aspects are focal points within investigations by Stephan et al. (*Stephan/Müller-Fürstenberger* 1998, *Stephan et al.* 1997), Manne (*Manne* 1999), Nordhaus (*Nordhaus* 1994, who argues in a Ramsey-type-model) and the more qualitative paper by Schelling (*Schelling* 1995) as well. In general, they argue that distributional reasons are the most important arguments for not abate at all (or, respectively, not as aggressive as in the paper by Howarth). If today's living generations would heavily abate, future generations will not only be wealthier due to conventional capital accumulation but also due to returns induced by GHG-abatement. On the other hand, renunciation of GHG-abatement leads to more equal distributional effects. Conventional capital formation is used more intensively which leads to increasing consumption and investment possibilities for future generations. At the same time decreases "green capital"

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[1] World economic implications by meeting the Kyoto target are described in *Kemfert* (1999)*,* sensitivity analysis due to emissions baseline variations and limitations of Emissions Trading is written in *Kemfert* (2000).

[2] See *Blanchard/Fischer* (1989), pp. 98-100.

which leads to welfare losses for future generations. Irreversibilities as well as peculiarities of the global climate are neglected. The possibility of dramatic wealth reductions due to global warming is completely ignored, and - as is usual in neoclassical environmental and resources economic theory - environmental and man-made capital is assumed to almost fully be substitutable. Losses in environmental capital can completely be compensated by increasing man-made capital units.

Gerlagh (*Gerlagh* 1999) and Gerlagh/Van der Zwaan (*Gerlagh/van der Zwaan* 1999) illustrate that climate change measures depend on the implementation of property rights. If they are grandfathered within all nowadays living generations (e.g. tradable permits are distributed within all today's living generations according to their historical per capita emissions), sustainable paths cannot be reached and the economy moves on inefficient paths. This changes if the distribution of property rights is carried out according to a "trust fund-idea": Each future living individual obtains the same amount of pollution rights as today living ones. This allocation of property rights leads to an efficient path in the economy. Additionally, Gerlagh/van der Zwaan presume increasing life-expectancies of all affected individuals, but the line of argument does not change much. They further stress the importance of the polluter pays principle which is no point of interest in all the other models we referred to. Of course, for practical policy the polluter pays principle is the most important normative as well as positive criterion for the implementation of any instruments in environmental policy.[3]

However, complete intergenerational comparisons have not been carried out in all mentioned models. It is, firstly, insufficient to conclude like Manne, Stephan et al. and Nordhaus that due to intertemporal transfers from current to future living generations it is necessary to refrain from abatement measures, or - less stringent - to cut emissions not as sharp as necessary. These transfers do of course increase (decrease) generation-specific welfare levels. However, from a societal point of view - having in mind welfare levels of all affected generations - occurring distributional effects are not the "core problem", especially if we assume drastic environmental losses as a result of not abate GHG-emissions at all. A more meaningful objective is the overall efficiency in terms of GDP-shares of all affected generations in total. Secondly, reflections with respect to "sustainability", especially measured according to the non-declining-welfare-criterion, where different GDP-paths are used as indicator for utilities, are not undertaken in the most of the mentioned analyses - except the investigations by *Gerlagh* (1999) and *Gerlagh/van der Zwaan* (1999). It is worth to compare GDP-paths which result by using "conventional" discounting techniques and a modified one - Generation Adjusted Discounting (GAD, see below) - with respect to long-term sustainable growth. Additionally, full cost-bearance of all GHG-emitting generations according to the polluter pays principle means that each generation has to internalize their external costs of GHG-emissions. Intertemporal externalities have to be avoided which is done by reducing long-term discount rates according to the idea of GAD. Risk-averse - and even risk-neutral - climate policy has to take into account that GHG-abatement should be undertaken in these generations which pollute and emit GHG, respectively. We will show, that in sharp contrast to conventional OLG-models, the implementation of the polluter pays principle leads to sharper emissions reductions and, additionally, higher GDP-losses for today's living generations. However, these costs are more than compensated by reaching strictly monotonous increasing GDP-paths which overcompensate welfare losses of

[3] The polluter pays principle requires full cost-bearance of all individuals and, therefore, reflects individual and generational responsibility. Economically, it simply states that everybody who takes advantage of (environmental) goods or services has to pay for it, see *Cansier* (1996), pp. 128-129.

current living generations. Arguing from a societal viewpoint, aggregated overall welfare increases by implementing GAD in comparison to conventional discounting.

2 Generation Adjusted Discounting (GAD)

Discounting in intertemporal decision-making is of highest importance for reaching efficient paths of all macroeconomic variables. Even marginal changes in the discount rate modify the results of cost-benefit analyses. Usually, simulation models show highest sensitivities of discount rate changes for intertemporal paths of all macro-variables. However, they do not concentrate on the most interesting question sufficiently: Is the well-known discounting technique adequately applied in intergenerational decision making? Neither the descriptive nor the prescriptive approach depict intergenerational peculiarities completely.[4]

The conventional application of discounting-techniques in OLG- as well as in Ramsey-models distorts intertemporal decisions in favor of current living generations and discriminates against future living ones. Our discounting method - the GAD[5] - avoids such distortions implementing the following key assumption: As soon as the oldest currently living generation dies, the discount rate is lowered according to the extent of the intragenerational myopic factor for societal present value calculations. This means, during each generations lifetime we use higher discount rates in comparison to intergenerational calculations. As a consequence, carbon abatement effects in the remote future are not as heavily discounted. The reason for a lower intergenerational discount rate is the irrelevance of the pure time preference rate which can only be observed in *individual* decisions and is, therefore, not applicable for intergenerational, societal comparisons. Thus, the GAD does not penalize current living generations due to higher weights for future living ones in societal decision-making, it furthermore implements the necessity of equal treatment of all affected generations which is the central requirement of utilitarianism where neoclassical theory is based upon.

