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On the shorter-term economic motivation for carbon emissions reductions

Abstract

It is often suggested that there is not least an economic interest in climate change mitigation because the negative implications from and the adaptation to longer-term climate change will easily exceed the costs of preventive measures in terms of carbon emissions reduction. This paper revises whether this hypothesis also holds over shorter time horizons, in particular the current decade, and for individual states.

For most considered states it is found that the minimum of the national cost functions is associated with a slight reduction of carbon emissions. However, this reduction amounts to less than 1% of the total emissions expected until 2020 under a business-as-usual scenario. Unilateral advances in emissions reductions at the national scale hardly affect the optimal strategies and costs of other states. Some states are still profiting from a moderate extent of shorter-term climate changes and will not be motivated towards carbon emissions reductions, while other states already experience climate-related economic damage. Overall, the shorter-term economic motivation alone cannot be expected adequate to initiate the necessary and urgent measures in carbon emissions reduction required to achieve the +2°C goal in climate change mitigation.

Keywords: climate mitigation, economics of climate change, cost functions.
JEL Classification: Q50, Q54.

Introduction

There is an increasing consensus among scientists and policymakers that the Earth's climate system is currently changing and that this change is very likely due to human activity (IPCC, 2007a, Paeth et al., 2008). It is also commonly accepted that the negative implications for ecosystems and livelihood will dominate the positive effects (IPCC, 2007b). The consequences will be manifold, while some of them are still badly understood nor quantifiable (Heal, 2009). While the macroeconomic systems may be less vulnerable to climate change, individual sectors will be largely affected with severe implications for labor markets in industrialized countries and even hunger in developing countries (Smith, 1996). Among the most sensitive sectors agricultural production and pasture have to be mentioned first, especially in underdeveloped and overpopulated regions of the tropics and subtropics (Butt et al., 2005; Thomson et al., 2006). This will further hamper the economic development of the poorest (Brown et al., 2011), leading to political conflicts and societal instability (Hsiang et al., 2011), especially because water resources are running short in many regions of the globe (Guo et al., 2003). Anyway, the economic loss due to climate change will also concern the highly developed states of our planet, particularly through damage of infrastructure in the course of more intense and more frequent extreme events (Bouwer, 2011) with implications for the insurance industry (Changnon, 2003; Murnane, 2004). In addition, the energy production sector will be subject to infrastructural damage and exploitation risks which will further boost the energy prices worldwide (Golombek et al., 2012).

In the light of these economic risks, it would be a logical consequence that mankind will use all available means to avoid the negative implications of climate change. Undoubtedly, the reduction of carbon emissions represents the best option in climate change mitigation (IPCC, 2007c) but also an expensive way whose benefits will become discernible not before several decades into the future (Johns et al., 2011).

Thus, climate policy is part of a generation problem and still fails in the light of the 'anarchy', egoism and purblindness of the international economic and political systems (Thompson, 2006). Nonetheless, carbon emissions reduction is an official key topic on the agenda of national and international political authorities (Heal, 2009). As a certain extent of global warming cannot be obviated anymore (Meehl et al., 2005), our efforts now tend towards limiting the amount of future warming to 2°C compared with pre-industrial conditions in order to prevent dangerous interference from climate change (Mastrandrea and Schneider, 2004; Hansen et al., 2006; Anderson 2011, May 2011; Pardaens et al., 2011). To obtain this goal the paradigm shift in favor of climate change mitigation must take place now and not in a few decades (Meinshausen et al., 2009), especially since early measures in emissions reduction will save money (Gerlagh and van der Zwaan, 2004).

In summary, we are nowadays in a difficult and trendsetting situation where a tangible emission policy at international level is urgently required but the intrinsic motivation for climate change mitigation is still quite low on the part of most decision makers in policy and economy. In view of this dilemma it would be an excellent argument to demonstrate that the economic risks arising from climate change clearly outperform the costs for carbon emissions reduction. An early attempt in this direction was made by Fankhauser (1995) and, more recently, the report by Stern (2006) has attracted much attention. Indeed, both authors support the argument mentioned above but failed to initiate a general rethinking and, in particular, concrete actions bythe persons in charge. Apart from some questionable assumptions and errors in reasoning, one explanation for this failure is that longer-term and partly quite vague benefits from carbon emissions reductions, as predicted by Stern (2006), are bought dearly by present-day efforts and costs during a time when the negative consequences of climate change are still not sufficiently perceptible for many people. In addition, the assessment by Stern (2006) is confined to the global and continental scale, whereas it is more likely that efficient measures in climate change mitigation will emerge at the scale of national initiatives and decision processes (Kruger et al., 2007; Sharma et al., 2012).

