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Survey

# Targets for global climate policy: An overview

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ABSTRACT

A survey of the economic impact of climate change and the marginal damage costs shows that carbon dioxide emissions are a negative externality. The estimated Pigou tax and its growth rate are too low to justify the climate policy targets set by political leaders. A lower discount rate or greater concern for the global distribution of income would justify more stringent climate policy, but would imply an overhaul of other public policies. Catastrophic risk justifies more stringent climate policy, but only to a limited extent.

## 1. Introduction

Climate change is one of today's defining problems. It is often described as the largest problem, or the largest environmental problem of the 21st century (Stern et al., 2006)—without much evidence. Climate change has been said to fundamentally challenge economics as a discipline (van den Bergh, 2004). More sober people would recognize greenhouse gas emissions as an externality. It is an externality that is global, pervasive, long-term, and uncertain – but even though the scale and complexity of this externality is unprecedented, economic theory is well equipped for such problems – and advice based on rigorous economic analysis is anyway preferred to wishy-washy thinking. This paper surveys literature on first-best climate policy.

The first benefit–cost analysis of greenhouse gas emission reduction was published in 1991 by William D. Nordhaus of Yale University (Nordhaus, 1991). It was a static, aggregate analysis, but was soon followed by dynamic studies (Nordhaus, 1992, 1993) and regionally disaggregated ones (Nordhaus and Yang, 1996). Nordhaus research was influential and his findings controversial. Nordhaus concluded (i) that modest emission reduction is desirable now; (ii) that the ambition of climate policy should accelerate over time; but (iii) that the atmospheric concentration of greenhouse gases should not be stabilized. Conclusion (ii) is qualitatively uncontroversial, but the rate of acceleration is disputed. Conclusions (i) and (iii) are controversial, within the economics profession but particularly outside.

I discuss these topics in Sections 4–6, after reviewing the benefits and costs of climate policy in Sections 2 and 3. In Section 7, I discuss the notion of optimality and the specification of the welfare function. Section 8 concludes.

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## 2. Benefits of climate policy

### 2.1. Impact of climate change on welfare

There are 16 studies and 17 estimates of the *global* welfare impacts of climate change. Nordhaus (1994a) interviewed a limited number of experts. Fankhauser (1994, 1995), Nordhaus (1994b, 2008) and Tol (1995, 2002a, 2002b) multiplied estimates of the "physical effects" of climate change with estimates of their price. Bosello et al. (2012) use similar estimates of the physical impacts but compute the general equilibrium effects on welfare. Maddison (2003); Mendelsohn et al. (2000a, 2000b) and Nordhaus (2006) used observed variations (across space) in prices and expenditures to discern the effect of climate. Maddison and Rehdanz (2011) and Rehdanz and Maddison (2005) used self-reported well-being.

There is broad agreement between these studies in four areas. First, the welfare effect of a doubling of the atmospheric concentration of greenhouse gas emissions on the current economy is relatively small—a few percentage points of GDP. The impact of a century of climate change is roughly equivalent to a year's growth in the global economy.

Second, the initial benefits of a modest increase in temperature are probably positive, followed by losses as temperatures increase further. Fig. 1 illustrates this pattern. The initial benefits arise partly from $CO_2$ fertilization, and partly from reduced heating costs and cold-related health problems in temperate zones. However, the initial warming can no longer be avoided; these are sunk benefits.

Third, as illustrated in Fig. 1, the uncertainty is vast and right-skewed. Undesirable surprises are more likely than desirable surprises. For instance, the climate sensitivity – the equilibrium warming due to a doubling of the atmospheric concentration of carbon dioxide – is bounded from below by the laws of physics, but it is hard to put an upper bound on its value. It is relatively easy to paint disastrous pictures of the impacts of climate change – rapid sea level rise in the Bay of Bengal leading to mass migration and nuclear war – but difficult to imagine that climate change would make the world prosperous and peaceful. Estimates stop at 3 °C of global warming, but climate change may well go beyond that. The uncertainties about the impacts are compounded by extrapolation (Tol, 2012).

Fourth, not shown in Fig. 1, poorer countries tend to be more vulnerable to climate change. Poorer countries have a large share of their economic activity in sectors, such as agriculture, that are directly exposed to the weather. Poorer countries tend to be in hotter places, and thus closer to their biophysical limits and with fewer technical and behavioral analogs. Poorer countries also tend to be worse at adaptation, lacking resources and capacity (Yohe and Tol, 2002).

### 2.2. Social cost of carbon

The marginal damage cost of carbon dioxide is defined as the net present value of the incremental damage due to a small increase in carbon dioxide emissions (Newbold et al., 2010). If evaluated along an arbitrary emissions trajectory, I refer to the marginal damage costs as the social cost of carbon. If evaluated along the optimal emission trajectory, it is of course the Pigou tax (Pigou, 1920).

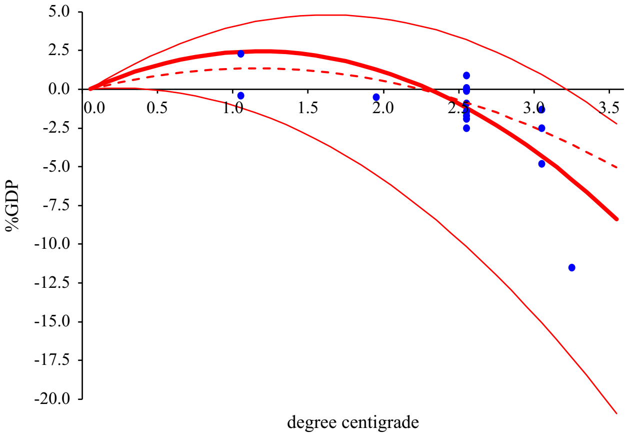

**Fig. 1.** 17 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income loss, as functions of the increase in global mean temperature relative to today. The blue dots represent the estimates. The central line is the least squares fit to the 14 observations: $D=4.33(1.49)T-1.92(0.56)T^2$, $R^2=0.62$, where $D$ denotes impact and $T$ denotes temperature. The dotted line is from Tol (2009), omitted the three most recent estimates. The outer lines are the 95% confidence interval, where the standard deviation is the least squares fit to the five reported standard deviations or half confidence intervals (cf. Table 1): $S_{\text{optimistic}}=0.87(0.28)T$, $R^2=0.70$ and $S_{\text{pessimistic}}=1.79(0.87)T$, $R^2=0.51$, where $S$ is the standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

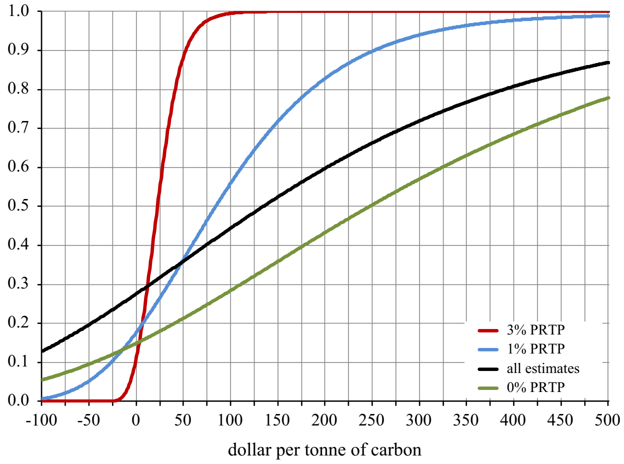

**Fig. 2.** Cumulative density function of the marginal damage cost of carbon dioxide emissions for all estimates and for all estimates that use a particular pure rate of time preference.

