COPENHAGEN CONSENSUS CENTER

The Costs And Benefits Of EU Climate Policy For 2020

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June 1, 2010

Acknowledgements

Comments by the Copenhagen Consensus Center and an anonymous referee helped to improve the exposition. All errors and opinions are mine.

1. Introduction

The European Union aims to limit its 2020 greenhouse gas emissions to 80% of its 1990 emissions. The European Commission has published an impact assessment, but not a cost-benefit analysis – an earlier cost-benefit analysis covered the eventual target but not the intermediate ones, let alone the details of policy implementation. This paper fills the gap, estimating the costs and the benefits of reducing greenhouse gas emissions by 20% in a decade.[1]

The results of cost-benefit analyses should always be interpreted with care, because estimates of the costs and the benefits of an intervention are never complete and rarely do justice to the complexity of the situation. These problems are particularly pronounced for evaluations of such problems as climate change, which is global, diffuse, unequal, long-lived, and uncertain. Nevertheless, cost-benefit is far superior as a guide to good policy than the hand-waving practised by some politicians. The results of this paper should therefore be treated with caution but not dismissed out of hand.

In Section 2, I survey the economic impacts of climate change. In Section 3, I study the impacts of greenhouse gas emission reduction. In Section 4, I combine the two in a cost-benefit analysis of the EU 20/20/2020 package. Section 5 concludes.

2. Impacts of climate change: A survey

2.1. Estimates of the Total Economic Effect of Climate Change

The first studies of the welfare impacts of climate change were done for the United States by (Cline 1992; Nordhaus 1991; Smith 1996; Titus 1992). Although (Nordhaus 1991) extrapolated his U.S. estimate to the world, and (Hohmeyer and Gaertner 1992) published some global estimates, the credit for the first serious study of the global welfare impacts of climate change goes to (Fankhauser 1994; Fankhauser 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change that have followed.

Any study of the economic effects of climate change begins with some assumptions on future emissions, the extent and pattern of warming, and other possible aspects of climate change, such as sea level rise and changes in rainfall and storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches are possible here. (Nordhaus 1994a) interviewed a limited number of experts.

The studies by (Fankhauser, 95), (Nordhaus 1994b), and (Tol 1995; Tol 2002a; Tol 2002b) use the *enumerative method*. In this approach, estimates of the "physical effects" of climate change are obtained one by one from natural science papers, which in turn may be based on some combination of climate models, impact models and laboratory experiments. The physical impacts must then each be given a price, and added up. For traded goods and services, such as agricultural products,

[1] Note that total emissions in 2008 were very close to those in 1990. Note also that EU emissions were reasonably stable because emissions are increasingly outsources to other countries, particularly in Asia (Davis and Caldeira 2010;Helm et al. 2007;Peters 2008;Peters and Hertwich 2008a;Peters and Hertwich 2008b;Yunfeng and Laike 2010)

Table 1. Estimates of the welfare loss due to climate change, expressed as an equivalent income loss, in percent GDP; where available, estimates of the uncertainty are given in brackets, either as standard deviations or as 95% confidence intervals.

Study	Warming	Impact	Worst-off region		Best-off region	
	(˚C)	(%GDP)	(%GDP)	(Name)	(%GDP)	(Name)
(Nordhaus, William D. 94b)	3.0	-1.3				
(Nordhaus 1994a)	3.0	-4.8 (-30.0 to 0.0)				
(Fankhauser, Samuel 95)	2.5	-1.4	-4.7	China	-0.7	Eastern Europe and the former Soviet Union
(Tol 1995)	2.5	-1.9	-8.7	Africa	-0.3	Eastern Europe and the former Soviet Union
(Nordhaus and Yang 1996)[a]	2.5	-1.7	-2.1	Developing countries	0.9	Former Soviet Union
(Plamberk and Hope 1996)[a]	2.5	-2.5 (-0.5 to –11.4)	-8.6 (-0.6 to - 39.5)	Asia (w/o China)	0.0 (-0.2 to 1.5)	Eastern Europe and the former Soviet Union
(Mendelsohn et al. 2000a)[a,b,c]	2.5	0.0[b] 0.1[b]	-3.6[b] -0.5[b]	Africa	4.0[b] 1.7[b]	Eastern Europe and the former Soviet Union
(Nordhaus, William D. and Boyer, Joseph G. 00)	2.5	-1.5	-3.9	Africa	0.7	Russia
(Tol 2002a)	1.0	2.3 (1.0)	-4.1 (2.2)	Africa	3.7 (2.2)	Western Europe
(Maddison 2003)[a,d,e]	2.5	-0.1	-14.6	South America	2.5	Western Europe
(Rehdanz and Maddison 2005)[a,c]	1.0	-0.4	-23.5	Sub-Saharan Africa	12.9	South Asia
(Hope 2006)[a,f]	2.5	0.9 (-0.2 to 2.7)	-2.6 (-0.4 to 10.0)	Asia (w/o China)	0.3 (-2.5 to 0.5)	Eastern Europe and the former Soviet Union
(Nordhaus 2006)	2.5	-0.9 (0.1)				

[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] Note that Mendelsohn et al. only include market impacts.
[d] Note that the national results were aggregated to regions by the current author for reasons of comparability.
[e] Note that Maddison only considers market impacts on households.
[f] The numbers used by Hope are averages of previous estimates by Fankhauser and Tol; Stern *et al.* (2006) adopt the work of Hope.

agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value that change in output. As another example, the impact of sea level rise constitutes coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in this case is not only the cost of dike building and the value of land, but also the decision which properties to protect. For non-traded goods and services, other methods are needed. An ideal approach might be to study how climate change affects human welfare through health and nature in each area around the world, but a series of "primary valuation" studies of this kind would be expensive and time-consuming. Thus, the monetisation of non-market climate change impacts relies on "benefit transfer," in which epidemiology papers are used to estimate effects on health or the environment, and then economic values are applied from studies of the valuation of mortality risks in other contexts than climate change.