Here, we offer a regionally more differentiated view on the basis of selected countries. Due to the inertia of the atmosphere climate related damage is generally expected to be higher in the long rather than the short run. Therefore, it is assumed that from an economic point of view there is little incentive for short-term emissions reductions as long as no additional supranational environmental strategy, such as an emissions trading scheme, is set up (del Río González, 2008). This paper aims at giving support to this hypothesis by considering country-specific climate-related damage functions and respective abatement cost curves. As such, the short-term approach is useful to identify those regions or countries where substantial emissions reductions can be realized most cost-efficiently and on a rather short time horizon.

Our approach is focused on the decade 2011 to 2020 for three reasons: (1) This choice is closer to the time frame of current economic and political decision processes, as seen by the 10-year horizon of the Copenhagen Accord. Typically, politicians hesitate to facilitate urgently required radical innovations due to their long (out of election periods) development and the corresponding high short-term costs, often implying a negative long-term effect (Kemp, 1994). (2) Estimates of implication and mitigation cost functions as well as of gross domestic product (GDP) and business-as-usual emissions are more accurate for shorter-term forecasts. (3) It is now the time period to ultimately set the course for the prevention of dangerous interferences from climate change. Thus, an analysis of the short-term economic viability of emissions reductions seems necessary because emissions reductions prove especially beneficial, if the declining of (global) CO_2 emissions starts the earliest possible (Weyant et al., 2006; Hansen et al., 2006; Stern, 2006). The current decade 2011-2020 has been chosen as a case study which is more dedicated to the evaluation of our scientific hypotheses than to practical action guidelines. The method could be applied to any subsequent period, once updated accurate estimates of cost and damage functions are available.

Our calculations are based on estimates of climate-related damage functions and marginal abatement (costs) curves from the literature which are applied to nine states selected thoroughly in order to be representative of the World's population, economy, socio-economic development and vulnerability to global warming. These are the USA, Germany, Japan, Russia, Brazil, China, India, Nigeria and Bangladesh, standing for 53.3% of the global population, almost two-thirds of the total carbon emissions and an important share of the World's total economic performance (cf. Table 1 in Appendix). In addition to the computation of national cost functions and related economically optimized carbon emissions reductions over the next ten years we investigate the impact of unilateral national efforts in climate change mitigation on the best strategies of other states and evaluate national and transnational options in emission policy.

The next section describes the derivation of the national cost functions indicating the economic damage from climate change. Section 2 is dedicated to the mitigation cost functions, and section 3 deals with the composed total cost functions which are minimized to determine the optimal emissions reductions from an economic point of view. Results are discussed and conclusions are drawn in the final section.

1. Costs of damage

The estimate of damage functions related to global warming is subject to large uncertainties because many implications of climate change are still unknown due to the complexity of the system or can hardly be quantified (Stern, 2006; IPCC, 2007b; Heal, 2009). In addition, the vulnerability to climate change is also influenced by political and economic measures like investments in knowhow and access to loans (Bowen et al., 2012). Here, we rely on the often cited and generally approved regional damage functions from Nordhaus and Boyer (2000) with the various assumptions made therein. Thus, our results must be interpreted conditional on these assumptions. For most states considered here damage functions are directly given by Nordhaus and Boyer

(2000), for other states we have chosen the best representatives: Germany = Western Europe, Brazil = lower-middle income, Nigeria = Africa, Bangladesh = low income.