There are 75 studies of the social cost of carbon, with 588 estimates.[1] The social cost of carbon depends on many things. The total welfare impact of climate change is but one input. Other parameters are the rate of pure time preference, the growth rate of per capita consumption, and the elasticity of marginal utility of consumption. Estimates also differ with regard to projections of $CO_2$ emissions, the carbon cycle, the rate of warming, and so on. Different studies may calibrate a different curve to the same benchmark estimate of the total impact. Alternative population and economic scenarios also yield different estimates, particularly if vulnerability to climate change is assumed to change with a country or region's degree of development and if forecasts about development patterns are different. Marginal cost estimates further vary with the way in which uncertainty is treated and with how regional effects of climate change are aggregated.

I applied a kernel density estimator to the 588 observations (expressed in 2010 US dollars, and pertaining to emissions in the year 2010). I use one parameter from each published estimate of the social cost of carbon (the mode) and the standard deviation of the entire sample[2]—and build up an overall distribution of the estimates and their surrounding uncertainty on this basis.[3] Fig. 4 illustrates the method. Fig. 2 shows the cumulative distribution function of the marginal damage costs of carbon dioxide emissions. Just looking at the distribution of the medians or modes of these studies is inadequate, because this does not give a fair sense of the uncertainty surrounding these estimates—it is particularly hard to discern the right tail of the distribution, which may dominate the policy analysis (Weitzman, 2009b).

Fig. 2 reaffirms that uncertainty about the social costs of climate change is very large. Table 2 shows some characteristics. The mean estimate in these studies is a marginal cost of carbon of $196 per metric tonne of carbon, but the modal estimate is only $49/tC. Of course, this divergence suggests that the mean estimate is driven by some very large estimates. This large divergence is partly explained by the use of different pure rates of time preference in these studies. Fig. 2 extracts three subsamples from the complete list of studies, each using a different common pure rate of time preference. A higher rate of time preference means that the costs of climate change incurred in the future have a lower present value, and so for example, the mean social cost of carbon for the studies with a 3 percent rate of time preference is $25/tC, while it is $296/tC for studies that choose a zero percent rate of time preference. But, even when the same discount rate is used, the variation in estimates is large. The means are pulled up by some studies with very high estimated social costs. This effect is stronger for lower discount rates. Fig. 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

Although Table 2 reveals a large estimated uncertainty about the social cost of carbon, there is reason to believe that the actual uncertainty is larger still. First of all, the social cost of carbon derives from the total economic impact estimates, of which there are few, incomplete estimates. Second,, the researchers who published impact estimates are from a small and close-knit community who may be subject to group-thinking, peer pressure and self-censoring.

Fig. 3 shows the kernel density, splitting the sample between those studies that use an arbitrary scenario and an optimal scenario. The sample is limited to a 3% pure rate of time preference, the common assumption in optimal control

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[1] The studies are listed in the appendix. The data are linked there.

[2] In a conventional Kernel density estimation, sometimes referred to a Laplacean mixing, the spread parameter is chosen so as to minimize the distance to some assumed density function. This may imply overconfidence. If both the kernels and the target density are Normal, for instance, then the spread parameter is 1.06 times the sample standard deviation over the number of observations to the power 0.2; $1.06 \times 588^{-0.2} = 0.3$.

[3] I used the Fisher–Tippett distribution, the only two-parameter, right-skewed, fat-tailed distribution that is defined on the real line. A few published estimates are negative, and given the uncertainties about risk, fat-tailed distributions seem appropriate (Tol, 2003; Weitzman, 2009b). I use weights that reflect the age and quality of the study as well as the importance that the authors attach to the estimate—some estimates are presented as central estimates, others as sensitivity analyses or upper and lower bounds.

**Table 1**
Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.

| Study | Warming (°C) | Impact (%GDP) |
|---|---|---|
| Nordhaus (1994b) | 3.0 | −1.3 |
| Nordhaus (1994a) | 3.0 | −4.8 (−30.0 to 0.0) |
| Fankhauser (1995) | 2.5 | −1.4 |
| Tol (1995) | 2.5 | −1.9 |
| Nordhaus and Yang (1996)[a] | 2.5 | −1.7 |
| Plamberk and Hope (1996)[a] | 2.5 | −2.5 (−0.5 to −11.4) |
| Mendelsohn et al. (2000a)[a,b,c] | 2.5 | 0.0[b] 0.1[b] |
| Nordhaus and Boyer (2000) | 2.5 | −1.5 |
| Tol (2002a) | 1.0 | 2.3 (1.0) |
| Maddison (2003)[a,d] | 2.5 | −0.1 |
| Rehdanz and Maddison (2005)[a,c] | 1.0 | −0.4 |
| Hope (2006)[a,e] | 2.5 | 0.9 (−0.2 to 2.7) |
| Nordhaus (2006) | 2.5 | −0.9 (0.1) |
| Nordhaus (2008) | 3.0 | −2.5 |
| Maddison and Rehdanz (2011)[a] | 3.2 | −11.5 |
| Bosello et al. (2012) | 1.9 | −0.5 |

[a] Note that the global results were aggregated by the current author.

[b] The top estimate is for the "experimental" model, the bottom estimate for the "cross-sectional" model.

[c] Mendelsohn et al. only include market impacts.

[d] Maddison only considers non-market impacts on households.

[e] The numbers used by Hope are averages of previous estimates by Fankhauser (1995) and Tol (2002a); Stern et al. (2006) adopted the work of Hope.

