TECHNOLOGY PROTOCOLS FOR CLIMATE CHANGE: AN APPLICATION OF *FUND*

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Abstract

A technology protocol to govern long-term international greenhouse gas emission reduction is proposed. The protocol consists of three parameters: a graduation income, below which countries have no emission reduction obligations; a convergence rate, at which emission intensities should approach that of the most carbon-extensive countries; and an acceleration rate, at the which the most carbon-extensive countries should improve its technology over and above the business as usual scenario. Depending on the parameter values, emission reduction ranges from draconian to almost nil. The graduation income and acceleration rate have the expected effects. The effect of the convergence rate is strongly scenario-dependent; some scenarios, perhaps unrealistically assume strong technological convergence in the no policy case; in other scenarios, adopting best commercial technology in the whole world would lead to substantial emission reduction. Not surprisingly, regions prefer different parameters in the technology protocol. Adopting the opinion of the median voter, atmospheric concentrations of carbon dioxide in the year 2200 would be reduced from 1650 ppm to 950 ppm. This reduction is relatively robust to changes in crucial model parameters. The costs of complying to the technology protocol can be reduced substantially through international trade in emission permits and, particularly, banking and borrowing.

Key Words

climate change, international climate policy, technology, integrated assessment

JEL Classification

Q25, Q28, Q48

1. Introduction

Although the Kyoto Protocol was apparently saved in Bonn and Marrakech, the reinterpretation of the initial agreement also showed the limitations of an international treaty based on targets and timetables. At the end of the day, the Kyoto Protocol turned out to be only politically acceptable after targets of some countries were watered down considerably, and after sanctions for non-compliance were expressed relative to yet to be defined future targets. Still, one major party rejected the Kyoto Protocol altogether, while others are undecided.

These difficulties illustrate the inherent problems of managing global public goods, something economists have long stressed, also in the context of climate change (Barrett, 1990, 1994; Bohm, 1993; Carraro and Siniscalco, 1992, 1993; Chen, 1997; Escapa and Gutierrez, 1997; Fankhauser and Kverndokk, 1996; Nordhaus and Yang, 1996; Xepapadeas, 1995). If we take the conclusions of non-cooperative game theory seriously, then the international climate negotiations will not become easier in the future. Perhaps, it is time to explore alternatives to the legally binding targets and timetables that are at the heart of the Kyoto Protocol.

Various people have expressed various kinds of critique on the Kyoto Protocol (Barrett, 2002; Böhringer, 2002; Buchner *et al.*, 2002; Common, 1998; Cooper, 1997; Eyckmans *et al.*, 2002; Grubb *et al.*, 1999; Lashof, 2000; Manne and Richels, 1999; Metz *et al.*, 2001; Moomaw *et al.* 1999; Noble and Scholes, 2001; Nordhaus and Boyer, 1999, Reiner and Jacoby, 2001; Tol, 1998; Victor and MacDonald, 1997; Yamin, 1998), and various people have suggested alternatives (see Müller *et al.*, 2002, for an overview). Edmonds *et al.* (1994, 1997; see also Edmonds and Wise, 1998) propose and analyse a technology protocol: As of a specified date, in all countries with an average per capita income above a certain threshold, all new investments have to have zero carbon emissions (or need to fully compensate their emissions). This protocol drives carbon dioxide emissions to zero and stabilizes the atmospheric concentration of CO_2, if the specifications are properly chosen, at an acceptable level.

Here, I analyse a potentially interesting alternative technology protocol. The protocol specifies three things. First, the speed at which best available technologies would progress and, second, the speed at which inferior technologies would need to converge to that. Third, only sufficiently rich countries are subject to the regime.

A major advantage is that such a protocol is simple. It is easy to explain to governments, and to industries; indeed, the US government has adopted it, as have various European governments, albeit less openly. Technology protocols have worked in other fields, notably vehicle emissions. A major disadvantage is that the environmental result is uncertain because the outcome is scenario-dependent and policy is defined relative to the scenario. On the other hand, costs are less scenario-dependent than in the case of absolute standards. For instance, if technological progress is less than expected, policy automatically become less stringent. The simplicity itself is also a drawback: There is little place to hide, little room for political manoeuvring.

Using short-term planning models, BAT standards can readily be converted into emission targets, so that (international) trade in emission permits can be the policy instrument for implementation. The BAT standard is then only the means by which targets are set. This creates an incentive for companies at the technological frontier to invest in R&D. For, if a company moves the frontier, the emission target for other companies becomes more stringent, so that the company at the frontier can sell either its technology or its emission permits at a higher price. This reminds one of the role played by DuPont in the ban of CFC production and consumption, stimulation the demand for HFCs (Benedick, 1998). Note that, although this would create incentives to accelerate the development of environmental friendly technology, welfare would not necessarily improve, as too much may be spent on R&D. In this paper, we do not consider the above effect on technological progress. Instead, energy technology improves exogenously.