Damage functions are typically scaled by global temperature increase (cf. Nordhaus and Boyer, 2000). In this study we intend to merge damage functions with abatement curves which, usually, are a function of carbon emissions reduction (cf. Ellermann and Decaux, 1998). Therefore, we have rescaled the original damage functions leading to carbon emissions as independent variable. Figure 1 (in Appendix) illustrates this procedure for global-mean values. First, nonlinear functions have been fitted to the values given by Nordhaus and Boyer (2000) using a least-square approach (Figure 1a). In the next step, global temperature increase is linearly related to atmospheric CO_2 concentrations (Figure 1b). This implies an estimate of the so-called climate sensitivity, i.e. the temperature change caused by a doubling of the atmospheric CO_2 concentration. Actually, climate sensitivity represents a fairly unknown property of the Earth's climate system (Caldeira et al., 2003). It cannot readily be derived from paleo-climatological assessments and strictly depends on the interplay of negative and positive feedbacks in the system (Roe and Armour, 2011). According to Meinshausen et al. (2009) we assume a mean climate sensitivity of ΔT = 3°C per CO_2 doubling. This represents another crucial parameter of our study: higher values of ΔT, e.g. in a climate system whose positive feedbacks are not entirely known, imply a stronger increase of the straight line in Figure 1b and lead to a shift of the minimum in the total cost functions in section 4 towards higher (except countries which benefit from climate change) carbon emissions reductions – and vice versa. Finally, the atmospheric CO_2 concentration is translated into cumulative global carbon emissions using the year 2010 with 390 ppm as a reference basis (Figure 1c).

Increasing the atmospheric CO_2 concentration by 1 ppm is equivalent to a global carbon emission of 2.12 Gt (IPCC, 2007a). Thus, the carbon emission E at time t after 2010 can be calculated from the contemporaneous atmospheric CO_2 concentration C by

$$E(t) = (C(t) - 390\,ppm) \cdot 2.12 \cdot 10^9 \,\frac{t}{ppm}. \qquad (1)$$

Time t is varied over the period 2011-2020, $C(t)$ is extrapolated over this period on the basis of a business-as-usual (BAU) scenario using observed carbon emissions during 2000-2007 derived from the World Bank (http://data.worldbank.org). The same data source has been employed to assess the recent economic growth rate of each considered state. Assuming constant growth rates the national GDP could also be extrapolated over the decade 2011-2020.

This procedure is applied to the original damage functions for all nine states mentioned above, leading to the final quadratic damage functions in Figure 2. It is obvious that the economic sensitivity to climate change is very heterogeneous from state to state, according to Kropp et al. (2006) and Wheeler (2011). Some countries even profit from a low extent of global warming as expected over the next decade or two. This particularly holds for China. Russia and Brazil are still in the profit zone but will experience economic losses beyond a cumulative global carbon emission of about 50 Gt. This threshold will be exceeded during the next decade under a BAU scenario (see Table 2). In industrialized countries like the USA, Germany and Japan economic damage already occurred in 2010 and is exponentially increasing with carbon emissions. The same is true for India, Nigeria and Bangladesh but from a higher level of greenhouse gas emissions (and global warming) onward. At the level of the 9-states world the transition from economic gain to loss is very dramatic and will also happen within the next twelve years. Extrapolating the BAU scenario further into the 21st century, all states will suffer economically from climate change in at least 35 years. The fact that industrialized states are economically more sensitive even to a low amount of global warming is related to the enormous monetary values inherent to public and private infrastructure and possession which are already threatened by intensified weather extremes (Bouwer, 2011).

2. Mitigation costs

There is a variety of measures and related costs in climate change mitigation (IPCC, 2007c), not counting the costs for adaptation to the unavoidable dimension of global warming (Pielke et al., 2007). For instance, direct costs have to be expended for new technologies and infrastructure in energy production and transportation, while indirect costs incur for less efficient production processes and competitive disadvantages (Stern, 2006). Here, we only account for the costs associated with carbon emissions reductions. The corresponding abatement curves are also subject to uncertain assumptions on behalf of the physical and the socio-economic system: Johansson et al. (2011) have shown that the heat capacity of the oceans plays a crucial role. Fischer and Morgenstern (2003) have demonstrated that abatement costs decrease with foresightful behavior and increase with institutional and sectoral fragmentation in the organization of climate change mitigation. In addition, a combination of flexible instruments positively affects emissions reduction costs (Bürgenmeier et al., 2006).

In this study we rely on the marginal abatement curves by Ellermann and Decaux (1998) which are based on the EPPA model (Paltsev et al., 2005) and have been further developed by Morris et al. (2008). Marginal abatement costs indicate the economic expenses per (additional) unit mass of reduced carbon emissions. They are not constant but typically increase with each additional reduced unit mass because the first reductions are usually based on cheap measures whereas later measures become more and more expensive until a saturation level is reached. Thus, the marginal abatement curves in Morris et al. (2008) have the form of an arc tangent function for most states and regions. Due to our decadal focus we are only interested in the exponential increase on the left hand side of the functions and, hence, use the interpolation values below 400 Mt of carbon emissions reduction to which second-order polynomials are fitted. Finally, the marginal abatement curves are integrated in order to obtain the total mitigation costs per amount of reduced carbon emissions. Again, direct estimates are available for the USA, Japan, China, India and Russia while Germany is set equivalent to the European Union, Brazil to Central and South America, Nigeria to Africa and Bangladesh to Rest of World.