**Table 2**
Selected characteristics of the 2010 social cost of carbon and its growth rate.

| | All ($/tC) | 3% ($/tC) | 1% ($/tC) | 0% ($/tC) | Rate |
|---|---|---|---|---|---|
| Mean | 196 | 25 | 105 | 296 | 2.3 % |
| Mode | 49 | 19 | 55 | 144 | 2.0 % |
| Median | 135 | 23 | 83 | 247 | 2.2 % |
| Standard deviation | 322 | 22 | 128 | 309 | 1.3 % |

studies. As expected, the Pigou tax is lower than the social cost of carbon – for instance, the median Pigou tax is $21/tC and the median social cost of carbon is $26/tC – but the difference is not statistically significant. (Few studies report estimates in both, so we cannot match observations to compute the difference.) The Pigou tax is lower because imposing a carbon tax would reduce emissions and hence impacts as well as marginal impacts.

## 3. Costs of climate policy

### 3.1. Total cost of climate policy

The Kaya identity helps to understand trends in carbon dioxide emissions and options for emission reduction. It states that total emissions ($M$) equal the number of people ($P$) times per capita income ($Y/P$) times the energy intensity of production ($E/Y$) times the carbon intensity of the energy sector ($M/E$). This implies that emission reduction can be achieved by population and economic shrink. The latter proved to be an effective strategy by the collapse of the Soviet Union. China sometimes argues that its one-child policy is its main contribution to international climate policy (Ryan, 2012). Governments seeking re-election would, however, focus on improving energy and carbon intensity.

Because energy is a cost and energy use has no intrinsic benefit (as opposed to energy services such as heat, light and transport), energy efficiency has improved steadily for as long as we have data (Fouquet, 2008). Emission reduction would require accelerating that trend beyond what is the revealed preference, which implies a cost to the economy (unless the energy market is distorted). Improving the carbon intensity of the energy sector requires switching to energy sources that, at the moment, cannot compete in the market. Again, this implies a cost. Alternatively, carbon dioxide can be captured before being emitted and stored underground. There is no inherit benefit to this at the scale required, so again a cost is implied. Of course, these are the direct costs only. As energy use is pervasive, general equilibrium effects are substantial.

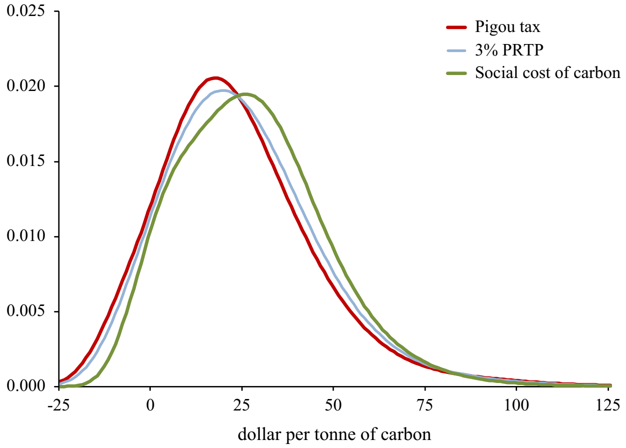

**Fig. 3.** Probability density function of the marginal damage cost of carbon dioxide emissions for all estimates with 3% pure rate of time preference, for the estimates along an arbitrary trajectory (social cost of carbon), and for estimates along an optimal trajectory (Pigou tax).

The IPCC[4] periodically surveys the costs of emission abatement (Barker et al., 2007; Hourcade et al., 1996, 2001); there are the EMF[5] overview papers (Weyant, 1993, 1998, 2004; Weyant et al., 2006; Weyant and Hill, 1999), and there are meta-analyses as well (Barker et al., 2002; Fischer and Morgenstern, 2006; Kuik et al., 2009; Repetto and Austin, 1997; Tavoni and Tol, 2010). There are two equally important messages from this literature. First, a well-designed, gradual policy can substantially reduce emissions at minimal cost to society. Indeed, it would be difficult to empirically detect this impact as it would be small relative to the variability in economic growth. The costs of emission reduction would also increase if emissions grow faster, if the price of fossil fuels is lower, or if the rate of technological progress in alternative fuels is slower than anticipated. This risk is two-sided. Emissions may grow more slowly, the price of fossil energy may be higher, and the alternative fuels may progress faster than expected.

The second message is that ill-designed policies, or policies that seek to do too much too soon, can be orders of magnitude more expensive. While the academic literature has focussed on the former, policy makers have opted for the latter. The costs of emission reduction increase if:

- different countries, sectors, or emissions face different explicit or implicit carbon prices (Boehringer et al., 2006a, 2006b, 2008; Manne and Richels, 2001; Reilly et al., 2006);
- the carbon prices rise faster or more slowly than the appropriate discount rate (Manne and Richels, 1998, 2004; Wigley et al., 1996);
- climate policy is used to further other, non-climate policy goals (Burtraw et al., 2003); and
- climate policy adversely interacts with pre-existing policy distortions (Babiker et al., 2003; Parry and Williams III, 1999).

Unfortunately, each of these four conditions is likely to be met in reality. For instance, only select countries have adopted emissions targets. Energy-intensive sectors that compete on the world market typically face lower carbon prices than do other sectors. Climate policy often targets carbon dioxide but omits methane and nitrous oxide. Emission trading systems have a provision for banking permits for future use, but not for borrowing permits from future periods. Climate policy is used to try and enhance energy security, stimulate growth and create jobs. Climate policy is superimposed on energy and transport regulation and taxation. Second-best policies are, however, not the focus of this paper.

### *3.2. Marginal abatement costs*

As noted above, there are many studies on the impact of climate policy. I here rely on a single group of estimates, summarized by Clarke et al. (2009). This includes the models with the best academic pedigree, and the policy scenarios run by the models allows for comparing the results. The drawback of this choice is, of course, that relevant information from other studies is ignored.

The model comparison in Clarke et al. (2009) includes 10 models, each with a different structure. Some models are recursive-dynamic – that is, solve a sequence of static optima – and others use intertemporal optimization. Some models are partial equilibrium models of the energy sector and in some case agriculture and transport; others are general equilibrium models, but with a detailed representation of the same sectors.

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[4] Intergovernmental Panel on Climate Change; http://www.ipcc.ch/.

[5] Energy Modeling Forum; http://emf.stanford.edu/.

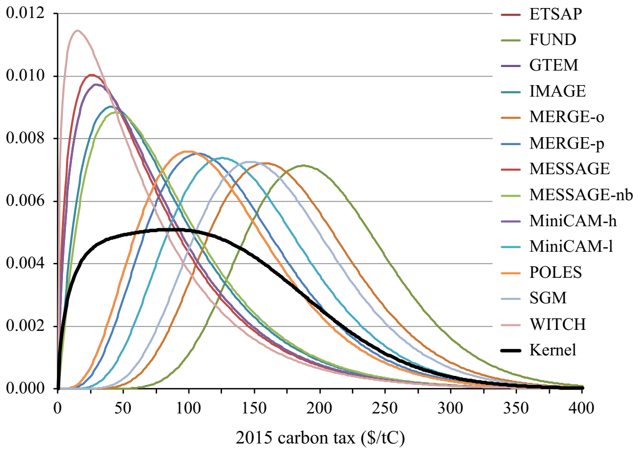

**Fig. 4.** Kernel density of the required initial carbon tax needed to meet a 550 ppm $CO_2e$ target in 2100; the constituent Gamma densities are shown for illustrative purposes.