In this paper, I will explore the technology protocol sketched above. I will do so using the *FUND* model, described in Section 2. Section 3 analyses the potential of the protocol to stabilize emissions for a variety of parameter choices, scenarios of future developments, and technology dynamics. Section 4 investigates the incentives of countries to vote for one protocol and not for another. Section 5 concludes.

2. The Model

The model used is version 2.3 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.3 of *FUND* is the same as version 1.6, described and applied by Tol (1999a-e, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c).[1] A further difference is the specification of emission reduction costs and technological change, detailed below.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model is specified for nine major world-regions: OECD-America (excl. Mexico); OECD-Europe; OECD-Pacific (excl. South Korea); Central and Eastern Europe and the former Soviet Union; Middle East; Latin America; South and Southeast Asia; Centrally Planned Asia; and Africa. The model runs from 1950 to 2200, in time steps of a year. The prime reason for starting in 1950 is to initialise the climate change impact module. In *FUND*, climate impacts are assumed to depend on the impact of the year before, to reflect the process of adjustment to climate change. Because the starting values in 1950 cannot be approximated very well, climate impacts (both physical and monetised) are misrepresented in the first few decades. This would bias optimal control if the first decades of the simulation coincided with the first decades of emission abatement. Similarly, the 22nd century is included to provide the forward-looking agents in the 21st century with a long time horizon. The calculated optimal emission reductions in 2100-2200 have little meaning (or policy relevance) in and of themselves.

The *IMAGE* database (Batjes and Goldewijk, 1994) is the basis for the calibration of the model to the period 1950-1990. Scenarios for the period 2010-2100 are based on the EMF14 Standardised Scenario, which lies between IS92a and IS92f (cf. Leggett *et al.*, 1992). Note that the original EMF14 Standardised Scenario had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 1990-2010 is a linear interpolation between observations and the EMF14 Standardised Scenario. The period 2100-2200 is an extrapolation of the EMF14 Standardised Scenario.

The scenarios concern the rate of population growth, urbanisation, economic growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population. The other sources of mortality do affect the number of births. Heat stress only affects urban population. The share of urban in total population is, up to 2025, based on the World Resources Databases; after 2025, urban population slowly

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[1] More information and the source code of the model can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

converges to 95% of total population (comparable to present day Belgium or Kuwait). Population also changes with climate-induced migration between the regions. Immigrants are assumed to assimilate immediately and completely with the host population.

The tangible impacts of climate change are dead-weight losses to the economy. Consumption and investment are reduced, without changing the saving's rate. Climate change thus reduces long-term economic growth, although at the short term consumption takes a deeper cut. Economic growth is also reduced by carbon dioxide emission abatement.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be sped up by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on economy and emissions, and the impact of the damages of climate change on the economy and the population.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$(1) \qquad C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right)$$

where *C* denotes concentration, *E* emissions, *t* year, and *pre* pre-industrial. Table 1 displays the parameters for both gases.

The atmospheric concentration of carbon dioxide follows from a five-box model:

$$(2a) \qquad Box_{i,t} = r_i Box_{i,t} + 0.000471 \alpha_i E_t$$

with

$$(2b) \qquad C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

where α_i denotes the fraction of emissions *E* (in million metric tonnes of carbon) that is allocated to box *i* (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and *r* the decay-rate of the boxes (*r* = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). The model is due to Meier-Reimer and Hasselmann (1987), its parameters are due to Hammitt *et al.* (1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is—on average—removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by radiative forcing *RF*), with a half-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$(3) \qquad T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t$$

Global mean sea level is also geometric, with its equilibrium level determined by the temperature and a life-time of 50 years. Temperature and sea level are calibrated to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module is based on Tol (2002b,c). A limited number of categories of the impact of climate change are considered: agriculture, forestry sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, and unmanaged ecosystems.

People can prematurely die (because of temperature stress or vector-borne diseases) or migrate (because of sea level rise). These effects, like all impacts, are monetized. The value of a statistical life is set at 200 times the per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set at 3 times the per capita income (Tol, 1995, 1996), the value of immigration at 40% of the per capita income in the host region (Cline, 1992). Dryland and wetland loss due to sea level rise are explicitly modelled. Dryland loss is valued at $4 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). Dryland value is assumed proportional to GDP per square kilometre. Wetland loss is valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). Wetland value is assumed to be logistic in per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to dike building and consequent coastal squeeze.

Other impact categories (agriculture, forestry, energy, water, ecosystems) are directly expressed in money, without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002b).

Damage can be due to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 2.5°C). Benchmark estimates are displayed in Table 2. Damage in the rate of temperature change slowly fades, reflecting adaptation (cf. Tol, 2002c).

Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. A mix of factors, including plant physiology and farmer behaviour, determines the climate optimum. Impacts are positive or negative depending on whether climate is moving to or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative (cf. Tol, 2002c).