The resulting national mitigation costs are displayed in Figure 3 (in Appendix) for emissions reductions between 0 and 500 Mt which is a realistic range for a decadal time span. In the section shown the third-order functions describe roughly an exponential increase of mitigation costs as a function of reduced carbon emissions. In detail, starting from the origin the mitigation costs for some states initially become slightly negative indicating that some early measures in emissions reduction are associated with economic benefits in terms of energy saving, reduced fuel costs, transfer of knowledge etc. (UNEP, 2008). In general, developing countries are characterized by a stronger increase of mitigation costs than industrialized states because they often do not possess the infrastructure and knowhow to develop new technologies. An exception is Japan where energy production is mainly based on nuclear power plants with relatively low carbon emissions. Thus, measures of climate change mitigation are already quite exploited and additional measures particularly expensive. The lowest mitigation costs are given at the level of the 9-states world which is a clear pleading for a supranational solution which is able to assign the reduction measures to the cheapest state, region or technology available (cf. Scott et al., 2004).

3. Total cost functions

From an economic point of view, the optimal strategy of a state is marked by the lowest costs and the highest profit, respectively. In term of carbon emissions reduction, the best strategy arises from a combination of the damage functions and mitigation functions described in sections 1 and 2: stronger efforts in emissions reductions enhance the mitigation costs but reduce the damage, and vice versa. The total cost functions presented here are derived by adding the damage and mitigation cost functions using carbon emissions reductions as independent variable. The resulting curves are third-order polynomials with noticeably different offsets for the individual states, according to the damage functions (cf. Figure 2), and a local minimum in the range between 0 and 500 Mt of reduced carbon emissions (Figure 4 in Appendix). They are characterized by a more or less intense exponential increase towards high reductions and, hence, reveal that most states will have no economic motivation for large carbon emissions reductions within the next ten years. Again the best strategy with the largest economic benefit occurs when an international solution is realized. This benefit would be in the order of more than US$ 320 bn over the next decade and, still, a slight emissions reduction would be achieved.

The minima of the total cost functions are listed in Table 2, together with the associated lowest costs (highest benefit) for each state. Except for Russia and Brazil, all states should reduce their emissions from an economic point of view, leading to a total reduction of more than 400 Mt which, however, is less than 1% of the entire carbon emissions under a BAU scenario over the decade 2011-2020. Under this optimal strategy China, Brazil and Russia would have the highest profit from climate change, while all other states have to spend money, especially Germany and India. Until 2020 the climate change-related costs and profits are everywhere below 3% of the national GDP, at the international level even below 1%.

Finally, we address how unilateral initiatives of individual states which implement emissions reductions beyond the economically motivated level, affect the optimal strategies of other states. Three cases are tested (Table 3): (1) Germany reduces by 20% and all other states follow the minimum of their cost functions adjusted to this unilateral reduction; (2) Germany is supported by the USA with the same relativeamount of national reduction; (3) both countries are supported by China. In summary, it can be noted that these national actions hardly impact on the economically optimized strategies of the remaining states. Nonetheless, the amount of reduced carbon emissions increases considerably, especially when China and the USA as most prominent emission sources reduce by 20%, finally reaching almost 15% of the total emissions until 2020. At the same time, the overall costs escalate dramatically from a gain of US$ 318 bn (no national actions) to a loss of US$ 2,672 bn over ten years, mainly arising from the enormous mitigation costs in China which now had to spend almost 20% of the national GDP. This demonstrates that individual advances in climate change mitigation can have very positive effects on the global carbon emissions but strain the acting states to a critical extent (cf. Nordhaus, 2001). Note that in our test cases the interplay between the national strategies is still limited to the economic optimization. In terms of classical game theory additional motivations such as sense of responsibility, equity, confidence, honor, diplomacy or ethics would render the national behavior patterns more complex (McCain, 2010).