An alternative approach, exemplified in Mendelsohn's work (Mendelsohn et al. 2000b; Mendelsohn et al. 2000a) can be called the *statistical approach.* It is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate. Mendelsohn assumes that the observed variation of economic activity with climate over space holds over time as well; and uses climate models to estimate the future impact of climate change. Mendelsohn's estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modelling is avoided. Other studies (Maddison 2003; Nordhaus 2006) use versions of the statistical approach as well. However, Nordhaus uses empirical estimates of the *aggregate* climate impact on income across the world (per grid cell), while Maddison looks at patterns of *aggregate* household consumption (per country). Like Mendelsohn, Nordhaus and Maddison rely exclusively on observations, assuming that "climate" is reflected in incomes and expenditures – and that the spatial pattern holds over time. (Rehdanz and Maddison 2005) also empirically estimate the aggregate impact, using self-reported happiness for dozens of countries.

The enumerative approach has the advantage that it is based on natural science experiments, models and data; the results are physically realistic and easily interpreted. However, the enumerative approach also raises concerns about extrapolation: economic values estimated for other issues are applied to climate change concerns; values estimated for a limited number of locations are extrapolated to the world; and values estimated for the recent past are extrapolated to the remote future. Tests of benefit transfer methods have shown time and again that errors from such extrapolations can be substantial (Brouwer and Spaninks 1999). But perhaps the main disadvantage of the enumerative approach is that the assumptions about adaptation may be unrealistic —as temperatures increase, presumably private and public-sector reactions would occur to both market and non-market events.

In contrast, the statistical studies rely on uncontrolled experiments. These estimates have the advantage of being based on real-world differences in climate and income, rather than extrapolated differences. Therefore, adaptation is realistically, if often implicitly, modelled. However, statistical studies run the risk that all differences between places are attributed to climate. Furthermore, the data often allow for cross-sectional studies only; and some important aspects of climate change, particularly the direct impacts of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

Given that the studies in Table 1 use different methods, it is striking that the estimates are in broad agreement on a number of points – indeed, the uncertainty analysis displayed in Figure 1 reveals that no estimate is an obvious outlier. Table 1 shows selected characteristics of the published estimates. The first column of Table 1 shows the underlying assumption of long-term warming, measured as the increase in the global average surface air temperature. The assumed warming typically presumes a doubling of concentrations of greenhouse gases in the atmosphere. It is reasonable to think of these as the temperature increase in the second half of the 21st century.[2] However, the impact studies in Table 1 are comparative static, and they impose a future climate on today's economy. One can therefore not attach a date to these estimates. The second column of Table 1 shows the impact on welfare at that future time, usually expressed as a percentage of income. For instance, (Nordhaus, William D. 94b) estimates that the impact of 3˚C global warming is as bad as losing 1.4% of income. In some cases, a confidence interval (usually at the 95 percent level) appears under the estimate; in other cases, a standard deviation is given; but the majority of studies does not report any estimate of the uncertainty. The rest of Table 1 illustrates differential effects around the world. The third column shows the percentage decrease in annual GDP of the regions hardest-hit by climate change, and the fourth column identifies those regions. The fifth column shows the percentage change in GDP for regions that are hurt least by climate change—and in most cases would even benefit from a warmer climate—and the final column identifies those regions.

A first area of agreement between these studies is that 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. This kind of loss of output can look large or small, depending on context. From one perspective, it's roughly equivalent to a year's growth in the global economy—which suggests that over a century or so, the economic loss from climate change is not all that large. On the other hand, the damage is not negligible. An environmental issue that causes a permanent reduction of welfare, lasting into the indefinite future, would certainly justify some steps to reduce such costs. Balancing these factors, cost-benefit analyses of climate change typically recommend only limited greenhouse gas emission reduction – for instance, (Nordhaus 1993) argues that the optimal rate of emission reduction is 10-15 percent (relative to the scenario without climate policy) over the course of the 21st century.[3] Recall that the EU calls for 20-30% emission reduction (relative to 2005) by 2020.

A second finding is that some estimates (Hope 2006; Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Tol 2002b), point to initial benefits of a modest increase in temperature, followed by losses as temperatures increase further. There are no estimates for a warming above 3˚C, although climate change may well go beyond that (see below). All studies published after 1995 have regions with net gains and net losses due to global warming, while earlier studies only find net losses. Figure 1 illustrates this pattern. The horizontal axis shows the increase in average global temperature. The vertical index shows the central estimate of welfare loss. The central line shows a best-fit parabolic line from an ordinary least squares regression. Of course, it is something of a stretch to interpret the results of these different studies as if they were a time series of

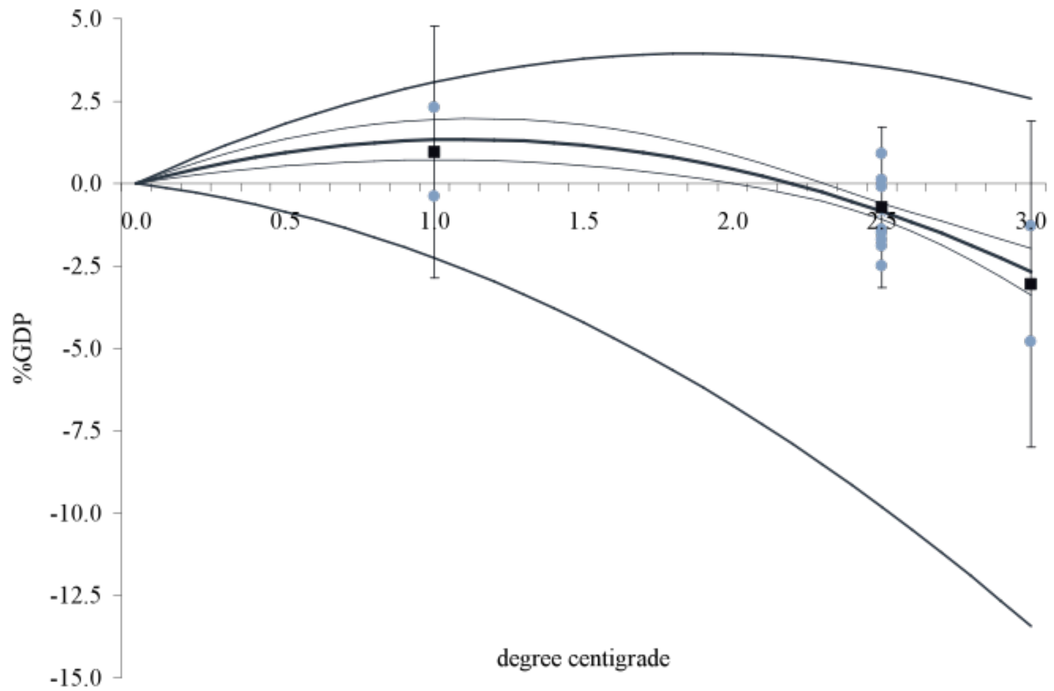
[2] Note that the temperatures in Table 1 and Figure 1 signify warming relative to today.