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, but do not change sign (cf. Tol, 2002c).

Vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector-borne diseases (with improved health care) (cf. Tol, 2002c).

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

$$(4) \qquad M_{r,t} = \frac{M_{r,t}}{E_{r,t}}\frac{E_{r,t}}{Y_{r,t}}\frac{Y_{r,t}}{P_{r,t}}P_{r,t} =: y_{r,t} j_{r,t} Y_{r,t}$$

The carbon intensity of energy use, and the energy intensity of production follow from:

$$(5) \qquad y_{r,t} = g^{y}_{r,t-1} y_{r,t-1} - a t^{y}_{r,t-1}$$

and

$$(6) \qquad j_{r,t} = g^{j}_{r,t-1} j_{r,t-1} - a t^{j}_{r,t-1}$$

where ô is policy intervention. Policy also affects emissions via

(4’) $$M_{r,t} = \left(y_{r,t} - c^{y}_{r,t}\right)\left(j_{r,t} - c^{j}_{r,t}\right) Y_{r,t}$$

(7) $$c^{y}_{r,t} = k_{y}\, c_{r,t-1} + (1-a)t^{y}_{r,t-1}$$

and

(8) $$c^{j}_{r,t} = k_{j}\, c_{r,t-1} + (1-a)t^{j}_{r,t-1}$$

Thus, the parameter 0 < á < 1 governs which part of emission reduction is *permanent* (reducing carbon and energy intensities) and which part of emission reduction is *temporary* (reducing energy consumptions and carbon emissions), fading at a rate of 0 < ê < 1. Alternatively, one can interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The behaviour of the emission reduction module is similar as the models of Grubb *et al.* (1995), Ha-Duong *et al.* (1997) and Hasselmann *et al.* (1997).

The costs of emission reduction are given by

(9) $$\frac{C_{r,t}}{Y_{r,t}} = \frac{b_{r,t}t^{2}_{r,t}}{H_{r,t}H^{g}_{t}}$$

The parameter â follows from

(10) $$b_{r,t} = 2.24 - 0.24\sqrt{\frac{M_{r,t}}{Y_{r,t}} - \min_{s}\frac{M_{s,t}}{Y_{s,t}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity. The calibration is such that a 10% emission reduction cut would cost 2.24% of GDP of the least carbon-intensive region. Emission reduction is relatively cheap for regions with high emission intensities. The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels. The model has been calibrated to the results reported in Hourcade *et al.* (1996).

The regional and global knowledge stocks follow from

(11) $$H_{r,t} = H_{r,t-1}\sqrt{1+g_{R}t_{r,t-1}}$$

and

(12) $$H^{G}_{t} = H^{G}_{t-1}\sqrt{1+g_{G}t_{r,t}}$$

Knowledge accumulates with emission abatement. The parameters ã determines which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, $ã_{R}$=0.9 and $ã_{G}$=0.1. The model is similar in structure and numbers to that of Goulder and Schneider (1999) and Goulder and Mathai (2000).

Governments intervene to reduce greenhouse gas emissions by increasing the price of emissions. The state of technology is measured by the overall emission intensity of the economy, that is, the carbon dioxide emitted per dollar GDP. The country with the lowest emission intensity needs to accelerate the decline in emission intensity with á percent per year. Other countries need to accelerate their emission intensity decline by the same amount plus â times the difference in their emission intensity with that of the technology leader. Formally,

(13) $$R_{c,t} = a - b\left(\frac{E_c}{Y_c} - \min_{i \in C}\frac{E_i}{Y_i}\right)$$

where R denotes emission reduction (in percent from baseline), E denotes emissions, Y denotes GDP, t denotes time, and $c \in C$ denotes country.

Countries with a per capita income lower than y_c are exempt from emission reduction. There is an additional advantage to this. If joint implementation is allowed for, countries below the income threshold can still engage in emission reduction and sell the credits to other countries. This reduces their emission intensity, so by the time they pass the income threshold, their emission reduction obligation is smaller.

3. Emission Reduction Potential

Figure 1 shows the atmospheric concentration in the year 2200, the final year of the model run, as a function of the key parameters of the technology protocol as well as the parameter that covers the dynamics of technology as driven by emission abatement policy. Qualitatively, Figure 1 offers no surprises. If emission intensities converge faster to that of the technology leader, the final CO_2 concentration falls. If the emission intensity of the technology leader falls faster, the final CO_2 concentration falls. If regions with lower incomes are subject to the protocol, the final CO_2 concentration falls. If a larger share of the policy induced emission reduction is permanent, the final CO_2 concentration falls. Quantitatively, the following pattern emerges. Concentrations range everywhere between 530 and 1650 ppm. Only implementing the same technologies as in the most advanced region could considerably cut concentrations. If all regions with an income above \$2500 per person per year participate, and converge at a rate of 20% per decade to the technology leader, concentrations fall from 1650 ppm to 930 ppm. If technological progress in the leading country is accelerated by 10% (20%) per decade, concentrations fall to 670 ppm (530 ppm). The income threshold has a smaller influence than do the convergence and acceleration parameters. Increasing the threshold from \$2500 to \$5000 would raise concentrations by some 60 ppm; decreasing the threshold to \$500 would decrease concentrations by some 100 ppm. The reason for this relatively low sensitivity is that the currently most important emitters are covered by the protocol anyway, while the future large emitters (Asia) are assumed to have very rapid economic growth. The assumptions about the permanence of emission abatement matter a lot – 300-400 ppm difference – particularly if emission reduction is not so strict. This emphasises the importance of technology.