Three alternative targets are examined. One set of scenarios are cost-effective: The same carbon tax is applied to all greenhouse gas emissions from all sectors in all countries (static efficiency) and the carbon tax rises with the appropriate discount rate over time (dynamic efficiency). In another set of scenarios, the concentration target applies in 2100 only, rather than throughout the 21st century. In a third set of scenarios, emerging countries delay their participation in international climate policy and developing countries delay further. In addition, three models reported sensitivity analyses on assumptions with regard to growth scenarios and developments in energy technology.

The data in Clarke et al. (2009) are incomplete: No model presents results for every policy scenario. There is selection bias: the more expensive models tend not to report the more ambitious policy targets. Following Tavoni and Tol (2010), I therefore first impute the missing observations using the following regression model for the carbon tax $\tau$ in 2015:

$$\ln(\tau_{m,s}) = -0.0175C_{2100} + 0.610I_{\{C_t \le \hat{C} \forall t\}} + 0.931I_{\{R_r > 0 \forall r\}} + \sum_{\mu} \delta_{\mu} I_{\{m=\mu\}} + u_{m,s}$$

$$(0.001) \qquad (0.180) \qquad (0.152) \tag{1}$$

where $C_{2100}$ is the greenhouse gas concentration in 2100. There are dummies, from right to left, for the model, for global participation, and for approaching the concentration target from below. The model fit is good: the adjusted $R^2$ is 95%. The estimated parameters are highly significant and have the expected sign: more stringent targets require higher taxes, disallowing temporary overshoot adds to the costs, and if some countries do not participate others will have to work harder.

I use Eq. (1) to impute the missing observations, and to consider additional targets. I apply a similar kernel density estimator as above to these 13 observations (per target). I use a Gamma kernel, as the required tax is bounded from below at zero. I use the mode as the location variable. I use the empirical standard deviation as the spread variable.

Fig. 4 shows the results for the 550 ppm $CO_2e$ target. It reveals that the kernel density has a plateau between $25/tC and $150/tC, indicating strong disagreement between models. That is, a best guess marginal cost estimates does not emerge. Reasonable models, reasonably parameterized, running reasonable scenarios find a range of different results. The left tail rapidly trails to zero. That is, models agree that emission reduction costs money. The right tail is much fatter than the left tail. That is, emission reduction to meet a particular target may be much more expensive than hoped.

For comparison, in December, 2012, the price of carbon dioxide emission permits in the EU Emissions Trading System (ETS) was about $30/tC. The ETS applies to about half of EU emissions. If the same carbon price would be applied to all emissions in the world, Fig. 4 shows that there is a small chance that this would put us on track towards stabilization at 550 ppm $CO_2e$. If a carbon price 10 times the ETS price would apply, there is a very good chance, but no guarantee, of staying below 550 ppm $CO_2e$.

Fig. 5 shows selected percentiles of the PDF as a function of the concentration target. Eq. (1) has shown that the *modal* marginal abatement costs are exponential in the ultimate target. Fig. 5 reveals that this assumption carries over to the percentiles of the kernel density.[6] Fig. 4 suggests that, in order to stay below 550 ppm $CO_2e$, EU climate policy should extended to all emissions, and the carbon price probably needs to be raised. Fig. 5 shows that the carbon price needs to raised very substantially if a stricter target for emission reduction is chosen.

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[6] Note that the 97.5% trails off for very stringent targets because the kernel density was knotted at $5000/tC.

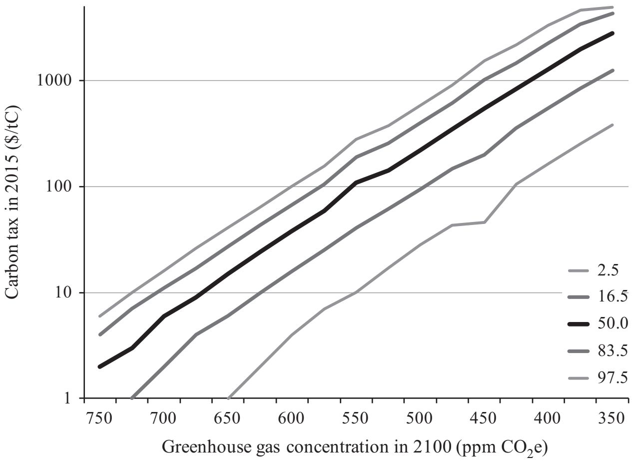

**Fig. 5.** Selected percentiles of the initial carbon tax as a function of the target concentration.

## 4. Desired ambition in the short term

In Section 2, I derived a probability density function $f^s(s)$ for the social cost of carbon $s$, the desired intensity of climate policy. In Section 3, I derived a probability density function of the carbon tax $\tau$ required to meet a particular target $C$, $f^{\tau|C}(\tau|C)$. I used a regression model to impute the missing values so as to avoid selection bias. That model has the required tax as a linear function of the natural logarithm of the target concentration. This implies that we also know the probability density of the concentration target.

By definition,

$$f^{\tau|C}(\tau|C)=\frac{f^{\tau C}(\tau,C)}{f^{C}(C)} \tag{2}$$

Therefore,

$$f^{C|\tau}(C|\tau)=f^{\tau|C}(\tau|C)\frac{f^{C}(C)}{f^{\tau}(\tau)}=f^{\tau|C}(\tau|C)\frac{f^{\tau}(g(C))}{f^{\tau}(\tau)}=f^{\tau|C}(\tau|C) \tag{3}$$

The last step is because $f^{\tau C}(\tau,C)$ is degenerate – $\tau$ is a function of $C$, $\tau=g(C)$ – so that $f^C(C)=f^\tau(\tau)$. Thus, we can derive a probability density function of the concentration that results from applying the Pigou tax, the level of which is uncertain:

$$f^{C}(C)=\int_{S}f^{C|\tau}(C|s)f^{s}(s)ds \tag{4}$$

Fig. 6 shows the result. The spread reflects the uncertainty about the impact of imposing a carbon tax. The uncertainty about the desirability of a carbon tax has been integrated out—see Eq. (4). With a 3% pure rate of time preference, a tax equal to the expected marginal damage cost of carbon would set us on course to 625 ppm $CO_2$e in 2100. The probability of meeting a target below 450 ppm $CO_2$e is 3%; and the chance of 700 ppm $CO_2$e or higher is 6%. With a 1% PRTP, the distribution is centered around 550 ppm $CO_2$e. There is a 9% of falling below 450 ppm $CO_2$e, and a 2% of 700 ppm $CO_2$e or higher. With a 1% PRTP, the mode is at 475 ppm $CO_2$e. There is 40% that concentrations will be below 450 ppm $CO_2$e, and a 1% probability of exceeding 700 ppm $CO_2$e.