[3] Later studies reached the same conclusion when using standard assumptions.

how climate change will affect the economy over time, and so this graph should be interpreted more as an interesting calculation than as hard analysis. But the pattern of modest economic gains due to climate change, followed by substantial losses, appears also in the few studies that report impacts over time (Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Nordhaus and Boyer 2000; Smith et al. 2001; Tol 2002b).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces "water stress" in plants and may make them grow faster (Long et al. 2006). In addition, the output of the global economy is concentrated in the temperate zone, where warming reduces heating costs and cold-related health problems. Although the world population is concentrated in the tropics, where the initial effects of climate change are probably negative, the relatively smaller size of the economy in these areas means that—at least over the interval of small increases in global temperatures—gains for the high-income areas of the world exceed losses in the low-income areas.

Figure 1. The 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income loss, as a functions of the increase in global mean temperature relative to today. The green dots represent the estimates (cf. Table 1). The blue squares are the sample means (for the specific global warming), and the lines are the sample means plus or minus twice the sample standard deviation. The central red line is the least squares fit to the 14 observations: $D = 2.46\ (1.25)\ T - 1.11\ (0.48)\ T^2$, $R^2 = 0.51$, where D denotes impact and T denotes temperature; standard deviations are between brackets. The thin red inner two lines are the 95% confidence interval for the central line re-estimated with one observation dropped. The thick red outer two lines are the 95% confidence interval, where the standard deviation is the least squares fit to the 5 reported standard deviations or half confidence intervals (cf. Table 1): $S_{optimistic} = 0.87\ (0.28)\ T$, $R^2 = 0.70$, $S_{pessimistic} = 1.79\ (0.87)\ T$, $R^2 = 0.51$ where S is the standard deviation.



However, this pattern should be interpreted with care. Even if, initially, economic impacts may well be positive, it does not follow that greenhouse gas emissions should be subsidized. The climate responds rather slowly to changes in greenhouse gas emissions. The initial warming can no longer be avoided; it should be viewed as a sunk benefit. The fitted line in Figure 1 suggests that the turning point in terms of economic benefits occurs at about 1.1ºC warming (with a standard deviation of 0.7ºC). Policy steps to reduce emissions of greenhouse gases in the near future would begin to have a noticeable effect on climate sometime around mid-century—which is to say, at just about the time that any medium-run economic benefits of climate change begin to decline (Hitz and Smith 2004; Tol et al. 2000; Tol 2002b). In short, even though total economic effects of 1-2ºC warming may be positive, incremental impacts beyond that level are likely to be negative. Moreover, if one looks further into the future, the incremental effects look even more negative.

Third, although greenhouse gas emissions per person are higher in high-income countries, relative impacts of climate change are greater in low-income countries (Yohe and Schlesinger 2002). Indeed, impact estimates for Sub-Saharan Africa go up to a welfare loss equivalent to the loss of a quarter of income (Table 1). The estimates are higher for several reasons. Low-income countries tend to be in tropical zones closer to the equator. They are already hotter, and their output already suffers to some extent from their higher temperatures in sectors like agriculture. Moreover, low-income countries are typically less able to adapt to climate change both because of a lack of resources and less capable institutions (Adger 2006; Alberini et al. 2006; Smit and Wandel 2006; Tol et al. 2007; Tol 2008a; Tol and Yohe 2007b; Yohe and Tol 2002).

The emissions of greenhouse gases are predominantly from high-income countries while the negative effects of climate change are predominantly in low-income countries. This has two policy implications. First, any justification of stringent abatement for greenhouse gases is at least in part an appeal to consider the plight of citizens of low-income countries around the world and the effects imposed on them by the citizens of high-income countries (Schelling 2000). Second, if pre-existing poverty is the one of the main causes for vulnerability to climate change, one may wonder whether stimulating economic growth or emission abatement is the better way to reduce the effects of climate change. Indeed, (Tol and Dowlatabadi 2001; Tol and Yohe 2006) argue that the economic growth foregone by stringent abatement of greenhouse gases would more than offset the avoided impacts of climate change, at least in the case of malaria. Similarly, (Tol 2005) shows that development is a cheaper way of reducing climate-change-induced malaria than is emission reduction. Moreover, high-income countries may find it easier and cheaper to compensate poorer countries for the climate change damages caused, rather than to pay for reducing their own greenhouse gas emissions. Such compensation could be explicit, but would more likely take the shape of technical and financial assistance with adaptation (Paavola and Adger 2006).

Although research is scarce (O'Brien et al. 2004) climate change impacts would not be homogeneous within countries; certainly, certain economic sectors (e.g., agriculture), regions (e.g., the coastal zone) and age groups (e.g., the elderly) are more heavily affected than others.

Fourth, estimates of the economic effects of greenhouse gas emissions have become less pessimistic over time. For the studies listed here, the estimates increase by 0.23 percent of GDP per year in which the study was done (with a standard deviation of 0.10 percent per year). There are several reasons for this change. Projections of future emissions and future climate change have become less severe over time – even though the public discourse has become shriller. The earlier studies focused on the negative impacts of climate change, whereas later studies considered the balance of positives and negatives. In addition, earlier studies tended to ignore adaptation. More recent studies – triggered by (Mendelsohn et al. 1994) – include some provision for agents to change their behaviour in response to climate change. However, more recent studies also tend to assume that agents have perfect foresight about climate change, and have the flexibility and appropriate incentives to respond. Given that forecasts are imperfect, agents are constrained in many ways, and markets are often distorted – particularly in the areas that matter most for the effects of climate change such as water, food, energy, and health – recent studies of the economic effects of climate change may be too optimistic about the possibilities of adaptation and thus tend to underestimate the economic effects of climate change.