However, in sharp contrast to the original GAD-approach we still employ a social discount rate for intergenerational comparisons which relates to utility units. This is due to the general equilibrium framework of our analysis. The idea of GAD is fulfilled by reducing the elasticity of marginal utilities with respect to consumption within the lifetime of each generation.[6] Diminishing marginal utility does not moderate effects occurring in the future as drastically as in the reference case of OLG-models; the implicit long-term or intergenerational discount rate with respect to consumption growth is of lower value. In other words: Future effects are not as sharp discounted as in "conventional" OLG-models. From a societal viewpoint, future effects are taken into account to a larger extent leading to future peculiarities representing higher present values and significance in our model-framework. Apparent occurring negative as well as positive effects influence today's decisions to a far more extent than in non-modified models.

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[4] See *Arrow et al.* (1996), pp. 131-134.

[5] See for further details *Bayer* (2000) and *Bayer/Cansier* (1999).

[6] More precisely, our discounting approach could be labeled "modified GAD" because of two principle differences to the original GAD: Firstly, the lower elasticity of marginal utility is analogic to the original GAD-approach with respect to its effect in intergenerational comparisons, although we still employ a positive pure time preference rate for intergenerational present value calculations. Secondly and minor important, original GAD has been developed for second-best frameworks where the opportunity cost rate usually exceeds the time preference rate. This is, of course, not the case in first-best models.

3 Model description

We use a model named GOLD (Generation Overlapping Discounting)[7] which is a dynamic general equilibrium model for Germany considering individual generations within an overlapping generations framework (OLG) of finite lived agents. At each point in time a new generation of n identical individuals is born, each period covers thirty five years of working, so that individuals have seventy year life spans. In contrast to the Ramsey-type-model characterized by a representative infinite agent maximizing utility through consumption over time, this OLG model encompasses different types of generations each of them living a separate life cycle.

One household born in period g chooses a consumption path $C_{g,p}$ maximizing its utility by considering the intertemporal budget constraint:

$$\max_{C_{g,t}} \sum_{t=g}^{g+LT} \frac{C_{g,t}^{1-\sigma}}{1-\sigma} \frac{1}{(1+\rho)^t} \quad s.t. \sum_{t=0}^{T} p_t^C C_{g,t} = M_g \perp M_g,$$

where σ represents the elasticity of marginal utility with respect to consumption (the inverse of the intertemporal substitution elasticity), ρ depicts the (additional) pure time preference rate of all living generations and M_g shows the present value of income.[8]

The model is based on the German statistical input output table of 1993. The economic sectors of the German input output table is aggregated and mapped to production sectors, of which 6 are energy sectors (soft- and hard coal, gas, oil, oil products and electricity). At a specific point in time, a backstop technology is available. All products are demanded by intermediate production, exports, investment and a representative consumer. All market actors behave within a full competition context, i.e. they take the market price as given. Firms choose investment in order to maximize the present value of their companies. Consumption is split by different generations and households which choose their optimal lifetime utility for their specific life cycle. A generation is defined by the sum of households living at the same time. A household born in period g lives its lifetime periods $g+LT$. Each household maximizes its individual consumption path under their budget constraints which implicitly determines the level of savings. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. The present value of income is determined by the specific labor and non labor income of each household, savings of every lifetime period is determined by a difference of the present value of future income and expenditures. In the beginning of each period the sum of savings of all agents living within this

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[7] The mathematical description of the model is demonstrated in the Appendix.

[8] The additional pure time preference rate ρ is being introduced to implement GAD. We use a discount and time preference rate of 3% for our calculations.

period is equivalent to the demanded capital stock when moving along equilibrium steady state optimal growth paths. The interest rate is determined by the future capital price equivalent to the discounted present value of capital. Considering a period determined budget constraint, the government has to balance its income and expenditures in each period.

In each region production of the non-energy macro good is captured by an aggregate production function which characterizes technology through transformation possibilities on the output side and substitution possibilities on the input side. Goods are produced for the domestic and for the export market. Production of the energy aggregate is described by a CES-function which reflects substitution possibilities for different fossil fuels (i.e., coal, gas, and oil) and capital, labor representing trade-off effects with a constant elasticity of substitution.[9] Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES-technology. The elasticity of substitution between the resource input and non-energy inputs is calibrated to meet a given price elasticity of supply. Exhaustion leads to rising fossil fuel prices at constant demand quantities. The carbon-free backstop technology establishes an upper bound on the world oil price. This backstop fuel is a perfect substitute for the three fossil fuels and is available in infinite supply at constant price, which is calculated to be a multiple of the world oil price in the benchmark year. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalized (first-best assumption).

Domestic and imported varieties for the non-energy good for all buyers in the domestic market are treated as incomplete substitutes by a CES-Armington aggregation function providing a constant elasticity of substitution. With respect to trade in energy, fossil fuels are treated as perfect substitutes, net trade cannot be cross-moved. International capital flows reflect borrowing and lending at the world interest rate, and are endogenous subject to an intertemporal balance of payments constraint considering no changes in net indebtedness over the entire model horizon.