The above analysis is for a single scenario of future developments only. As the future is uncertain, this is not very convincing. Figure 2 displays the atmospheric concentration of carbon dioxide in 2200 for 11 different scenarios. The convergence parameter is varied between 0 and 0.2, but the acceleration parameter is kept at 0. Consequently, the left most points of the graphs are the unregulated concentrations in 2200. These differ between 425 ppm (SRES B1) and 1833 ppm (IS92f), underlying the great uncertainty about future emissions. The right most points show the result of an aggressive convergence policy. Such as policy would reduce emissions anywhere between 30 ppm (SRES B1) and 794 ppm (IS92f). In general, the scenarios with low baseline emissions assume more rapid convergence of carbon intensities than do scenarios with high baseline emissions. This emphasizes the importance of technology diffusion in emission control, either as a deliberate policy or as by-product of other developments.

4. Incentives

The previous section analyses the potential of a technology protocol to reduce atmospheric concentrations of carbon dioxide. It finds that a technology protocol can be very effective, but also have only a negligible impact, depending on its specification and the business as usual scenario. Here, the attention is turned to the incentives of regions to advocate a certain specification of such a protocol. These incentives consist of two components, viz. the costs of emission reduction and the benefits of less climate change. The criterion used is the net present welfare of the year 2000.

Table 3 displays the preferred technology protocol of *FUND*'s nine regions. The regional optimum was found by a simple grid search in three dimensions: the threshold income, the acceleration parameter, and the convergence parameter. Three regions are not interested in greenhouse gas emission reduction whatsoever: OECD-America, the Middle East, and China. South and Southeast Asia and Africa advocate quite drastic emission reduction – recall that the technology protocol applies to all regions. OECD-Europe and the former Soviet Union are less enthusiastic about emission abatement, and OECD-Pacific and Latin America even less so.

If we take the CO_2 concentration as a criterion, OECD-Pacific casts the median vote, that is, there are four regions that advocate a lower concentration than does OECD-Pacific, and four regions that advocate a higher concentration. An advantage of median voting (for targets) is that it is robust to strategic behaviour. The only way for, say, OECD-America to influence the outcome is to bid lower than does OECD-Pacific, while OECD-America already thinks the outcome is too low. Table 3 also shows regional welfare if the proposal by OECD-Pacific is implemented. Welfare is shown relative to the case without emission reduction, and relative to the regional optimum. Welfare losses are small: The maximum is 1.2%.

If instead of the median vote, some cooperative welfare criterion (additive or multiplicative, relative or absolute, population-weighted or none) is maximised, then the do-nothing policy advocated by OECD-America, the Middle East and China would result. The reason is that these three regions agree, whereas the preferred policies of the other regions are far apart.

Tables A1 and A2 (in the Appendix) repeat the information of Table 3, but now for the case in which most of the policy induced emission reduction is transient (Table A1) and for the case in which most of it is permanent (Table A2). If the effects of emission abatement last longer, emission reduction becomes cheaper – therefore, all regions vote for a more stringent protocol. The relative positions of regions are not affected, so OECD-Pacific remains the median voter. If the effects of emission abatement policy last shorter, emission reduction becomes more expensive – therefore, all regions vote for a less stringent protocol. In this case, OECD-Pacific looses interest in emission reduction altogether, and Latin America becomes the median voter – with a little ambitious proposal.

Tables A3 and A4 vary the speed of learning-by-doing, 50% up and down. For most regions, faster (slower) learning implies more (less) ambitious emission reduction targets; the effect is small, however, reflecting the fact that future learning has a limited effect on net present welfare. South and Southeast Asia and Africa are the exception. Both regions prefer substantially less emission reduction, regardless whether learning is faster or slower than in the base case. South and Southeast Asia will become a large emitter of carbon dioxide, while Africa, under the rules of the technology protocol, cannot get China and South and Southeast Asia to cut emissions without accepting emission reduction targets itself. Slower learning, including less international technology spillover, would increase abatement costs in South and Southeast Asia and Africa considerably. On the other hand, in the base case, South and Southeast Asia and Africa prefer drastic emission reduction in the richer countries, not only by cutting emissions directly but also through slower economic growth. With faster learning, the latter effect disappears, so that South and Southeast Asia and Africa would have to take more emission reduction onto themselves – while international technology spillover is still considerably slower than intra-regional learning. South and Southeast Asia is the median voter with both faster and slower learning; note that its preferred policy does not deviate much from the median policy in the base case.