A fifth common conclusion from studies of the economic effects of climate change is that the uncertainty is vast and right-skewed. For example, consider only the studies that are based on a benchmark warming of 2.5ºC. These studies have an average estimated effect of climate change on average output of -0.7 percent of GDP, and a standard deviation of 1.2 percent of GDP. Moreover, this standard deviation is only about best estimate of the economic impacts, given the climate change estimates. It does not include uncertainty about future levels of greenhouse gas emissions, or uncertainty about how these emissions will affect temperature levels, or uncertainty about the physical consequences of these temperature changes. Moreover, it is quite possible that the estimates are not independent, as there are only a relatively small number of studies, based on similar data, by authors who know each other well.

Only five of the 14 studies in Table 1 report some measure of uncertainty. Two of these report a standard deviation only—which suggests symmetry in the probability distribution. Three studies report a confidence interval – of these, two studies find that the uncertainty is right-skewed, but one study finds a left-skewed distribution. Although the evidence on uncertainty here is modest and inconsistent, and I suspect less than thoroughly reliable, it seems that negative surprises should be more likely than positive surprises. While it is relatively easy to imagine a disaster scenario for climate change – for example, involving massive sea level rise or monsoon failure that could even lead to mass migration and violent conflict – it is not at all easy to argue that climate change will be a huge boost to economic growth.

Figure 1 has three alternative estimates of the uncertainty around the central estimates. First, it shows the sample statistics. This may be misleading for the reasons outlined above; note that there are only two estimates each for a 1.0˚C and a 3.0˚C global warming. Second, I re-estimated the parabola 14 times with one observation omitted. This exercise shows that the shape of the curve in Figure 1 does not depend on any single observation. At the same time, the four estimates for a 1.0˚C or 3.0˚C warming each have a substantial (but not significant) effect on the parameters of the parabola. Third, five studies report standard deviations or confidence intervals. Confidence intervals imply standard deviations, but because the reported intervals are asymmetric I derived two standard deviations, one for negative deviations from the mean, and one for positive deviations. I assumed that the standard deviation grows linearly with the temperature, and fitted a line to each of the two sets of five "observed" "standard deviations. The result is the asymmetric confidence interval shown in Figure 1. This probably best reflects the considerable uncertainty about the economic impact of climate change, and that negative surprises are more likely than positive ones.

In other words, the level of uncertainty here is large, and probably understated—especially in terms of failing to capture downside risks. The policy implication is that reduction of greenhouse gas emissions should err on the ambitious side.

The kinds of studies presented in Table 1 can be improved in numerous ways, some of which have been mentioned already. In all of these studies, economic losses are approximated with direct costs, ignoring general equilibrium and even partial equilibrium effects.[4]

In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap—for example, losses in water resources and losses in agriculture may actually represent the same loss. Estimates are often based on extrapolation from a few detailed case studies, and extrapolation is to climate and levels of development that are very different from the original case study. Little effort has been put into validating the underlying models against independent data – even though the findings of the first empirical estimate of the impact of climate change on agriculture by (Mendelsohn et al. 1994) were in stark contrast to earlier results like those of (Parry 1990), which suggests that this issue may be important. Realistic modeling of adaptation is problematic, and studies typically either assume no adaptation or perfect adaptation. Many effects are unquantified, and some of these may be large (see below). The uncertainties of the estimates are largely unknown. These problems are gradually being addressed, but progress is slow. Indeed, the list of warnings given here is similar to those in (Fankhauser and Tol 1996; Fankhauser and Tol 1997).

A deeper conceptual issue arises with putting value on environmental services. Empirical studies have shown that the willingness to pay (WTP) for improved environmental services may be substantially lower than the willingness to accept compensation (WTAC) for diminished environmental services (Horowith and McConnell 2002). The difference between WTP and WTAC goes beyond income effects, and may even hint at loss aversion and agency effects, particularly around involuntary risks. A reduction in the risk of mortality due to greenhouse gas emission abatement is viewed differently than an increase in the risk of mortality due to the emissions of a previous generation in a distant country. The studies listed in Table 1 all use willingness to pay as the basis for valuation of environmental services, as recommended by (Arrow et al. 1993). Implicitly, the policy problem is phrased as "How much are we willing to pay to buy an improved climate for our children?" Alternatively, the policy problem could be phrased as "How much compensation should we pay our children for worsening their climate?" This is a different question, and the answer would be different if the current policy makers assume that future generations would differentiate between WTP and WTAC much like the present generation does. The

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[4] General equilibrium studies of the effect of climate change on agriculture have a long history (Darwin 2004;Kane et al. 1992). These papers show that markets matter, and may even reverse the sign of the initial impact estimate (Yates and Strzepek 1998). (Bosello et al. 2007) and (Darwin and Tol 2001) show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater. Similarly, (Bosello et al. 2006) show that the direct costs are biased towards zero for health, that is, countries that would see their labour productivity fall (rise) because of climate change would also lose (gain) competitiveness. (Berrittella et al. 2006) also emphasize the redistribution of impacts on tourism through markets.

marginal avoided compensation would be larger than the marginal benefit, so that the tax on greenhouse gas emission would be higher.

2.2. Missing Impacts

The effects of climate change that have been quantified and monetized include the impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, and human health. Obviously, this list is incomplete. Even within each category, the assessment is incomplete. I cannot offer quantitative estimates of these missing impacts, but a qualitative and speculative assessment of their relative importance follows. For more detail, see (Tol 2008c).

Many of the omissions seem likely to be relatively small in the context of those items that have been quantified. Among the negative effects, for example, studies of the effect of sea level rise on coastal zones typically omit costs of saltwater intrusion in groundwater (Nicholls and Tol 2006). Increasing water temperatures would increase the costs of cooling power plants (Szolnoky et al. 1997). Redesigning urban water management systems, be it for more of less water, would be costly (Ashley et al. 2005), as would implementing safeguards against increased uncertainty about future circumstances. Extratropical storms may increase, leading to greater damage and higher building standards (Dorland et al. 1999). Tropical storms do more damage, but it is not known how climate change would alter the frequency, intensity, and spread of tropical storms (McDonald et al. 2005). Ocean acidification may harm fisheries (Kikkawa et al. 2004).