Germany has to meet its emissions reduction target committed by the Kyoto protocol within the commitment period of 2008 to 2012. Within our model we assume - for example -, emission limits induce a system of emission permits tradable within this region such that the marginal costs of abatement are equalized across sectors. The permit price is then equivalent to a domestic carbon tax which would be necessary to achieve the given emission limit. We assume within our model

[9] We use a substitution elasticity of capital and labor and energy of 0.8

calculations that the Kyoto emissions reduction target is reached even after the commitment period of 2010 ("Kyoto-forever").[10]

4 Results

Within each scenario, Germany has to meet its emissions reduction target reached by domestic abatement measures. In the first scenario, we use the conventional OLG discounting procedure and in the second scenario, we use the adjusted GAD discounting procedure described in part two of this paper. All numbers are expressed in total or percentage values in comparison to the so called *B*usiness *A*s *U*sual scenario (BAU) where no climate change strategies are implemented. The model horizon comprise 150 years *t=0,10,...,T=150*, i.e. 15 periods with 10 years periods. In order to simulate the impacts of terminal constraints, simulation results are demonstrated for all 150 years. Each household or cohort lives 7 periods (*LT: 0,10,...,LT*), that means 70 years, within a model horizon of 150 years as described in Figure 1.[11] Three types of cohorts can be distinguished: 1. households born before *t=0* dying within the model horizon, 2. households whose life cycle include birth and death within the reflected model horizon ($0 \leq t \leq T=150$), and 3. households born within but dying after the considered model horizon. At each period in time, seven cohorts are alive, at initial time *t=0* the index of births *g* encompass considered periods of –60 to 150 because cohorts born before the reflected time horizon have also impacts on model results. Income of each household grows within time period 20 to 40 and diminishes after period 40.

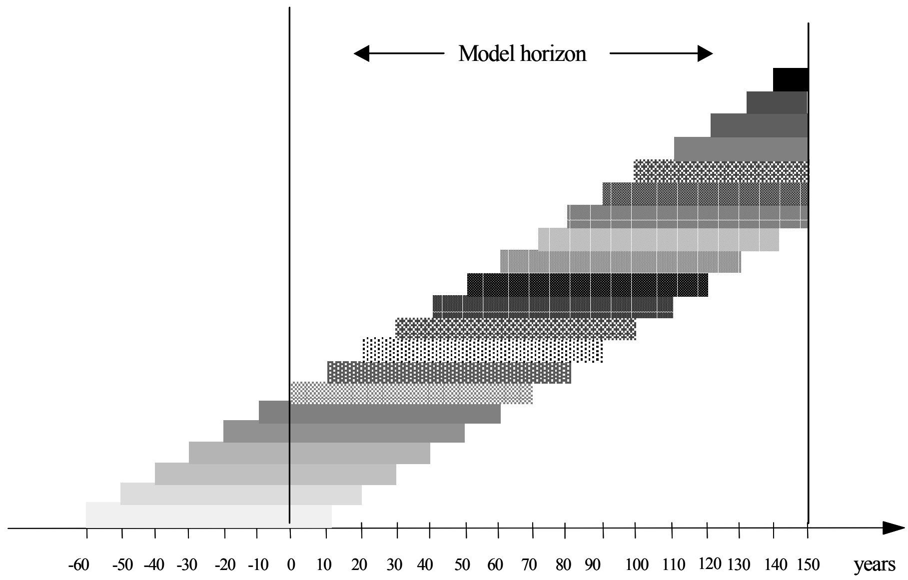

Figure 1: Time horizon and overlapping generations

Within this context, all results of the implementation of GAD changes are exposed as outcome in comparison to the original model-results. Therefore, we concentrate on the most important macro-variables in the following four figures

[10] Of course, there exists the possibility to induce increasing GHG-abatement measures by (sharp) devaluations of permission rights which can be undertaken by the national authorities.

[11] Although we argue in an OLG-model, each generation is allowed to bequeath not spent fortune to their descendants.

(figures 2 to 5). GHG-emissions and GHG-concentrations in the atmosphere are not of high importance within this paper due to the explicitly given and binding Kyoto emissions reduction target.