As above, there is an economic rationale for emission reduction. Leaving emissions unabated is suboptimal. Greenhouse gas emissions do damage at the margin, and this not only justifies but also buys emission reduction. It is more difficult, however, to justify very stringent emission reduction—at least with the information presented thus far (the argument is further refined below). The EU and UN have adopted an ultimate target of 2 °C global warming. If greenhouse gas concentrations stabilize around 450 ppm $CO_2$e, there is a 50% of staying below 2 °C warming. It is hard to argue that this is the optimal target. If the numbers above are correct, a 1% PRTP would imply only a $40\times50=20\%$ chance of meeting the 2 °C target.

## 5. Desired trajectory

The optimal trajectory of greenhouse gas emission reduction has attracted a lot of scholarly attention in a cost-effectiveness setting, where the ultimate target is exogenous to the analysis. If technological progress is exogenous, welfare is maximum if abatement targets are modest in the short term but get more ambitious over time (Wigley et al., 1996). There are four factors that explain this. (i) The capital stock turns over slowly, so that overly stringent emission reduction in the short term would require premature scrapping of capital and durable consumption goods.

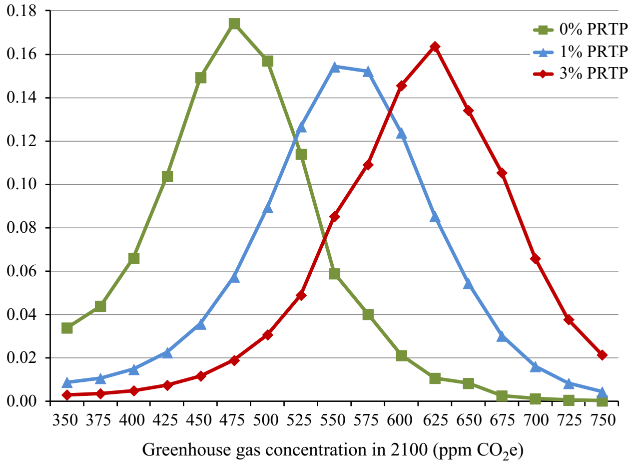

**Fig. 6.** Probability density function for the optimal greenhouse gas concentration for three alternative pure rates of time preference.

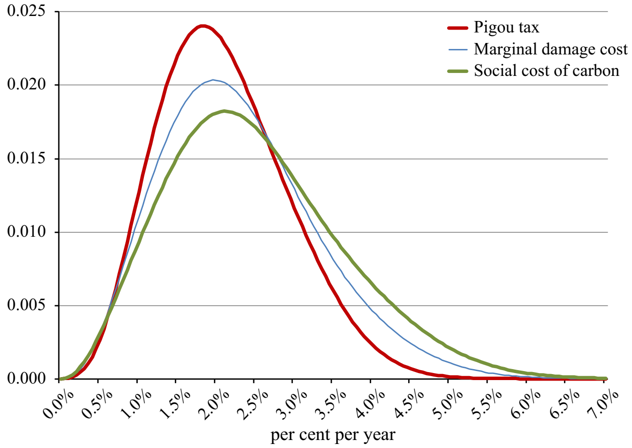

**Fig. 7.** Kernel density of the annual growth rate of the marginal damage cost of carbon dioxide emissions, the Pigou tax, and the social cost of carbon.

(ii) Technological progress is typically assumed to narrow the gap in costs between fossil energy and renewables. Future emission reduction is thus cheaper than current emission reduction. (iii) The discount rate puts a premium on costs incurred in the short run. (iv) Greenhouse gases degrade in the atmosphere, so that later emission reduction is more effective than earlier emission reduction.

If technology is endogenous, and progresses through investment in R&D, the optimal trajectory does not change qualitatively (Goulder and Mathai, 2000; Schwoon and Tol, 2006). If technology progresses through learning-by-doing, the qualitative pattern may change (Goulder and Mathai, 2000; Schwoon and Tol, 2006). With learning-by-doing, current emission reduction makes future emission reduction less expensive. This is a reason for more stringent climate policy in the short run. However, as the costs of future emission reduction fall, an incentive is created to postpone emission reduction. Calibrated models show that learning-by-doing does not have much effect on the optimal emission reduction trajectory (Bosetti et al., 2006; Gerlagh and van der Zwaan, 2003).

If policy aims to meet some concentration or temperature target in the long-term, then the cost-effectiveness analysis is essentially a Hotelling problem (Hotelling, 1931). If the target is to cap carbon dioxide concentration at say 550 ppm, then we can emit only so and so much carbon dioxide. Each emitted ton further exhausts the resource of permitted emissions. The optimal solution to a Hotelling problem is that the shadow price rises with the rate of discount. In fact, carbon dioxide degrades in the atmosphere so this is a renewable resource problem. Therefore, the shadow price should rise with the rate of discount plus the rate of degradation (Dasgupta, 1982). Over a hundred year period, carbon dioxide degrades by about 0.6% per year.

Less attention has been paid to the optimal trajectory in a welfare-maximizing framework. There are a number of studies of the evolution over time of the marginal damage costs of greenhouse gas emissions (see Appendix). The results are displayed in Fig. 7. As above, kernel density estimation is used, assuming a Gamma distribution with the sample standard deviation and the estimate as mode.

If we take all studies, the mean growth rate of the marginal damage cost is 2.3% per year, with a standard deviation of 1.5%. If we take all studies that use a no-policy scenario, the mean growth rate of the social cost of carbon is 2.5% with a standard deviation of 1.8%. If we take all studies that use an optimal scenario, the mean growth rate of the Pigou tax is 2.1% with a standard deviation of 1.0%.

The difference in growth between the social cost of carbon and the Pigou tax is because climate policy affects climate change in the long run, but not in the short run. The Pigou tax is therefore not only lower than the social cost of carbon (cf. Fig. 3), it also rises more slowly.

There is a sharp contrast between dynamic efficiency and dynamic cost-efficacy. In the latter case, the price of carbon should rise at the Hotelling rate, which is about 0.6%[7] higher than the rate of discount. In the former case, the price of carbon should rise at some 2% per year.