The list of relatively small missing effects would also include effects that are probably positive. Higher wind speeds in the mid-latitudes would decrease the costs of wind and wave energy (Breslow and Sailor 2002). Less sea ice would improve the accessibility of Arctic harbours, would reduce the costs of exploitation of oil and minerals in the Arctic, and might even open up new transport routes between Europe and East Asia (Wilson et al. 2004). Warmer weather would reduce expenditures on clothing and food, and traffic disruptions due to snow and ice(Carmichael et al. 2004).

Some missing effects are mixed. Tourism is an example. Climate change may well drive summer tourists towards the poles and up the mountains, which amounts to a redistribution of tourist revenue (Berrittella et al. 2006). Other effects are simply not known. Some rivers may see an increase in flooding, and others a decrease (Kundzewicz et al. 2005; Svensson et al. 2005).

These small unknowns, and doubtless others not identified here, are worth some additional research, but they pale in comparison to the big unknowns: extreme climate scenarios, the very long term, biodiversity loss, the possible effects of climate change on economic development and even political violence.

Examples of extreme climate scenarios include an alteration of ocean circulation patterns—such as the Gulf Stream that brings water north from the equator up through the Atlantic Ocean (Marotzke 2000). This may lead to a sharp drop in temperature in and around the North Atlantic. Another example is the collapse of the West-Antarctic Ice Sheet (Vaughan 2008; Vaughan and Spouge 2002), which would lead to sea level rise of 5-6 meters in a matter of centuries. A third example is the massive release of methane from melting permafrost (Harvey and Zhen 1995), which would lead to rapid warming worldwide. Exactly what would cause these sorts of changes or what effects they would have are not at all well-understood, although the chance of any one of them happening seems low. But they do have the potential to happen relatively quickly, and if they did, the costs could be substantial. Only a few studies of climate change have examined these issues. (Nicholls et al. 2008) find that the impacts of sea level rise increase ten-fold should the West-Antarctic Ice Sheet collapse, but the work of (Olsthoorn et al. 2008) suggests that this may be too optimistic as Nicholls et al. may have overestimated the speed with which coastal protection can be build. (Link and Tol 2004) estimate the effects of a shutdown of the thermohaline circulation. They find that the resulting regional cooling offsets but does not reverse warming, at least over land. As a consequence, the net economic effect of this particular change in ocean circulation is *positive*.

Another big unknown is the effect of climate change in the very long term. Most static analyses examine the effects of doubling the concentration of atmospheric CO_2; most studies looking at effects of climate change over time stop at 2100. Of course, climate change will not suddenly halt in 2100. In fact, most estimates suggest that the negative effects of climate change are growing, and even accelerating, in the years up to 2100 (cf. Figure 1). It may be that some of the most substantial benefits of addressing climate change occur after 2100, but studies of climate change have not looked seriously at possible patterns of emissions and atmospheric concentrations of carbon after 2100, the potential physical effects on climate, nor the monetary value of those impacts. One may argue that impacts beyond 2100 are irrelevant because of time discounting, but this argument would not hold if the impacts grow faster than the discount rate – because of the large uncertainty, this cannot be excluded.

Climate change could have a profound impact on biodiversity (Gitay et al. 2001), not only through changes in temperature and precipitation, but in the ways climate change might affect land use and nutrient cycles, ocean acidification, and the prospects for invasion of alien species into new habitats. Economists have a difficult time analyzing this issue. For starters, there are few quantitative studies of the effects of climate change on ecosystems and biodiversity. Moreover, valuation of ecosystem change is difficult, although some methods are being developed (Champ et al. 2003). These methods are useful for marginal changes to nature, but may fail for the systematic impact of climate change. That said, valuation studies have consistently shown that, although people are willing to pay something to preserve or improve nature, most studies put the total willingness to pay for nature conservation at substantially less than 1 percent of income (Pearce and Moran 1994). Unless scientists and economists develop a rationale for placing a substantially higher cost on biodiversity, it will not fundamentally alter the estimates of total costs of climate change.

A cross-sectional analysis of per capita income and temperature may suggest that people are poor because of the climate (Acemoglu et al. 2001; Gallup et al. 1999; Masters and McMillan 2001; Nordhaus 2006; van Kooten 2004), although others would argue that institutions are more important than geography (Acemoglu et al. 2002; Easterly and Levine 2003). There is an open question about the possible effects of climate change on annual rates of economic growth. For example, one possible scenario is that low-income countries, which are already poor to some extent because of climate, will suffer more from rising temperatures and have less ability to adapt, thus dragging their economies down further. (Fankhauser and Tol 2005) argue that only very extreme parameter choices would imply such a scenario. In contrast, (Dell et al. 2008) find that climate change would slow the *annual* growth rate of poor countries by 0.6 to 2.9 per cent points. Accumulated over a century, this effect would dominate all earlier estimates of the economic effects of climate change. However, Dell *et al.* have only a few explanatory variables in their regression, so their estimate may suffer from specification or missing variable bias; they may also have confused weather variability with climate change. One can also imagine a scenario in which climate change affects health, particularly the prevalence of malaria and diarrhoea, in a way that affects long-term economic growth (Galor and Weil 1999); or in which climate-change-induced resource scarcity intensifies violent conflict (Tol and Wagner 2008; Zhang et al. 2006; Zhang et al. 2007) and affect long-term growth rates through that mechanism (Butkiewicz and Yanikkaya 2005). These potential channels have not been modeled in a useful way. But the key point here is that if climate change affects annual rates of growth for a sustained period of time, such effects may dominate what was calculated in the total effects studies shown earlier in Table 1.

Besides the known unknowns described above, there are probably unknown unknowns too. For example, the direct impact of climate change on labor productivity has never featured on any list of "missing impacts", but (Kjellstrom et al. 2008) show that it may well be substantial.