Conclusions

In this study we investigate whether the selected states have an economic motivation for carbon emissions reductions at the time horizon of the next decade. We rely on well-elaborated estimates of damage functions and abatement costs from the literature and merge these functions to assess the total climate change-related costs at national level. Our results indicate that most states actually should reduce their carbon emissions in terms of an economic optimization, yet the resulting total reduction is below 1% of the expected entire emissions. The related costs are in the order of 0.01 up to 2.55% of the national GDP, whereas some states still appear to profit from a low degree of climate change until 2020. Politically motivated national advances in carbon emissions reductions hardly affect the economically optimized strategies of other states. The highest economic benefit is achieved when mitigation measures are organized at the supranational level.

From the perspective of climate research and climate policy our findings are promising and disappointing at the same time: on the one hand there is indeed an economic argument in favor of carbon emissions reductions, on the other hand, it is not sufficient to accomplish the reduction goals necessary to induce the turnaround towards a limitation of global warming to 2°C with respect to pre-industrial conditions. Thus, further motivations at national and international level are currently indispensable, assuming that political and economic decisions during the next ten years are still dominated by a shorter-term profit mentality rather than an awareness of the longer-term economic risks from climate change. Among these additional motivations ethic principles like equity, justice and the sense of historic responsibility may play a crucial role (Grasso, 2007). In addition, the motivation for emissions reduction of a particular state is also influenced by the environmental awareness of its population (Endres and Finus, 1998). This is the way individuals can contribute to national and international decision processes in terms of climate change mitigation.

Another interesting outcome of our study is that a supranational solution outperforms all national strategies – at least in the context of our 9-states world. This is in agreement with Scott et al. (2004) and Bürgenmeier et al. (2006) and seems to apply to aerosol emissions as well (Cowan and Cai, 2011).

Our results strictly depend on the assumptions made in the context of the regional damage functions (Nordhaus and Boyer, 2000) and the marginal abatement costs (Ellermann and Decaux, 1988; Morris et al., 2008). It would be useful, if error bars were given for the basic values in the considered functions. Thereby, uncertainty levels could be transferred down to the level of optimized carbon emissions reductions and related costs or benefits. Economic risks could also be highlighted more properly, when damage functions were regionally differentiated, accounting for highly vulnerable systems like desert margins, coastal and high-mountain areas. Finally, a better knowledge of feedbacks and tipping points in the Earth's climate systemwould allow for a more accurate assessment of damage functions over longer time scales when the negative economic implications of global warming become more and more relevant to the national and global GDP. In fact, we have also extended our computations until 2050 based on the damage and abate costs functions described above. This has led to the somewhat counter-intuitive result that the minima of the total cost functions are located at much higher than present-day CO_2 levels in most countries, because currently available abate costs functions are increasing stronger than the damage curves.

Another interesting option for further investigation would be to design a game of interdependent national behavior in climate change mitigation, in the sense of game theory (McCain, 2010), in order to evaluate additional motivations and strategies beyond the economic optimization.

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Appendix

Table 1. Economic and emission-related indicators of the selected nine states, comprising 53.3% of the world's population and 65.2% of the global CO_2 emissions.

State	GDP in bn US$	Population in 1000	GPD per capita in US$	Carbon emissions in Mt	Contribution to global CO_2 emissions in %
USA	14,675	313,232	48,850	1,606	19.3
Germany	3,085	81,472	37,866	211	2.6
Japan	4,263	126,476	33,706	344	4.2
Russia	2,907	138,740	20,953	438	5.3
Brazil	2,106	203,430	10,352	102	1.2
China	9,789	1,366,718	7,162	2,181	26.3
India	4,063	1,189,173	3,417	475	5.7
Nigeria	362	155,216	2,332	30	0.4
Bangladesh	243	158,571	1,532	14	0.2

Source: International Monetary Fund (www.imf.org), Central Intelligence Agency: The World Factbook (www.cia.gov/library), The World Bank (data.worldbank.org), Earth's CO_2 Home Page (co2now.org), Center for Global Development (www.cgdev.org).
Notes: The values are representative for 2010 (GDP = gross domestic product).