There is a further twist to this story. The marginal cost of emission reduction should equal either the shadow price of carbon or the Pigou tax, and the marginal cost of emission reduction should thus go up with the growth rate of either—unless there are intertemporal spillovers in emission reduction costs. If emission reduction now makes future emission reduction cheaper (dearer), then the current carbon tax should be higher (lower) and the growth rate of the carbon tax lower (higher). This effect is implicit in many models but I am not aware of any explicit estimates of the impact on the growth rate of the price of carbon.

## 6. Ultimate objective

Article 2 of the United Nations Framework Convention on Climate Change (UN, 1992) states that “the ultimate objective [...] is to achieve [...] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner”. At first sight, this may seem to be the typical diplomatic waffle that allows for a broad agreement on an essentially meaningless statement. The conditions for the level of stabilization are indeed vague and open to any interpretation. In a typical stock model, stabilization of concentrations implies stabilization of emissions. Article 2 appears to be void of meaning.

Carbon dioxide, however, is not a typical stock. Carbon dioxide is removed from the atmosphere by a number of processes. Maier-Reimer and Hasselmann (1987) show that, mathematically, it is better to think of ambient carbon dioxide as five different stocks each with a distinct removal rate, rather than a single stock. Broadly, the stocks are associated with different processes of carbon dioxide degradation. About 10% of carbon dioxide is removed by the terrestrial biosphere; this carbon dioxide has an atmospheric half-life of two years. On the other hand, about 13% of carbon dioxide is removed by geological processes (e.g., rock weathering) at a geological time-scale. At a human time-scale, this carbon dioxide stays in the atmosphere forever. As the degradation rate is zero, stabilization of concentrations implies zero emissions.

The ultimate objective of the UNFCCC is therefore a complete elimination of carbon dioxide emissions.

Zero emissions as stipulated by international law are hard to justify in a benefit–cost analysis. Emission reduction is easy to justify. You have to show that carbon dioxide is a negative externality, as was done in Section 3.2. Total emission reduction is much more difficult. There are two sides to a cost-benefit analysis. A little bit of emission reduction has a certain benefit. If emissions are cut further, benefits fall because you improve upon a smaller problem. As emissions approach zero, benefits approach zero too. There is a real benefit if the world warms by 3 °C instead of 4 °C. Is there a measurable benefit if the world warms by 2.00 °C instead of 2.01 °C?[8] At the same time, a little bit of emission reduction is cheap, more emission reduction is more expensive, and total emission reduction is very expensive. Total emission reduction requires that an acceptable alternative is found for every use of fossil fuel, including its many niche applications. That is expensive—and the benefits are low.

Benefit–cost analysis therefore cannot justify a complete elimination of carbon dioxide emissions.

On the one hand, international law says that emissions should be eliminated. On the other hand, welfare optimization says they should not. This problem is less fundamental than it appears. Climate policy in the short term is reasonably independent of the ultimate target. Cost-benefit analysis recommends that carbon dioxide emissions should not be eliminated for the sake of climate change. However, finite fossil fuel resources and technological progress in renewable energy imply that emissions would go to zero anyway. Climate policy would accelerate that process.

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[7] The average atmospheric degradation over 100 years.

[8] Impact functions of climate change are misspecified in the limit. Continuous warming cannot be optimal. If it gets warm enough, the oceans will evaporate. The human body cannot tolerate prolonged exposure to temperatures above 55 °C. Impact functions do not include these issues, and a cost–benefit analysis will therefore not keep temperatures below these thresholds. However, these thresholds are so far removed from realistic assessments of future temperatures that this discussion is irrelevant in practice.

## 7. Time, space, uncertainty

### 7.1. Discount rate

The discount rate is one of economists' favorite topics for discussion. At an axiomatic level, however, things are relatively clear. An intertemporal welfare function cannot simultaneously satisfy two conditions: either one prefers a situation in which one generation is better off and none worse off (Pareto), or one is sensitive to a re-ordering of generations (anonymity) (van Liedekerke and Lauwers, 1997). Axiomatic violation is not pretty, but because generations arrive in order, discounted utilitarianism seems to be the better choice (Koopmans, 1960; Koopmans, 1966; Koopmans, 1967). Asheim and Mitra (2010) and Zuber and Asheim (2012) define welfare functions that satisfy anonymity (and hence violate Pareto) and Dietz and Asheim (2012) explore the implications for climate policy (while assuming, incongruently, that discounted utility informs all other decisions)[9] and find a modest acceleration of "optimal" emission control.

Most of the discussion, however, is focused on (1) the pure rate of time preference in the (Ramsey, 1928) discount rate and (2) hyperbolic discounting.

Fig. 2 shows estimates of the marginal damage cost of carbon dioxide emissions for three alternative pure rates of time preference. Unsurprisingly, a lower pure rate of time preference implies a greater concern about a problem with slow dynamics like climate change. Some authors argue, on ethical grounds, for a low discount rate (Cline, 1992; Stern et al., 2006). Other authors argue, on ethical grounds, that the will of the people should be respected and that all empirical evidence has that people discount future utility (Bradford, 2001; Nordhaus, 2007).

So, there are good reasons to use a high discount rate and good reasons to use a low discount rate. Hyperbolic discounting allows one to use both. The standard discount rate is geometric. The discount factor falls by the same fraction per period. This implies that the relative difference between year 10 and year 11 is the same as the relative difference between year 100 and year 101. That is counterintuitive. Year 10 versus 11 is more like year 100 versus 110. Empirical evidence has that people indeed use a hyperbolic discount factor (Cropper et al., 1992; Henderson and Bateman, 1995).[10] The discount rate falls as the time horizon expands.[11] The near future of climate policy is then discounted at a rate comparable to other short term problems, while the far future is not discounted much further. This implies, obviously, that "optimal" emission control is more stringent (Guo et al., 2006; Newell and Pizer, 2003).

### 7.2. Equity weighting

In Section 2, the impacts of climate change are measured in welfare-equivalent income losses. Care needs to be taken that the measure used is indeed a welfare-equivalent. In the older literature on the impacts of climate change, researchers estimated the impact in various regions of the world and added up the dollars to a world total. That is incorrect (Sandmo, 2011).

The starting point of an optimal climate policy is a global welfare function. The marginal damage cost of climate change is the first partial derivative of global welfare to emissions, divided by the marginal utility of consumption. Adding the dollar impacts on regions to a global total assumes that there is neither risk aversion nor inequity aversion—a rather debatable assumption.

The correct welfare equivalent uses so-called equity weights when adding impacts across regions (Azar and Sterner, 1996; Fankhauser et al., 1997, 1998). Assuming a utilitarian welfare function – global welfare is the sum of regional utility – and a CRRA utility function – regional utility is a power function of average consumption—equity weights equal global average per capita consumption over regional average per capita consumption raised to the power of the rate of risk aversion.

Equity weights are greater (smaller) than one for regions whose income falls below (above) the world average. Typically, impacts are found to be greater in poor countries, so equity weighing increases the global impacts of climate change.