The "missing impacts" are a reason for concern and further emphasize that climate change may spring nasty surprises. This justifies greenhouse gas emission reduction beyond that recommended by a cost-benefit analysis under quantified risk. The size of the "uncertainty premium" is a political decision. However, one should keep in mind that there is a history of exaggeration in the study of climate change impacts. Early research pointed to massive sea level rise (Schneider and Chen 1980), millions dying from infectious diseases (Haines and Fuchs 1991) and widespread starvation (Hohmeyer and Gaertner 1992). Later, more careful research has dispelled these fears.

2.3. Estimates of the Marginal Cost of Greenhouse Gas Emissions

The marginal damage cost of carbon dioxide, also known as the "social cost of carbon," is defined as the net present value of the incremental damage due to a small increase in carbon dioxide emissions. For policy purposes, the marginal damage cost (if estimated along the optimal emission trajectory) would be equal to the Pigouvian tax that could be placed on carbon, thus internalizing the externality and restoring the market to the efficient solution.

A quick glance at the literature suggests that there are many more studies of the marginal cost of carbon than of the total cost of climate change. Table 1 has 13 studies and 14 estimates; in contrast, (Tol 2009b) reports 47 studies with 232 estimates. Some of the total cost estimates (Maddison 2003; Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Nordhaus 2006; Rehdanz and Maddison 2005) have yet to be used for marginal cost estimation. Therefore, the 200-plus estimates of the social cost of carbon are based on nine estimates of the total impact of climate change. The empirical basis for the size of an optimal carbon tax is much smaller than is suggested by the number of estimates.

How can nine studies of total economic cost of climate change yield well over 200 estimates of marginal cost? Remember that the total cost studies are comparative static, and measure the economic cost of climate change in terms of a reduction in welfare below its reference level. This approach to describing total costs can be translated into marginal costs of current emissions in a number of ways. The rate at which future benefits (and costs) are discounted is probably the most important source of variation in the estimates of the social cost of carbon. The large effect of different assumptions about discount rates is not surprising, given that the bulk of the avoidable effects of climate change is in the distant future. Differences in discount rates arise not only from varying assumptions about the rate of pure time preference, the growth rate of per capita consumption, and the elasticity of marginal utility of consumption.[5] Some more recent studies have also analyzed variants of hyperbolic discounting, where the rate of discount falls over time.

However, there are other reasons why two studies with identical estimates of the total economic costs of climate change, expressed as a percent of GDP at some future date, can lead to very different estimates of marginal cost. Studies of the marginal damage costs of carbon dioxide emissions can be based on different projections of CO_2 emissions, different representations of the carbon cycle, different estimates of the rate of warming, and so on. 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 development.

For example, the estimate of (Nordhaus 1991) of the total welfare loss of a 3.0˚C warming is 1.3% of GDP. In order to derive a marginal damage cost estimate from this, you would need to assume when in the future 3.0˚C would occur, and whether damages are linear or quadratic or some other function of temperature (and precipitation et cetera). And then the future stream of incremental damages due to today's emissions needs to be discounted back to today's value.

Marginal cost estimates further vary with the way in which uncertainty is treated (if it is recognized at all). Marginal cost estimates also differ with how regional effects of climate change are aggregated. Most studies add monetary effects for certain regions of the world, which roughly reflects the assumption that emitters of greenhouse gases will compensate the victims of climate change. Other studies add utility-equivalent effects – essentially assuming a social planner and a global welfare function. In these studies, different assumptions about the shape of the global welfare function can imply widely different estimates of the social cost of carbon (Anthoff et al. 2009; Fankhauser et al. 1997; Fankhauser et al. 1998).

Table 2 shows some characteristics of a meta-analysis of the published estimates of the social cost of carbon. Columns 2-5 show the sample statistics of the 232 published estimates. One key issue in attempting to summarize this work is that just looking at the distribution of the medians or modes of these studies is inadequate, because it 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 (Tol 2003; Tol and Yohe 2007a; Weitzman 2009). Because there are many estimates of the social cost of carbon, this can be done reasonably objectively. (The same would not be the case for the total economic impact estimates.) Thus, the idea here is to use one parameter from each published estimate (the mode) and the standard deviation of the entire sample—and then to build up an overall distribution of the estimates and their

[5] The elasticity of marginal utility with respect to consumption plays several roles. It serves as a measure of risk aversion. It plays an important role in the discount rate (Ramsey 1928), as it also partly governs the substitution of future and present consumption. Furthermore, this parameter drives the trade-offs between differential impacts across the income distribution, both within and between countries. Although conceptually distinct, all climate policy analyses that I am aware of use a single numerical value (Atkinson et al. 2009;Saelen et al. 2008). The reason is simply that although these distinctions are well-recognized, welfare theorists have yet to find welfare and utility functions that make the necessary distinctions and can be used in applied work.

surrounding uncertainty on this basis using the methodology in (Tol 2008b).[6] The results are shown of Table 2.

Table 2 reaffirms that the uncertainty about the social costs of climate change is very large. The mean estimate in these studies is a marginal cost of carbon of $105 per metric tonne of carbon, but the modal estimate is only $13/tC. Of course, this divergence suggests that the mean estimate is driven by some very large estimates—and indeed, the estimated social cost at the 95th percentile is $360/tC and the estimate at the 99th percentile is $1500/tC. The fitted distribution suggests that the sample statistics underestimate the marginal costs: the mode is $41/tC, the mean $151/tC and the 99th percentile $1687/tC.

This large divergence is partly explained by the use of different pure rates of time preference in these studies. Columns 3-5 (sample statistics) and 7-9 (fitted distribution) of Table 2 divide up the studies into three subsamples which use the same pure rate of time preference. A higher rate of time preference means that the

Table 2. The mean and standard deviation of social cost of carbon (euro/tonne CO_2) for a Fisher-Tippett distribution fitted to 232 published estimates, and to three subsets of these estimates based on the pure rate of time preference.