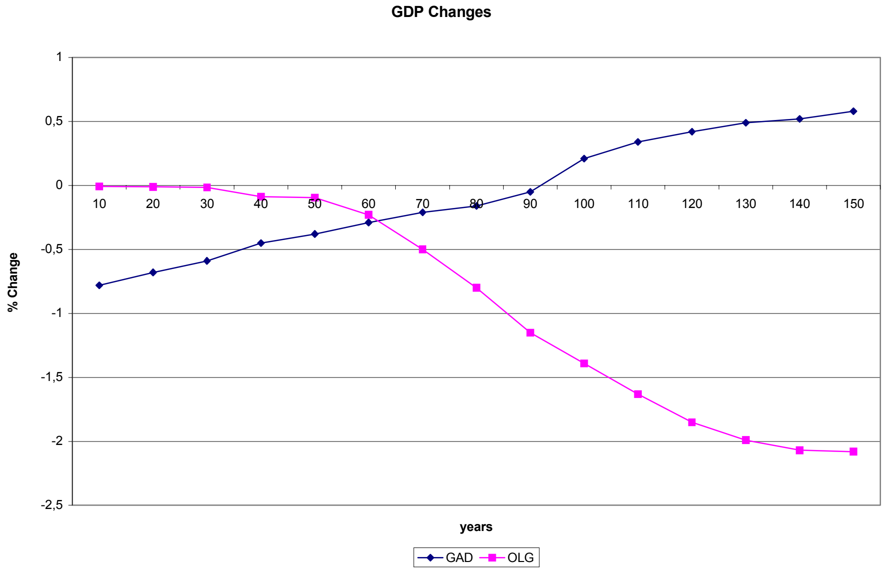

Figure 2: GDP Changes in % comparison to the BAU case

Model results demonstrate the GAD discounting procedure as adjustment measure towards a polluter pays principle: within the reflected time period of the first 70 years younger generations have to pay the burden in order to reduce emissions (see figure 2). Because of increased investment within former time periods generations living after period 70 benefit from this development and are able to increase their welfare. In the conventional OLG discounting procedure, GDP decreases within the first time periods less durable as in the longer periods because older generations consummate their capital increases and income of previous periods. Young generations earn mainly labor, older generation primarily capital income. GDP declines in the long run much more than in the GAD scenario where we find positive GDP changes after period 90. It seems that we will be faced with drastic GDP-losses due to GHG emissions reductions in the early periods of the planning horizon. In contrast, within the OLG scenario we detect only slight differences to the BAU GDP-path for the first 30 years, but especially starting with the year 2060, the GDP-losses in the GAD scenario are not as sharp as in the OLG case. Beginning with 2090, the GAD scenario leads to increasing GDP which is never realized in the OLG scenario. The differences between our two approaches will become even larger if we would extend our planning horizon due to the increasing GDP path in the GAD scenario and the decreasing one in the OLG case. This can mainly be explained by the assumption of growing GDP paths of 1.5 to 2 % in the BAU case and might be different if we use lower growth rates due to varying factor productivities.

Thus, first generations have to accept higher GDP and welfare losses in terms of employment, consumption as well as GDP in order to reach the Kyoto emissions reduction target, older generations benefit not only by an improved environmental situation (which is not accounted in real numbers in this model) but also by an improved economic situation. Overall analyses which are strictly oriented on aggregated welfare levels of all affected generations throughout the whole planning horizon cannot ignore that the GAD approach leads to higher aggregated GDP present values for all affected generations.

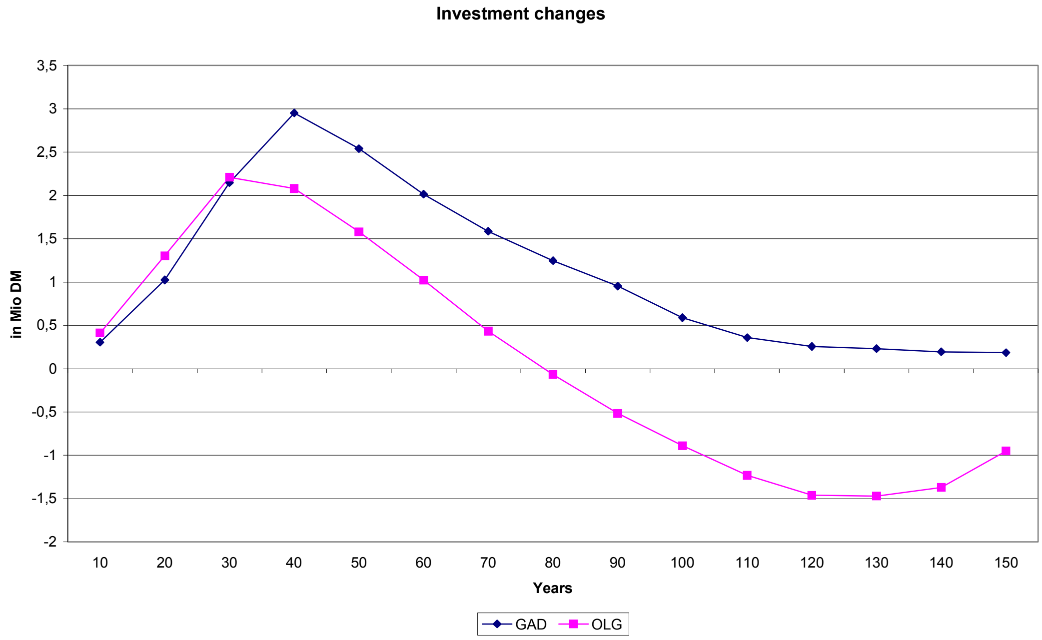

Figure 3: Investment changes in comparison to the BAU case

Our considerations are now demonstrated having a closer look on the path of net investments. In both scenarios, net investments are increased in the next 30 years by about 2 % compared to the BAU. In the GAD scenario, investments are augmented ten more years up to almost 3 %. Afterwards, the enhancement is being reduced. In the GAD scenario, a long-term net investment increase is still observable at the end of the planning horizon, whereas in the OLG case net investments are negative after the year 2080. Obviously, this leads to decreasing absolute GDP-levels as well, which can be seen in figure 2.

Concentrating on employment and per capita consumption changes confirm our observations with respect to GDP and net investment.