This conclusion is not universal. Anthoff et al. (2009b) found substantial benefits from carbon dioxide fertilization of agriculture. These benefits are in the near future (because ocean heat diffusion is irrelevant, unlike for temperature) and fall disproportionally on the poor.

Anthoff et al. (2009a) and Anthoff and Tol (2010b) explore equity weights in the context of a regional decision maker. In the latter paper, equity weights vanish if impacts are compensated—that is, there are income transfers between regions. However, monetized impacts are then discounted at a different rate, namely the discount rate of the compensator rather than the compensated.

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[9] Alvarez-Cuadrado and Van Long (2009) and Chichilnisky (1996) replace anonymity with weaker non-dictatorship axioms, but this has yet to be applied to climate policy.

[10] A hyperbolic discount factor also emerges as the certainty equivalent of a geometric discount factor. See below.

[11] This implies time-inconsistency: decisions are revised because of the mere passing of time.

### 7.3. *Uncertainty*

Uncertainty is one of the key features of the climate problem, and it has played an important role in decision analysis of climate policy (Pindyck, 2012). Indeed, the results above are conveyed in a probabilistic manner. Most economists would be aware of the standard certainty equivalences. In many cases, a cost–benefit analysis under uncertainty is tantamount to equating the *expected* marginal costs to the *expected* marginal benefits. Because climate change is a large scale and long term problem, things are not as simple.

For example, Gollier (2002a, 2002b), Gollier and Weitzman (2010) and Weitzman (2001) show that if there is uncertainty about the pure rate of time preference or future economic growth, then the certainty-equivalent consumption discount rate is not constant, but rather falls over time. One could apply a falling discount rate to the expected costs and benefits. However, a function of two certainty equivalents is not necessarily a certainty equivalent—and certainly not if climate change or climate policy affects the growth path of the economy. Analytical results on certainty equivalents can provide shortcuts in a numerical analysis, but some of the underlying assumptions may be violated. It is better, therefore, to do the full policy analysis under uncertainty and use the analytical results to help interpret the results.

Tol (1999) first showed that the Pigou tax on greenhouse gas emissions is larger under risk than under perfect information. This is because of a combination of risk aversion and asymmetric uncertainties. See above. Table 2 confirms that the mean social cost of carbon is indeed greater than the mode. Therefore, risk increases the desired ambition for greenhouse gas emission reduction.

Nordhaus (2008) suggests that the risk premium—the difference between (i) a conversion from utility to money followed by a risk analysis and (ii) a risk analysis followed by a conversion to money—is negative because high climate change impact scenarios are more likely high income, high emission scenarios. It is unclear whether this result will hold if one assumes that richer countries are less vulnerable to climate change (Anthoff and Tol, 2012).

The prospect of learning about the properties of the climate system reduces the impact of risk. Irreversibilities enhance the impact of risk on decisions. It is generally believed that irreversibilities are stronger on the side of the impacts of climate change than on the side of the impacts of greenhouse gas emission reduction (Kelly and Kolstad, 1999, 2001; Kolstad, 1996). Irreversibilities thus call for more stringent abatement in the short term.

Besides the uncertainty about model parameters, there is the prospect of things going dramatically wrong because of the climate change. Analysts have used three approaches to incorporate such catastrophic risk. In the first, catastrophe is interpreted as zero utility (Baranzini et al., 2003; De Zeeuw and Zemel, 2012; Gjerde et al., 1999; Tsur and Zemel, 1996). The probability of a catastrophe then acts as a discount rate—and under particular assumptions about the probability density function, the probability of a catastrophe is simply added to the discount rate. This again calls for more stringent emission reduction. This is counterintuitive at first sight: a higher discount rate implying more concern for the future? The explanation is that greenhouse gas emission reduction would reduce the catastrophe probability, and hence the effective discount rate. This would increase the net present value.

Keller et al. (2000, 2004, 2005) show that the above is true, as long as catastrophe can be avoided. If a catastrophe becomes inevitable, its impact is sunk and should not affect policy.

In the second approach to catastrophic risk, a premium is added to the impact of climate change (Nordhaus, 2008; Stern et al., 2006), or highly non-linear term to the impact function (Manne et al., 1995; Weitzman, 2012). The former has the effect of increasing the general level of policy stringency. The latter may imply that a particular degree of global warming is avoided at almost any cost. Both approaches are ad hoc.

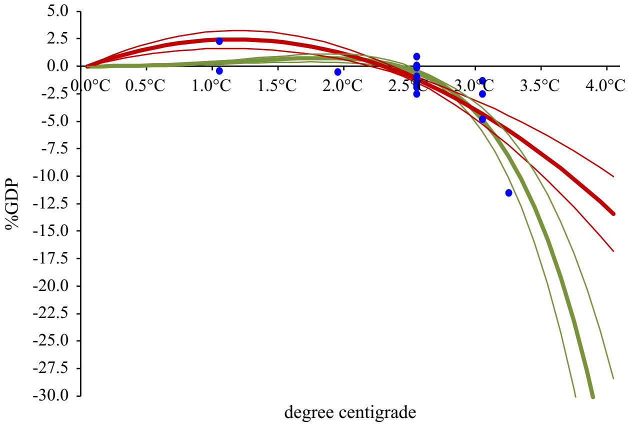

**Fig. 8.** Estimates of the global economic impact of climate change (blue dots) and two fitted functions: $I=4.33(1.49)T-1.92(0.56)T^2$ (red line) and $I=0.348(0.166)T^2-0.0109(0.0025)T^6$ (green line); the thin lines demarcate the 95% confidence interval based on the bootstrapped standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8 illustrates the effect of replacing the parabola of Fig. 1, $I = aT + bT^2$ as proposed by Tol (2009), with $I = aT^2 + bT^6$, as proposed by Weitzman (2012). According to this, initial warming has hardly any impact, intermediate warming is beneficial, and large warming is disastrous. This function actually fits the observations better ($R^2 = 0.74$ versus $R^2 = 0.62$ for the parabola). However, two (rather than one) of the observations are deemed outliers. More importantly, the out-of-sample behavior of the function is driven by a few observations only.

The third approach to catastrophic risk is better founded. Weitzman (2009b) shows that, under relatively general assumptions, the expected value of the net present impact of climate change may not exist or be arbitrarily large. See also Nordhaus (2011), Tol (2003), Tol and Yohe (2006, 2007) and Weitzman (2007, 2009a). This could be interpreted as a call for arbitrarily stringent climate policy. That would be wrong (Hennlock, 2009; Pindyck, 2011). Arbitrarily stringent climate policy means that we should stop burning fossil fuel now. Unfortunately, we cannot grow enough food without artificial fertilizers, and we cannot transport that food from the fields to the people without fossil fuels. Arbitrarily stringent climate policy would be a disaster: Billions of people would starve to death.