	Fitted distribution (weighted)			
	All	Pure rate of time preference		
		0%	1%	3%
Mean	49	76	24	5
StDev	81	71	26	5
Mode	14	35	13	3
33%ile	10	35	10	2
Median	32	58	20	4
67%ile	59	93	32	7
90%ile	135	177	58	12
95%ile	185	206	72	15
99%ile	439	265	103	19

[6] I fitted a Fisher-Tippett distribution to each published estimate using the estimate as the mode and the *sample* standard deviation. The Fisher-Tippett distribution is the only two-parameter, 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 2009). The joint probability density function follows from addition, using 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. See http://www.fnu.zmaw.de/Social-cost-of-carbon-meta-analy.6308.0.html

costs of climate change incurred in the future have a lower present value, and so for example, the sample mean social cost of carbon for the studies with a 3 percent rate of time preference is $18/tC, while it is $232/tC for studies that choose a zero percent rate of time preference. But these columns also show that even when the same discount rate is used, the variation in estimates is large. For the fitted distribution, the means are roughly double the modes—showing that the means are being pulled higher by some studies with very high estimated social costs.[7] Table 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

The sample and distribution characteristics of Table 2 also allow us to identify outliers. On the low side, the results of (Tol 2005) stand out with a social cost of carbon of -$6.6/tC for a 3% pure rate of time preference and $19.9/tC for a 0% rate. The reason is that Tol's model was the first used for marginal cost estimation that had initial benefits from climate change. In later work by the same author, the early benefits are less pronounced. On the high side, the results of (Ceronsky et al. 2006) stand out, with a social cost estimate of $2400/tC for a 0% pure rate of time preference and $120/tC for a 3% rate. The reason is that Ceronsky et al. consider extreme scenarios only – while they acknowledge that such scenarios are unlikely, they do not specify a probability. At a 1% pure rate of time preference, the $815/tC estimate of (Hope 2008) stands out. Again, this is the result of a sensitivity analysis in which Hope sets risk aversion to zero so that the consumption discount rate equals 1% as well.

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 – and I argue above that their uncertainty is underestimated too. Second, the estimates only contain those impacts that have been quantified and valued – and I argue below that some of the missing impacts have yet to be assessed because they are so difficult to handle and hence very uncertain. Third, although the number of researchers who published marginal damage cost estimates is larger than the number of researchers who published total impact estimates, it is still a reasonably small and close-knit community who may be subject to group-think, peer pressure and self-censoring.

3. Impacts of emission reduction: A survey

3.1. Options

Carbon dioxide emissions are driven by the Kaya-Bauer identity:

$$(1) \qquad M = P\frac{Y}{P}\frac{E}{Y}\frac{C}{E}\frac{M}{C}$$

[7] Some readers may wonder why the estimates with a discount rate of zero percent don't look all that substantially higher than the estimates with a discount rate of 1%. The main reason is that most estimates are (inappropriately) based on a finite time horizon. With an infinite time horizon, the social cost of carbon would still be finite, because fossil fuel reserve are finite and the economy would eventually equilibrate with the new climate, but the effect of the zero discount rate would be more substantial. For the record, there is even one estimate (Hohmeyer and Gaertner 1992) based on a zero consumption discount rate (Davidson 2006;Davidson 2008) and thus a *negative* pure rate of time preference.

where *M* is emissions, *P* is population, *Y* is income, *E* is energy, and *C* is carbon dioxide generated. That is, Equation (1) has that emissions are equal to the number of people times their per capita income, times the energy intensity of the economy, times the carbon intensity of the economy, times the fraction of emissions that is vented to the atmosphere.

Although it is an accounting identity, Equation (1) provides insight into how emissions can be abated. One may reduce the number of people (*P*). This is generally not considered to be a policy option, but a few governments are actively pursuing this strategy (albeit for other reasons than climate change). One may also reduce economic growth (*Y/P*), or induce economic shrink. Again, this is not typically seen as an option for climate policy, but the economic downturn that followed the collapse of the Soviet Union (Victor et al. 2001) and the current depression (IEA 2009) have reduced emissions considerably.

The three right-most terms of Equation (1) are seriously considered for climate policy. First, one may increase the overall energy efficiency of the economy (*E/Y*), that is, deliver the same economic value using less energy. Second, one may decrease the overall carbon intensity of the energy system (*C/E*), that is, deliver the same amount of energy emitting less carbon. Third, one may prevent carbon dioxide from entering the atmosphere (*M/C*), particularly through carbon capture and storage.

None these options is free or easy. Energy is a cost to businesses and households. The market therefore pushes for increased energy efficiency. When energy is cheap, this often means that more services are delivered for the same amount of energy input. When energy is dear, the same services are typically delivered with less energy. Historically, the rate of energy efficiency improvements has ranged between 0.5% and 1.5% per year (Lindmark 2002; Tol et al. 2009). This is quite an achievement considering that this rate is maintained over the long term and applies to often mature technologies.

Suppose for the sake of argument that, in the absence of climate policy, energy efficiency (E/Y) improves by 1% per year, that the economy (Y) grows by 2%, and that the carbon intensity (C/E) is constant. Then, emissions (E) grow by 1% per year. In order to stabilise emissions, the rate of energy efficiency improvement has to double from 1% to 2%. Because of decreasing returns to scale in research and development, doubling the rate of technological progress means that the effort that is being put into improving energy efficiency has to be more than doubled. This is easy to do for a specific technology, but hard across the entire economy. For a specific technology, you would take engineers from their current projects and put them to work on the technology of choice. If you want to accelerate the rate of technological progress for the entire economy, you would need to train additional engineers.

Furthermore, only a fraction of appliances, vehicles and machines are replaced each year (Grubb et al. 1995). That is, technological progress applies to a fraction of the capital stock only. Premature retirement of capital is very expensive. Consider an economy in its steady state, with a savings rate of 20% and a capital stock that is five times as large as output. Then, the depreciation rate of capital is 4% per year – capital is replaced on average every 25 years. If the depreciation rate increases to 5%, technological progress more than triples in the first years. However, the savings rate would need to increase to 25% to finance the additional investment, and consumption would fall by 6%. Furthermore, the rate of technological progress rapidly falls to its original level: More but newer equipment is replaced and these two effects exactly cancel in the long run.