Table 2. Estimates over the projection period 2011-2020 for the selected nine states

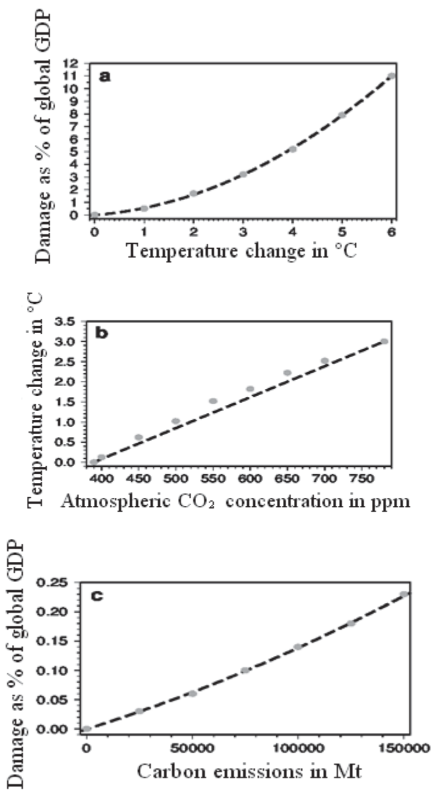
State	BAU carbonemissions in Mt	Optimal carbon emissions reduction in Mt	Optimal carbon emissions reduction in % of BAU	Mean GDP 2011-2020 in bn US$	Minimal climate costs in bn US$	Minimal climate costs in % of mean GDP
USA	20,231.2	54.8	0.27	17,457	1.91	0.01
Germany	2,769.5	58.1	2.10	3,634	52.69	1.45
Japan	4,353.7	14.6	0.36	4,904	5.06	0.10
Russia	5,309.0	0.0	0.00	4,017	-102.50	-2.55
Brazil	1,260.8	0.0	0.00	2,591	-64.62	-2.49
China	21,309.1	114.1	0.53	13,281	-312.12	-2.35
India	5,393.8	71.5	1.33	5,337	68.32	1.28
Nigeria	326.7	26.1	7.99	468	9.69	2.07
Bangladesh	145.8	68.7	47.12	311	5.94	1.91
Σ	**61,099.6**	**407.9**	**0.67**	**52,000**	**-335.63**	**-0.65**

Source: Own calculation, see text for explanation.
Notes: carbon emissions under the business-as-usual (BAU) scenario, absolute and relative optimal carbon emissions at the minimum of the total cost functions in Figure 4, mean gross domestic product (GDP), absolute and relative minimal costs related to climate change.

Table 3. Estimates over the projection period 2011-2020 for the selected nine states

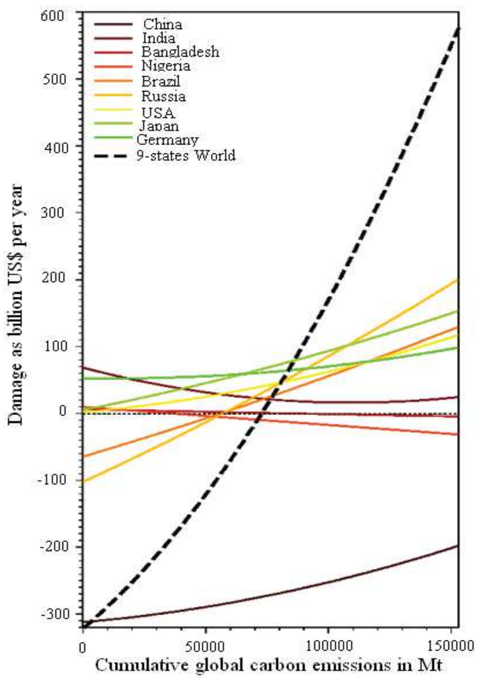
State	Optimal carbon emissions reduction in Mt	Minimal climate costs in bn US$	Optimal carbon emissions reduction in Mt	Minimal climate costs in bn US$	Optimal carbon emissions reduction in Mt	Minimal climate costs in bn US$
USA	54.7	2.00	4,046.2	36.35 4,082.047	4,046.2	37.09 4,082.780
Germany	553.9	69.27	553.9	69.07	553.9	68.88
Japan	14.6	5.28	14.6	6.89	14.6	8.61
Russia	0.0	-101.95	0.0	-97.95	0.0	-93.71
Brazil	0.0	-64.28	0.0	-61.77	0.0	-59.12
China	113.7	-312.03	110.9	-311.37	4,261.8	2,633,38
India	71.5	67.99	71.3	65.57	71.0	63.10
Nigeria	26.1	9.60	26.1	8.96	26.1	8.29
Bangladesh	68.7	5.91	68.7	5.75	68.7	5.58
Σ	**903.2**	**-318.21**	**4,891.7**	**-278,50** **3,767.191**	**9,042.3**	**2,672.10** **6,717.785**

Source: Own calculation, see text for explanation.
Notes: Optimal carbon emissions and minimal costs at the minimum of the total cost functions, provided that Germany implements a unilateral 20% emissions reduction (left), Germany and the USA do so (middle), and Germany, the USA and China do so (right). Values related to a politically forced instead of optimized emissions reduction are highlighted in grey.