The selected protocols stress convergence of energy intensities over technology acceleration. As convergence is relative, this implies rapid emission reduction in the early decades, and slower abatement later on. However, a cost-effective trajectory to any given concentration target would stress later rather than earlier emission reduction (Manne and Richels, 1998, 1999; Richels and Edmonds, 1995; Wigley *et al.*, 1996). We adopt the technology protocol in two alternative ways. Firstly, the convergence parameter – the $\hat{a}$ in equation (13) – grows linearly over time with a factor that is subject to optimisation as well. Table A5 shows the results. Secondly, the protocol enters into force only after a certain date, another parameter subject to optimisation. Table A6 shows the results. The two alternatives show a clear pattern. Timing is not the crucial issue. The regions who oppose emission reduction do not change their position if they can start later or slower. The regions who advocate emission reduction are less affected by relative convergence, and more or less maintain their position.

5. Costs

Figure 3 presents the costs of the technology protocol as preferred by OECD-Pacific, the median voter (cf. Table 3). Costs are measured as consumption losses in the period 2000-2200, discounted to 2000 with a discount rate of 5% per year. Total costs are some \$26 trillion, a hefty price for keeping CO_2 concentrations under 950 ppm (Weyant, 1993, 1998; Weyant and Hill, 1999). The reason is that this technology protocol places a lot of emphasis on (relative!) convergence. Consequently, most emission reduction is concentrated in the early decades. The carbon-inefficient economies of Central and Eastern Europe and the former Soviet Union bear a lot of the costs.

The regional emission reductions under the technology protocol can be interpreted as the initial allocations of carbon permits in an international market. Figure 3 shows that the costs fall if where flexibility is introduced, and that the burden of emission reduction shifts towards the OECD. Note that the costs after trade, as presented in Figure 3, are only a *potential* Pareto improvement.

Figure 3 also displays the costs of technology protocols with an intermediate and high emphasis on acceleration rather than convergence, keeping the same concentration targets. Costs are very sensitive to this, as emission reduction (costs) are shifted to the future. Costs are also shifted from CEE&fSU to the OECD. Emissions trade would lower costs further, but only to a limited extent. This is a reflection of the fact that, under the technology protocol, all regions have emission obligations, including the regions that under Kyoto-like agreements would be great suppliers of cheap emission reduction.

Finally, Figure 3 shows the costs of cost-effective path towards 950 ppm, introducing when-flexibility or banking & borrowing. Costs fall considerably, as emission reduction is pushed further into the future. This underlines that, without introducing flexibility, a technology protocol may be a needlessly expensive manner of reducing emissions. Still, it should be emphasized that, although \$26 trillion may seems a lot of money, economic growth continues largely unabated.

6. Discussion and Conclusion

This paper presents an alternative to the absolute emission standards of the Kyoto Protocol. The international treaty analysed here focuses on reducing emission intensities (as proposed by President Bush) as well as on reducing the differences in emission intensities between countries. The main advantage of this strategy is that the costs of emission reduction are robust against economic variability. The main disadvantage is that emissions are uncertain. Another advantage is that this protocol emphasizes improving technology (a positive thing) rather than reducing emission (a negative thing).

The technology protocol analysed here consist of three parts: a threshold income, above which countries are obliged to partake; a convergence rate, at which differences between countries are closed; and an acceleration rate, at which the most carbon-efficient country gets even more efficient. Depending on the parameters chosen, virtually any long-term concentration target can be met.

In some scenarios, convergence leads to substantial emission reduction. If the whole world were as energy- and carbon-efficient as Japan, total emissions would be a lot less. Other scenarios assume that other countries converge rapidly to Japanese standards, even in the absence of climate policies.

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Table 1 Parameters of equation (1).

Gas	α[a]	β[b]	pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

Source: After Schimel *et al*. (1996).

Table 2. Estimated impacts of a 1°C increase in the global mean temperature. Standard deviations are given in brackets.

	Billion dollar		percent of GDP	
OECD-A	175	(107)	3.4	(2.1)
OECD-E	203	(118)	3.7	(2.2)
OECD-P	32	(35)	1.0	(1.1)
CEE&fSU	57	(108)	2.0	(3.8)
ME	4	(8)	1.1	(2.2)
LA	-1	(5)	-0.1	(0.6)
S&SEA	-14	(9)	-1.7	(1.1)
CPA	9	(22)	2.1	(5.0)
AFR	-17	(9)	-4.1	(2.2)

Source: Tol (2002b).

Table 3. The technology protocols as preferred by the nine regions.