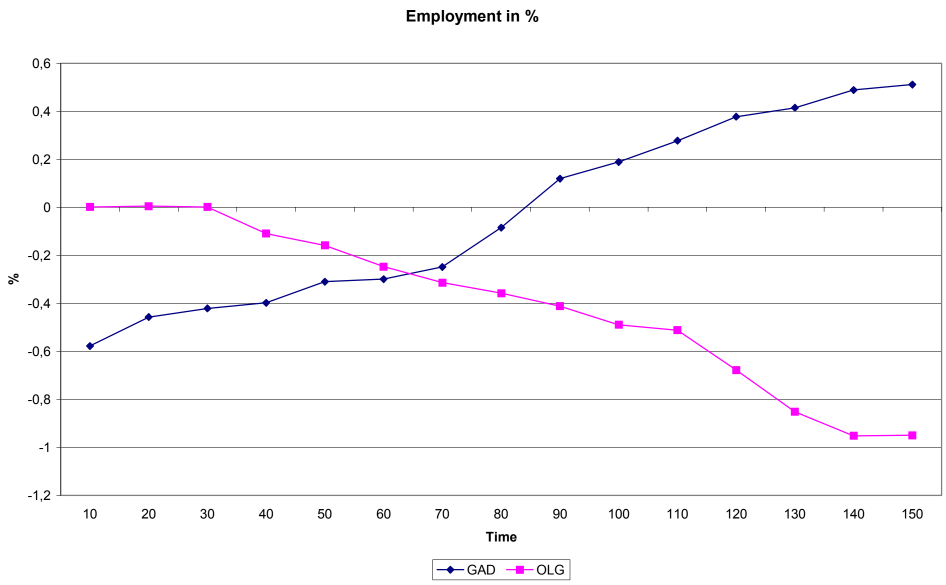

Figure 4: Employment changes in % in comparison the BAU scenario

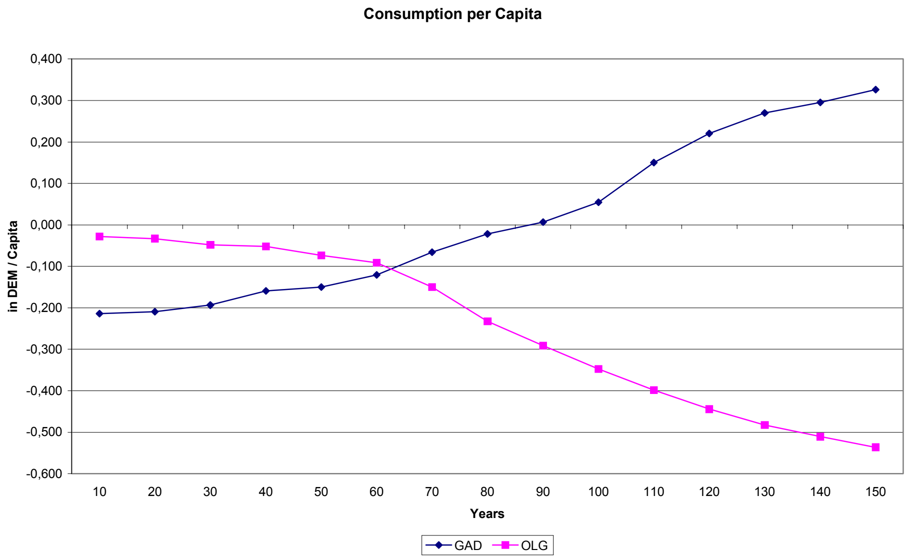

Figure 5: Changes of per capita consumption

Augmented investment because of intergenerational lower discount rates induce an increasing GDP of long run living generations. Welfare changes of each generation can be described by employment and consumption figures for both scenarios which show the same structure of development. Within a sectoral consideration, mainly energy intensive sectors like all energy sectors, iron and chemical industry are suffering because of drastic emission and energy reduction obligations. Less energy intensive industries like the service sector or sectors using less energy intensive technologies receive investment increases and can enhance their employment potentials in the long run, i.e. within future generations. We identify a substitution process from energy intensive towards more labor intensive sectors gaining from new technological improvements. That means a substitution process of investment in pollution intensive sectors towards more “clean” investment in new and environmental friendly technologies as well as labor intensive sectors. Primary generations of the GAD scenario have to accept higher employment as well as consumption declines where generations in the long run can benefit by increased development. Scenario OLG demonstrate the contrary results. GAD discounting induces higher welfare losses to generations living in period 0 to 70 whereas the generations living beyond these periods are better off due to GDP and investment increases.

5 Conclusions

An intergenerational discounting technique - GAD -, which actually takes into account intergenerational peculiarities, leads to completely different statements than using the same model with the conventional discounting method. Additionally, having in mind all affected generations throughout the relevant planning horizon, far-sighted policy necessitates the usage of GAD due to its overall dominance with respect to overall welfare units in comparison to the conventional OLG discounting method. Furthermore, applying GAD discounting leads to sustainable paths of all economic variables at the expense of currently living ones. Their contribution to the achievement of "sustainability" can be interpreted as an application of an intertemporal polluter pays principle, where (negative) intertemporal externalities are - to a large extent - avoided. This is not only fair from a normative viewpoint, but also efficient due to the internalization of today's occurring external costs with respect to climate change.

The achievement of the Kyoto emissions reduction target is guaranteed in the OLG scenario as well as in the GAD one at every point in time of the planning horizon. However, in the OLG scenario the society has to accept negative economic effects in the long run. All generations throughout the whole planning horizon are affected by decreasing paths of the relevant macro variables due to pronounced short-sightedness of today's living generations. In contrast, in the GAD scenario previous generations reach the Kyoto target at the expense of GDP-units, consumption units and increasing unemployment. But welfare reductions of current generations are overcompensated by additional welfare units of future living ones. From a societal point of view, the GAD scenario strictly dominates the OLG one due to higher overall societal welfare present values, which can exemplary be seen in figure 2.