In fact, Weitzman (2009b) shows that one cannot apply expected utility maximization to a problem like climate change. It follows that alternative decision criteria should be applied or perhaps developed. Lempert et al. (1996) and Anthoff and Tol (2010a) attempt to do this, and call for climate policy that is stringent but not arbitrarily so.

## 8. Discussion and conclusions

I review optimal targets for international climate policy in the short and long run. Carbon dioxide emissions are probably a negative externality, and should therefore be taxed. Using a discount rate similar to the one typically used for public investments, the expected value of the carbon tax is $25/tC. That carbon tax corresponds to the initial carbon tax of a cost-effective emission reduction trajectory towards stabilization at 625 ppm $CO_2$e—considerably higher than the implicit political aim to stabilize at 450 ppm $CO_2$e. Furthermore, the efficient carbon tax would increase at some 2.3% per year whereas the cost-effective carbon tax would increase at some 5.5%. Efficient concentrations at the end of the 21st century would thus exceed 625 ppm $CO_2$e. Indeed, it is unlikely that a benefit–cost analysis would justify stabilization of the atmospheric concentration of greenhouse gases – as stipulated by international law – as that would require zero carbon dioxide emissions. Fossil fuel use may of course cease for reasons other than climate change. A lower discount rate and an aversion to inequity would justify more stringent climate policy, but would imply inconsistencies between climate policy and other areas of public policy. Catastrophic risk is a more powerful argument for more stringent climate policy, but to a limited extent as emission reduction has downside risks too.

The above analysis considers efficient climate policy in isolation. This is a useful yardstick for analysis, but not particularly realistic. Climate policy interacts with many other policies, but two areas stand out. Climate policy is intimately intertwined with technological progress in the energy sector and with the availability of energy resources. Recent break-throughs in the exploitation of shale gas reduce greenhouse gas emissions in the short term (as gas replaces coal) but increase emission reduction costs in the long term (as solar now competes with cheap gas and cheap coal). Even so, optimal climate policy is unaffected provided that technology policy is first-best (Bosetti et al., 2011; Fischer, 2008; Fischer and Newell, 2008; Popp and Newell, 2012) and that resources policy is first-best (Hoel, 2012; van der Ploeg and Withagen, 2012). Those are strong assumptions, yet it would not be wise to solve other problems through climate policy.

I assumed that adaptation is efficient. If so, it does not affect optimal mitigation policy (de Bruin et al., 2009). I also assumed that climate policy is implemented efficiently. In Section 3.1, I note that second- or higher-best policy implementation may be substantially more expensive. If emission abatement is more expensive, then climate policy should be less stringent.

I reasoned from the perspective of a global planner. Greenhouse gas emission reduction is, of course, a public good. A non-cooperative equilibrium has higher emissions (Babiker, 2001; Barrett, 1994; Carraro and Siniscalco, 1992, 1993, 1998; Nordhaus and Yang, 1996; Yang, 2003).

Although considerable progress has been made in our understanding of optimal climate policy, much research remains to be done. Quantitatively, the estimates of the costs and benefits of climate policy can be improved. Incremental improvements on the current state of the art are always feasible. Both sets of estimates have primarily relied on simulation modeling, but data have steadily improved so that impacts of climate variations should be measurable (Mendelsohn et al., 1994). Some countries now have two decades of experience with climate policy; the impacts and the model assumptions should be tested econometrically (Leahy and Tol, 2012). Such research would add confidence to current estimates, or new insights. Qualitatively, besides carefully exploring the myriad second-best features of climate policy, research to date has been limited to a fairly narrow class of welfare functions. The assumption of exogenous population growth is particularly troubling in the context of climate change. A convincing alternative to the intuitively incorrect conclusion that continued warming is optimum, is still elusive.

## Appendix. Targets For Global Climate Policy

The database on the marginal damage costs of carbon dioxide emissions and its growth rate can be found at: http://www.sussex.ac.uk/Users/rt220/marginaldamagecost.xlsx. The following papers are included in the database on the marginal damage costs of carbon dioxide emissions: (Ackerman and Munitz, 2012; Ackerman and Stanton, 2012; Anthoff et al. 2009a, 2009b, 2009c, 2011a, 2011b; Anthoff and Tol, 2010, 2011; Ayres and Walter, 1991; Azar, 1994; Azar and Sterner, 1996; Cai et al., 2012; Ceronsky et al., 2006, 2011; Clarkson and Deyes, 2002; Cline, 1992, 1997, 2004; Downing et al., 1996, 2005; EPA and NHTSA, 2009; Eyre et al., 1999; Fankhauser, 1994; Guo et al., 2006; Haraden, 1992, 1993; Hohmeyer, 1996, 2004; Hohmeyer and Gaertner, 1992; Hope, 2005a, 2005b, 2006a, 2006b, 2008a, 2008b, 2011; Hope and Maul, 1996; Kemfert and Schill, 2010; Link and Tol, 2004; Maddison, 1995; Manne, 2024; Marten, 2011; Mendelsohn, 2004; Narita et al., 2009; Narita et al., 2010; Newell and Pizer, 2003; Nordhaus, 2010, 1982, 1991, 1993, 1994, 2008; Nordhaus and Boyer, 2000; Nordhaus and Popp, 1997; Nordhaus and Yang, 1996; Parry, 1993; Pearce, 2003; Peck and Teisberg, 1993; Penner et al., 1992; Perrissin Fabert et al., 2012; Plambeck and Hope, 1996; Reilly and Richards, 1993; Roughgarden and Schneider, 1999; Schauer, 1995; Sohngen, 2010; Stern et al., 2006; Stern and Taylor, 2007; Tol, 1999, 2005, 2010, 2012; Uzawa, 2003; Wahba and Hope, 2006; Waldhoff et al., 2011).

The following papers are included in the database on the growth rate of the marginal damage costs of carbon dioxide emissions: (Ackerman and Stanton, 2012; Anthoff et al., 2011a, 2011b; Cai et al., 2012; Cline, 1992, 1997, 2004; EPA and NHTSA, 2009; Fankhauser, 1994; Haraden, 1992, 1993; Hope, 2008b; Maddison, 1995; Mendelsohn, 2004; Nordhaus, 1993, 1994, 2008, 2010; Nordhaus and Boyer, 2000; Nordhaus and Popp, 1997; Nordhaus and Yang, 1996; Peck and Teisberg, 1993; Perrissin Fabert et al., 2012; Roughgarden and Schneider, 1999; Sohngen, 2010; Tol, 1999, 2012; Wahba and Hope, 2006).

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