	Income[a]	Acceleration[b]	Convergence[c]	Concentration[d]	Loss (NC)[e]	Loss (Opt)[f]
OECD-A	-	0.000	0.000	1648	0.319	0.319
OECD-E	500	0.000	0.165	816	-0.065	0.066
OECD-P	**2500**	**0.000**	**0.185**	**945**	**-0.002**	**0.000**
CEE&fSU	500	0.015	0.025	655	0.530	0.810
ME	-	0.000	0.000	1648	0.910	0.910
LA	11500	0.000	0.050	1400	0.213	0.215
S&SEA	8500	0.200	0.035	440	0.033	0.141
CPA	-	0.000	0.000	1648	1.157	1.157
AFR	2000	0.290	0.005	347	-0.360	0.944

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The carbon dioxide concentration in 2200.

[e] The difference in net present welfare between the median scenario and the do nothing scenario, as a percentage of the do nothing scenario.

[f] The difference in net present welfare between the median scenario and the regionally optimal scenario, as a percentage of the regionally optimal scenario.

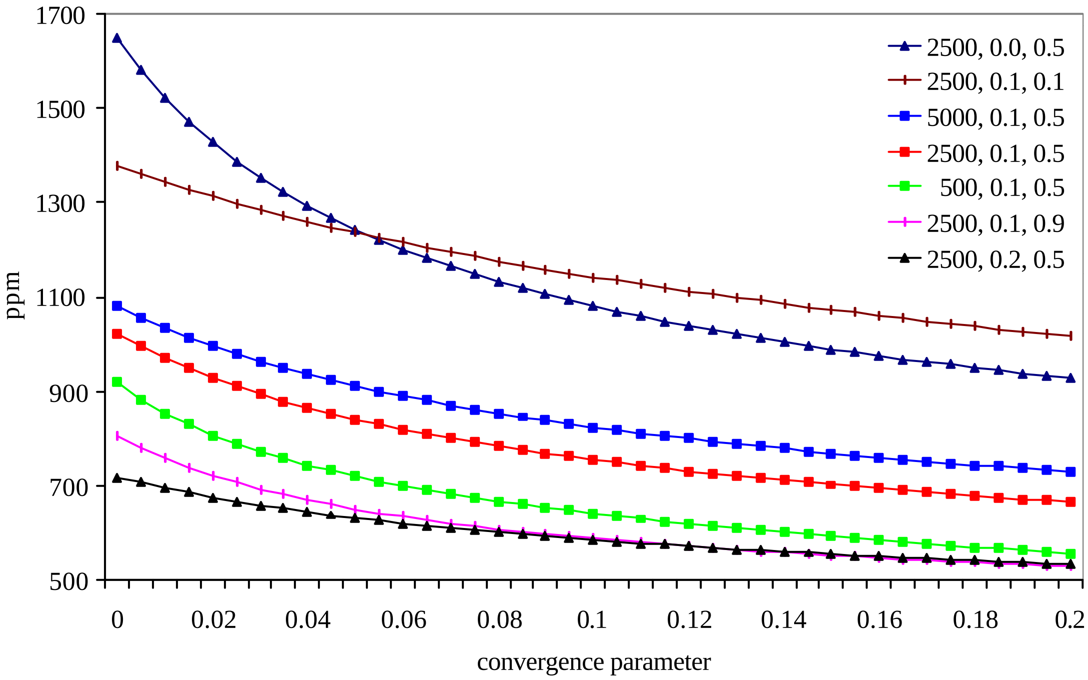

Figure 1. The atmospheric concentration of carbon dioxide in the year 2200 as a function of the three parameters of the technology protocol and as a function of the assumed technology dynamics. On the x-axis, 2200 concentrations are plotted as a function of the speed with which regions convergence to the most carbon-efficient region. The first element in the legend is the threshold income. It is varied between \$500 and \$5000, with a default value of \$2500. The second element of the legend is the rate of technological progress above the business as usual scenario for the technology leader. It is varied between 0.0 and 0.2, with a default value of 0.1, that is, 10% per decade. The third element of the legend is the share of permanent in total emission reduction. It is varied between 0.1 and 0.9, with a default value of 0.5.