Additionally, the GAD scenario dominates not only the OLG one, but also the business as usual path which is e.g. recommended by Nordhaus (1994) in his wait and see-strategy. This can be seen in figure 5, where we plotted the per capita consumption path. For the next 90 years, per capita consumption is lower in comparison to not abate any GHG-emissions at all. However, beginning with year 2090, a sharp increase in per capita consumption can be identified. Extending our planning horizon would show that per capita consumption rises strictly monotonous for several more decades. Thus, the result of Nordhaus (1994) - to adopt a policy strategy of wait and see until better a understanding of climate change and better technologies - is reversed: The longer we refrain from actions toward an improved environmental situation, the further in the future positive changes of GDP, employment rates, and per capita consumption occur and the higher is the burden share of today's living generations. Additionally, the longer previous generations sink into inertia and delay with starting GHG-abatement, the higher will be the probability for irreversibilities in climate change and the more serious will be future economic and environmental burden for next generations.

Although the GAD scenario dominates the OLG one from a theoretical viewpoint, it is possible that it is politically not acceptable even because of its far-sightedness. Each politician is mainly interested in the perceived welfare of current living people, simply because unborn future ones are not able to give her vote in (one of) the next elections. However, this is no neutral climate policy undertaken by a welfare oriented government. These politicians bias their decisions against future living generations, although there is - at least in industrialized countries - broad consensus to take into account interests of future generations which is documented in all declarations following the Earth Summit 1992 in Rio de Janeiro. Explicitly neglecting these statements by using non-sustainable theoretical tools cannot be interpreted as serious policy-making according to specified and, especially, in general accepted societal objectives.

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Appendix

Mathematical description of the GOLD model

GOLD is a dynamic OLG model and characterised by zero profit conditions, market equilibrium, income restrictions and trade relations (Armington).

The CES production structure follows the concept of ETA-MACRO combining nested capital and labour at lower level. Energy is treated as a substitute of a capital labour composite determining together with material inputs the overall output (see Figure 6).

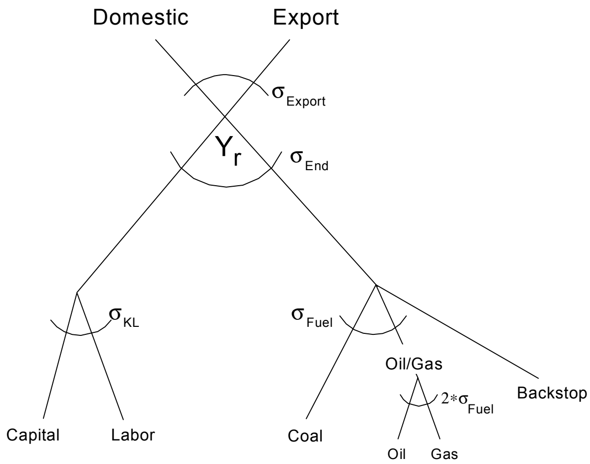

Figure 6: Production Structure

The representative producer of sector j ascertains the *profit function*

$$\Pi_j^Y(p) = \left[a_j^{DX}(p_j{}^{1-\sigma_{DX}} + (1-a_j^{DX})p^{FX\,1-\sigma_{DX}}\right]^{\frac{1}{1-\sigma_{DX}}}$$

$$-\left[a_j^M p_j^{M\,1-\sigma_{KEM}} + (1-a_j^M)\left[a_j^E p_j^{E\,1-\sigma_{KLE}} + (1-a_j^E)\left[a_j^K (p^{RK})^{1-\sigma_{KL}} + (1-a_j^K)(p_j^L)^{1-\sigma_{KL}}\right]^{\frac{1-\sigma_{KLE}}{1-\sigma_{KL}}}\right]^{\frac{1-\sigma_{KLEM}}{1-\sigma_{KLKE}}}\right]^{\frac{1}{1-\sigma_{KLEM}}}$$

with:

a_j^{DM} : Domestic production share of total production by sector j

a_j^K : Value share of capital within capital –energy composite

a_j^L :Value share of labour within capital -energy -labour aggregate

a_j^M : Value share of material within capital-energy-labour material aggregate

p_j : Price of domestic good j

p^{FX}: Price of foreign exchange (exchange rate)

p^{RK}: Price of capital

p_j^E : Price of energy

p_j^M : Price of material

p^L: Price of labour

σ_{KE}: Substitution elasticity between capital and energy

σ_{KEL}: Substitution elasticity between labour and capital and energy composite

σ_{KLEM}: Substitution elasticity between material and labour/ capital and energy- composite

Y: Activity level of production sector j.

Domestically produced and imported goods are aggregated by an Armington good demanded by final demand or by intermediate production as input factors within the economy. Profit function by *Armington production* is specified by:

$$\Pi_j^A(p) = p_j^A - \left[a_j^A p_j^{1-\sigma_{DM}} + (1-a_j^A)\left(p^{FX}\right)^{1-\sigma_{DM}}\right]^{\frac{1}{1-\sigma_{DM}}}$$

with:

p_j^A : Price of Armington good j

a_j^A : Domestically produced good j value share of domestic and import good aggregate

p^{FX}: Price of foreign exchange (exchange rate)

σ_{DM}: Substitution elasticity between domestically and imported good

A_j: Armington activity level

A composite energy good is produced by either conventional fossil fuels - oil, gas, and coal – represented by a nested CES technology (with an elasticity of interfuel substitution σ_{fuel}) or from a backstop source with Leontief technology structures. Oil and gas can be substituted by an elasticity of substitution twice as large as the elasticity between their aggregate and coal. The energy good production is determined by final demand of industry and households.