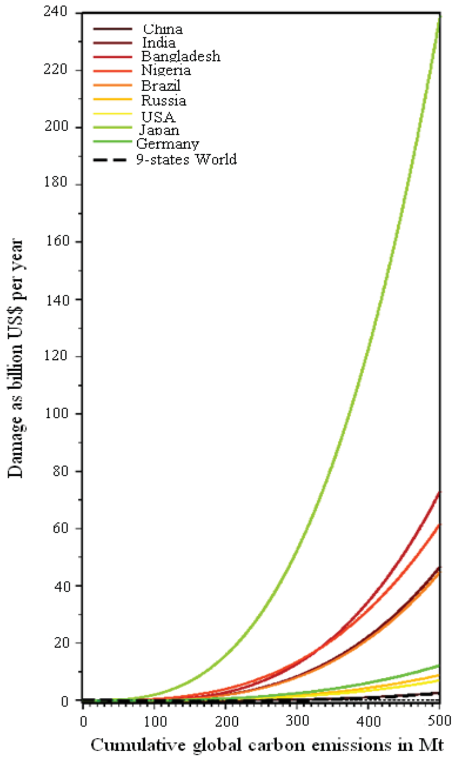
Source: See text for explanation.
Notes: Grey circles mark the estimates and data derived from (a) Nordhaus and Boyer (2000), (b) Meinshausen et al. (2009), and (c) own calculations. The dashed black lines denote the best statistical fit based on linear and nonlinear regression, respectively.

Fig. 1. Relationships between (a) economic damage per year and temperature change, (b) temperature change and atmospheric CO_2 concentrations, and (c) economic damage per year and carbon emissions



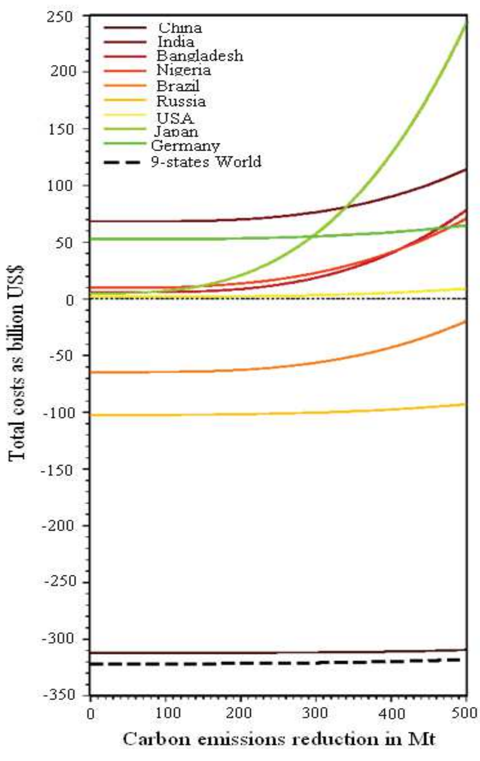
Source: Own calculation based on Nordhaus and Boyer (2000), see text for explanation.
Notes: Countries with negative damage are assumed to profit economically from global warming, at least in the range of these cumulative global emissions over the next ten years.

Fig. 2. Economic damage per year in the selected nine states and the 9-states World depending on the amount of cumulative global carbon emissions



Source: Own calculation based on the marginal abatement costs provided by Morris et al. (2008).
Notes: Mitigation costs are relatively low for the first reduced Mt and increase towards each additionally reduced Mt since cheap measures of emission reduction are realized first by each state. This leads to exponentially instead of linearly increasing mitigation costs as a function of carbon emissions reduction.

Fig. 3. Mitigation costs of the selected nine states and the 9-states World as the integral of the marginal abatement curves by Ellerman and Decaux (1998), updated by Morris et al. (2008)



Source: Own calculation based on functions in Figures 2 and 3.
Notes: The local minimum of each curve marks the economically best strategy of emissions reduction policy (cf. Table 2).

Fig. 4. Total costs of the selected nine states and the 9-states World associated with future carbon emissions