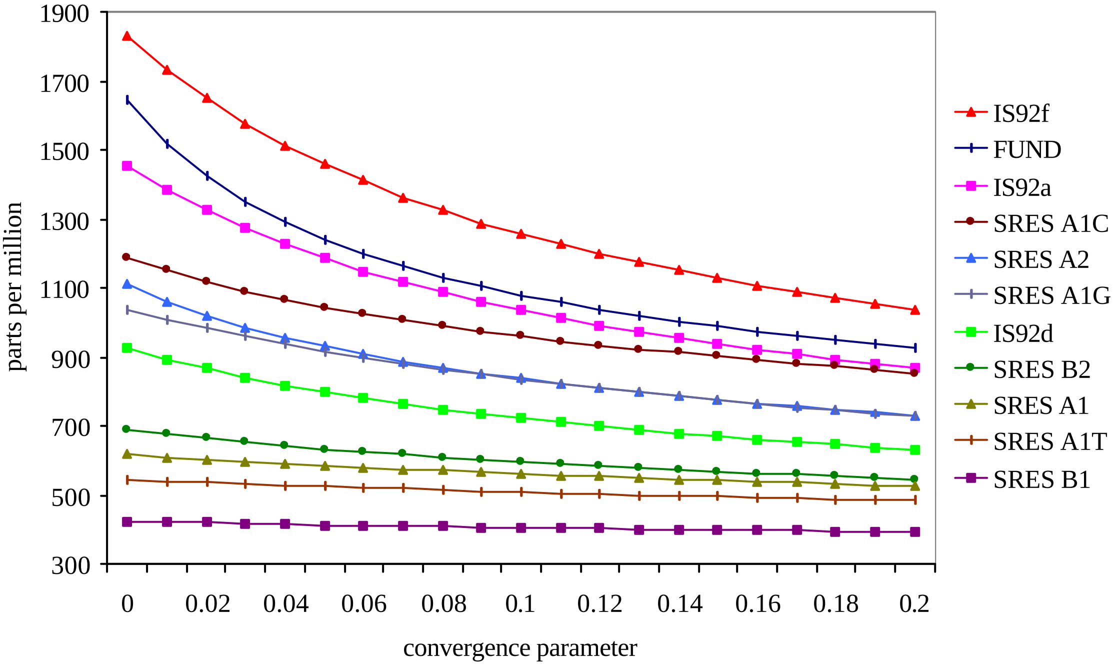

Figure 2. The atmospheric concentration of carbon dioxide in the year 2200 as a function of the speed with which regions converge to the most carbon efficient region for the FUND scenario, three IS92a scenarios, and seven SRES scenarios. The threshold income is $2500. The rate of technological progress above the business as usual scenario for the technology leader is 0.1, that is, 10% per decade. The share of permanent in total emission reduction is 0.5.

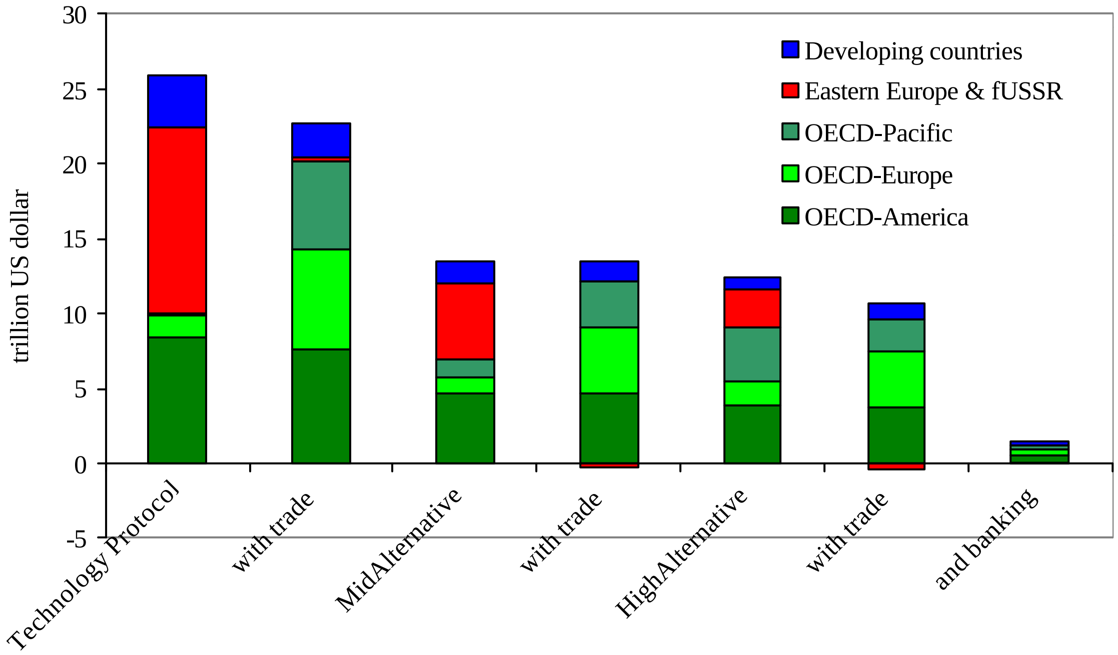

Figure 3. The net present consumption losses of the “technology protocol” proposed by OECD-Pacific (see Table 3), which has a low emphasis on technology acceleration and a high emphasis on technology convergence; a “mid alternative” with intermediate emphasis on technology acceleration, and a “high alternative” with high emphasis on acceleration. Costs are presented without and “with trade”. Also shown is the case the full where and when flexibility (“and banking”).