$$\Pi_j^E(p) = p_j^E - \Big[a_j^{ELE} p_j^{ELE\,1-\sigma_{ELE}} + (1-a_j^{ELE}) a_j^{OIL}(p_j^{OIL} + ef_j^{OIL,CO2} p^{CO2})^{1-\sigma_{FOSSIL}}\Big]$$
$$+ a_j^{GAS}(p_j^{GAS} + ef_j^{GAS,CO2} p^{CO2})^{1-\sigma_{FOSSIL}} + a_j^{COA}\Big[a_j^{HCO}(p_j^{HCO} + ef_j^{HCO,CO2} p^{CO2})^{1-\sigma_{COA}}\Big]$$
$$+ a_j^{SCO}(p_j^{SCO} + ef_j^{SCO,CO2} p^{CO2})^{1-\sigma_{COA}} \Big]^{\frac{1-\sigma_{FOSSIL}}{1-\sigma_{COA}}} \Big]^{\frac{1-\sigma_{ELE}}{1-\sigma_{FOSSIL}}} \Big]^{\frac{1}{1-\sigma_{ELE}}}$$

with:

a_j^{ELE} : Electricity value share of energy aggregate by sector j

a_j^{OIL} : Oil value share of fossil energy aggregate by sector j

a_j^{GAS} : Gas value share of fossil energy aggregate by sector j

a_j^{HCO} : Hard coal value share of coal aggregate by sector j

a_j^{SCO} : Soft coal value share of coal aggregate by sector j

σ_{ELE}: Substitution elasticity between electricity and fossil energy

σ_{FOSSIL}: Substitution elasticity between fossil energy inputs

σ_{COA}: Substitution elasticity between hard and soft coal

$ef_j^{OIL,CO2}$: CO_2 share of oil in sector j

$ef_j^{GAS,CO2}$: CO_2 share of gas in sector j

$ef_j^{HCO,CO2}$: CO_2 share of hard coalin sector j

$ef_j^{SCO,CO2}$: CO_2 share of soft coal in sector j

p^{CO2}: Price of carbon

E_j: Activity level of energy production

Demanded energy by households is produced by a CES function:

$$\Pi_{HH}^E(p) = p_{HH}^E - \left[\sum_{i=EG} a_{i,HH}^{CO2}(p_i^A + a_i^{CO2} p^{CO2})^{1-\sigma^{EG}}\right]^{\frac{1}{1-\sigma^{EG}}}$$

with:

$a_{i,HH}^{E}$: Value share of energy good i of household

p_{HH}^{E} : Price of energy by household demand

σ_{EG}: Substitution elasticities between energy goods

E_{HH}: Activity level of energy production by household

The dynamic model is a growth model, i.e. within equilibrium conditions all sizes are rising by a same growth rate. In the long run, a cap on emissions by an overall upper limit of emissions turns out to be difficult to meet. Because of that a carbon free backstop technology can be utilised within future times at price f^{BS} \$/t CO_2. Zero profit condition is determined by:

$$\Pi^{BS} = p^{CO2} - p^{CG} f^{BS}$$

with:

p^{CG}: Price of consumption good

f^{BS}: Costs of carbon free energy supply

BS: Activity level of backstop technology

Capital is used for production with a capital price p_t^K and an utility price of p_t^{RK} and is depreciated by rate δ:

$$\Pi_t^K(p) = (1-\delta) p_{t+1}^K + p_t^{RK} - p_t^K$$

with:

p_t^K : Price of capital in period t

p_t^{RK} : Price of capital services in period t

K_t: Activity level of capital in period t

Investments are produced by Leontief technology:

$$\Pi_{t+1}^I(p) = P\ p_{t+1}^K - \sum_j a_j^I p_{j,t}^A$$

with:

a_j^I : Value share investment of good j

I_t: Activity level of investments in period t

P: Time period

Labor is supplied by household and demanded by firms, all household are confronted with a specific time quota be spend for labor or leisure. This labor – leisure decision is determined by net wages ensuring a price elastic labor supply. Market clearance is determined by:

$$\sum_{g=-LT}^{T} L_{g,t}^{END} = \sum_{j} \frac{\partial \Pi_{j,t}^{Y}(p)}{\partial (p_t^L (1+\lambda^L t^L))} Y_{j,t} + \sum_{g=-LT}^{T} \frac{\partial \Pi_{g,t}^{C}(p)}{\partial (p_t^L (1+\lambda^L t^L))}$$

with:

$L_{g,t}^{END}$ Time budget in period t of household born in time period g

One household born in period g chooses a consumption path $C_{g,p}$ maximizing its utility by considering the intertemporal budget constraint:

$$\max_{C_{g,t}} \sum_{t=g}^{g+LT} \frac{C_{g,t}^{1-\sigma}}{1-\sigma} \frac{1}{(1+\rho)^t} \qquad \text{s.t.} \quad \sum_{t=0}^{T} p_t^C C_{g,t} = M_g \quad \perp \; M_g,$$

where σ represents the intertemporal substitution elasticity, ρ depicts the (additional) pure time preference rate of all living generations and M_g shows the present value of income. Present value of income is determined by the discounted sum of future labor and non labor income.

$$M_g = \sum_{t=0}^{T} p_t^L L_{g,t}^{END} + \theta_{g,t} p_t NF_t$$

with:

$L_{g,t}^{END}$: Labor endowment of household born in period g in time period t

NF_t : Non labor income in time period t

$\theta_{g,t}$: Share of non labor income in time period t of households born in time period g

Non labor income in period t can be calculated by the sum of balance of payment deficit or surplus and transfer income:

$NF = BOP + \lambda^{LS}\, TRANS$

with:

BOP: Balance of payment deficit or surplus

Trans: Transfer income

λ^{LS}: Adjustment multiplier of transfer income

Demand functions can be written as

$$C_{g,t} = \overline{C}_{g,t} \left(\frac{\overline{p}^{C}_{g,t}}{p^{C}_{g,t}} \right) \frac{M_g}{\overline{M}_g} \left\{ \frac{\overline{e}_g(\overline{p},\overline{U}_g)}{e_g(p,U_g)} \frac{U_g}{\overline{U}_g} \right\}^{1-\sigma}$$

with:

$p^{C}_{g,t}$: Price of consumption aggregate in time period t

M_g: Income of household born in time period g

$e_g(p,U_g)$: Expenditure function of household born in time period g

U_g: Utility of household born in time period g

σ: Intertemporal substitution elasticity

Expenditure function is determined by:

$$e_g(p,U_g) = \overline{e}_g(\overline{p},\overline{U}) \frac{U_g}{\overline{U}_g} \left[\sum_{t=g}^{g+LT} \theta_t \left(\frac{p^{C}_{g,t}}{\overline{p}^{C}_{g,t}} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, \quad \theta_{g,t} = \frac{\overline{p}_{g,t} \overline{C}_{g,t}}{\overline{M}}$$

with:

$\theta_{g,t}$: Value share of consumption in time period t of household born in time period g

By determining income and consumption paths saving $S_{g,t}$ of all households can be calculated for each lifetime period by the discounted sum of all expenditure surpluses of the remaining lifetime period.

$$S_{g,t} = \sum_{i=t}^{g+LT} (p^{C}_{g,i} C_{g,i} - p^{L}_{i} L^{END}_{g,i} - \theta_{g,i} p_i NF), \ \forall t = 0,...T$$

The primary factors, capital, labor, and energy are combined to produce output in period t. In addition, some energy is delivered directly to final consumption. Output is separated in consumption and investment, investment enhances the (depreciated) capital stock of the next period. Capital, labor, and the energy resource earn incomes, which are either spent on consumption or saved. Saving equals investment through the usual identity (see Figure 7).

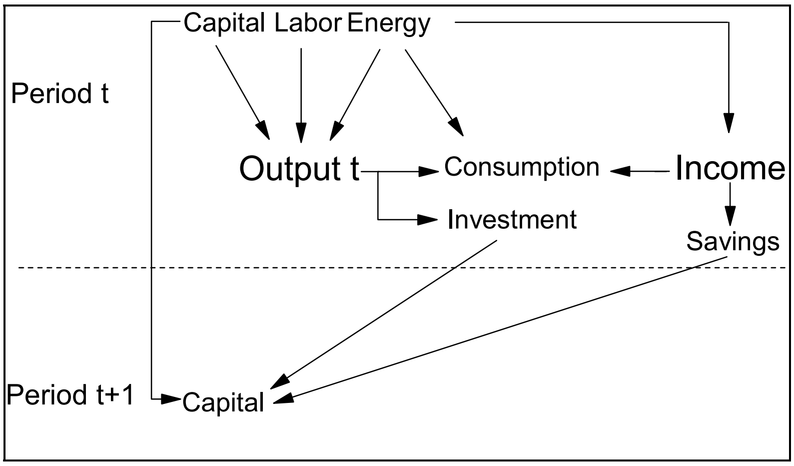

Figure 7: Dynamic structure

One representative agent of each generation by a region demands a composite consumption good produced by combining the Armington good and the household energy aggregate good according to a CES configuration. σ_{end} describes the elasticity of substitution between the composite macro good and the energy aggregate. Aggregate end-use energy is composed of oil, gas, and coal with an interfuel elasticity of substitution equal to one. The backstop fuel is a perfect substitute for the energy aggregate. Purchase of the good is financed from the value of the household's endowments of labor, capital, energy specific resources, and revenue from any carbon tax or permit prices, respectively (see Figure 8).

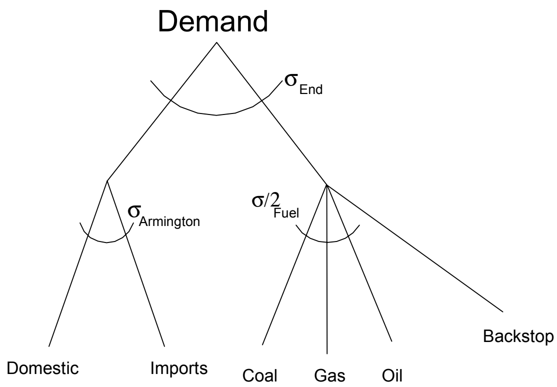

Figure 8: Final Demand Structure

Mathematically, this dependence can be written:

$$\Pi^{CG}(p) = p^{CG} - \left[a_E^{CG} (p_E^{HH})^{1-\sigma_C} + \sum_i a_i^{CG} (p_i^A)^{1-\sigma_C} \right]^{\frac{1}{1-\sigma_c}}$$

with:

p^{CG}: Price of consumption good

a_E^{CG}: Value share of energy aggregate in final demand

a_i^{CG}: Value share of non- energy good in final demand

CG: Activity level of real consumption good production