Appendix

Table A1. The technology protocols as preferred by the nine regions for á=0.1 (see Equations (5)-(8)).

	Income[a]	Acceleration[b]	Convergence[c]	Concentration[d]
OECD-A	-	0.000	0.000	1648
OECD-E	500	0.000	0.125	1170
OECD-P	-	0.000	0.000	1648
CEE&fSU	500	0.000	0.040	1430
ME	-	0.000	0.000	1648
LA	**11500**	**0.000**	**0.025**	**1581**
S&SEA	8500	0.210	0.005	439
CPA	-	0.000	0.000	1648
AFR	2000	0.290	0.005	350

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The carbon dioxide concentration in 2200.

Table A2. The technology protocols as preferred by the nine regions for *á*=0.9 (see Equations (5)-(8)).

	Income[a]	Acceleration[b]	Convergence[c]	Concentration[d]
OECD-A	-	0.000	0.000	1648
OECD-E	500	0.000	0.195	666
OECD-P	**2500**	**0.000**	**0.135**	**905**
CEE&fSU	500	0.020	0.015	439
ME	-	0.000	0.000	1648
LA	11500	0.000	0.055	1266
S&SEA	8500	0.210	0.005	437
CPA	-	0.000	0.000	1648
AFR	2000	0.265	0.015	346

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The carbon dioxide concentration in 2200.

Table A3. The technology protocols as preferred by the nine regions for $\tilde{a}_R$=1.35 and $\tilde{a}_G$=0.15 (see Equations (5)-(8)).

	Income[a]	Acceleration[b]	Convergence[c]	Concentration[d]
OECD-A	-	0.000	0.00	1648
OECD-E	500	0.000	0.16	821
OECD-P	2500	0.000	0.19	935
CEE&fSU	500	0.010	0.03	769
ME	-	0.000	0.00	1648
LA	9000	0.000	0.03	1443
S&SEA	**7000**	**0.000**	**0.15**	**1087**
CPA	-	0.000	0.00	1648
AFR	10500	0.100	0.17	642

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The carbon dioxide concentration in 2200.

Table A4. The technology protocols as preferred by the nine regions for $\tilde{a}_R$=0.45 and $\tilde{a}_G$=0.05 (see Equations (5)-(8)).

	Income[a]	Acceleration[b]	Convergence[c]	Concentration[d]
OECD-A	-	0.000	0.00	1648
OECD-E	500	0.000	0.14	853
OECD-P	2500	0.000	0.19	931
CEE&fSU	500	0.005	0.04	912
ME	-	0.000	0.00	1648
LA	9000	0.000	0.03	1443
S&SEA	**7000**	**0.000**	**0.17**	**1062**
CPA	-	0.000	0.00	1648
AFR	7500	0.100	0.17	447

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The carbon dioxide concentration in 2200.

Table A5. The technology protocols as preferred by the nine regions for ever faster convergence (see Equation (13)).

	Income[a]	Acceleration[b]	Convergence[c]	Inc. Conv.[d]	Concentration[e]
OECD-A	-	0.000	0.00	0.0000	1648
OECD-E	500	0.000	0.11	0.0005	763
OECD-P	2500	0.000	0.11	0.0000	1059
CEE&fSU	500	0.015	0.01	0.0005	603
ME	-	0.000	0.00	0.0000	1648
LA	7000	0.000	0.03	0.0000	1423
S&SEA	**7000**	**0.000**	**0.11**	**0.0000**	**1159**
CPA	-	0.000	0.00	0.0000	1648
AFR	500	0.020	0.18	0.0005	545

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The initial annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The annual rate at which the convergence rate increases; cf. note c.

[e] The carbon dioxide concentration in 2200.

Table A6. The technology protocols, including starting date, as preferred by the nine regions.

	Income[a]	Acceleration[b]	Convergence[c]	Year[d]	Concentration[e]
OECD-A	-	0.000	0.00	-	1648
OECD-E	500	0.000	0.15	2000	840
OECD-P	500	0.000	0.15	2040	1011
CEE&fSU	500	0.015	0.03	2000	644
ME	-	0.000	0.00	-	1648
LA	7000	0.000	0.03	2000	1423
S&SEA	**7000**	**0.005**	**0.00**	**2000**	**1344**
CPA	-	0.000	0.00	-	1648
AFR	2000	0.075	0.14	2000	364

[a] The threshold income above which regions reduce emissions.

[b] The annual rate at which the carbon efficiency of the technology leader improves over and above the no control scenario.

[c] The annual rate at which the carbon efficiency of regions converges to that of the technology leader.

[d] The starting year of emission reduction.

[e] The carbon dioxide concentration in 2200.

Working Papers

Research Unit Sustainability and Global Change

Centre for Marine and Climate Research, Hamburg University, Hamburg

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