Similar arguments apply to decarbonisation of the energy system (C/E). Energy supply has shifted dramatically in the past (Fouquet 2008). In the early stages of industrial development, carbon-neutral biomass was replaced by coal as the main source of energy, leading to a rapid rise of carbon dioxide emissions. Later, oil and gas started to replace coal. As oil and particularly gas emit less carbon dioxide per unit of energy, this reduced the carbon intensity of the energy supply, but not sufficiently so to reduce emissions (Tol et al. 2009). In times of high energy prices, alternative energy sources gained market share and have established niche applications but never captured the market. At present, non-fossil energy is too expensive for commercial application in the absence of government support.

There are a number of alternative, carbon-free energy sources: biomass, wind, water, wave, tidal, solar, geothermal, and nuclear power (Hoffert et al. 2002; Pacala and Socolow 2004). Hydro- and nuclear power are relatively cheap, but constrained by public opposition. Wave, tidal and geothermal power are experimental technologies, with a few niche applications. Wind power has expanded rapidly on the back of generous subsidies, but its unpredictable nature prevents it from ever attaining a dominant position in the market. Biomass energy and solar power are currently very expensive still, but rapid progress is being made piggy-backing on advances in biotechnology and materials science.

Finally, there is the option to capture carbon dioxide just before it would be released into the atmosphere and store it in a safe place (M/C) (Herzog 2001). Carbon capture, transport, and storage are all proven technologies, but have never been applied at the scale needed to reduce emissions. Cost is a major issue with carbon capture. The process significantly increases the capital invested in a power plant, while a substantial part of the energy generated is used to capture carbon. Reliability and safety are main issues with carbon storage. Leaky storage postpones rather than prevents emissions, and accidental releases of a large amount of carbon dioxide may kill animals and humans. At present, there are various plans to build demonstration plants for carbon capture and storage. Unlike energy efficiency improvement and fuel switching, carbon capture and storage always requires policy intervention. It is an end-of-pipe technology whose sole purpose is greenhouse gas emission reduction.

3.2. Drivers of Abatement Costs

The costs of emission reduction depend on several layers of facts, processes, and circumstances (Weyant 1993).

At the basis lies the fact that emission reduction requires that technologies or fuels be used that otherwise would not have been used, or to a lesser extent. For instance, power generators may switch from coal (4 c/KWh) to gas (6 c/KWh) or wind (8 c/KWh). Homeowners may invest in loft insulation. This part of the cost is obvious and relatively easy to estimate.

If energy and energy services are more expensive, then the cost of living and the cost of doing business go up. This implies that, in absolute terms, households save less and companies invest less. As a result, the growth rate of the economy falls. Different sectors of the economy use different amounts of energy. As climate policy pushes up the price of energy, some sectors will be more affected than other ones. The deceleration of economic growth will be strongest in energy-intensive sectors, and weakest in energy-extensive sectors. The sectoral composition of the economy will be different with and without climate policy.

The same is true internationally. If different countries run their climate policies at different intensities – e.g., a high carbon tax in one country, a low carbon tax in another, and a zero tax in a third country – then the growth rate of the most ambitious countries decelerates relative to the growth rates of other countries as production and investment shifts to the countries with lowest energy costs. This is particularly pronounced if countries are otherwise similar and transport costs are low.

This effect is even stronger if companies within the same sector and country are regulated differently. This would happen if the regulator proscribes a technological add-on which fits well with some machinery but not with other equipment; or if a permit system affects only large polluters. In such cases, certain companies gain a competitive advantage not because they serve the customer best (which creates wealth) but because they match the regulator (which creates rent, that is, redistributes wealth).

There may be excess welfare losses even if climate regulation affects every emitter in the same way at the margin. This is because of tax interactions. One may be tempted to think that second-order effects are minor. A carbon tax, say, would affect the cost of living and hence real wages. This would have a negligible effect on the labour market – unless there are substantial wage taxes, which would amplify the impact of the carbon tax on welfare.

The above holds for all types of regulation to reduce greenhouse gas emissions. There are two types, however, for which there is an additional twist. The regulator would gain substantial revenue if emissions are reduced through a carbon tax, or through a system of tradable permits with auctioning of those permits. That revenue can be used to offset the negative impact on welfare. Particularly, the tax or auction revenue should be used to reduce the most distorting tax in the economy. In that case, the overall distortionarity of the tax system falls, and welfare improves – perhaps sufficiently so to more than compensate the welfare losses due to emission reduction per se (Goulder 1995; Parry et al. 1999).

Emission reduction policy pressures emitters to change their behaviour. It would also lead to greater investments in research and development on energy efficiency and alternative sources of energy. That R&D would reduce the direct costs of emission reduction – that is, the additional price one would pay for energy-saving equipment or carbon-neutral energy. However, this does not necessarily imply an improvement in welfare. The reason is that the capacity to do R&D is limited. An increase in R&D in energy implies a decrease in R&D elsewhere, and the welfare gains in energy would be more than offset by welfare losses elsewhere (assuming that the allocation of R&D effort was not distorted against energy before climate policy). Welfare would improve only if climate policy would stimulate an increase in all R&D (Goulder and Schneider 1999; Smulders and de Nooij 2003).

3.3. Estimates of Abatement Costs

The IPCC[8] periodically surveys the costs of emission abatement (Barker et al. 2007; Hourcade et al. 1996; Hourcade et al. 2001); there are the EMF[9] overview papers (Weyant 1993; Weyant 1998; Weyant 2004; Weyant et al. 2006; Weyant and Hill 1999), and there a few recent meta-analyses as well (Barker et al. 2002; Fischer and Morgenstern 2006; Kuik et al. 2009; Repetto and Austin 1997). There are two equally important messages from this literature. First, a well-designed, gradual policy can substantially reduce emissions at low cost to society. Second, 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, and the feasibility of meeting a particular target decreases if:

- different countries, sectors, or emissions face different explicit or implicit carbon prices (Boehringer et al. 2006b; Boehringer et al. 2006a; Boehringer et al. 2008; Manne and Richels 2001; Reilly et al. 2006);

- the carbon prices rises faster or more slowly than the consumption discount rate (Manne and Richels 1998; Manne and Richels 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).

Unfortunately, each of these four conditions is likely to be violated in reality. For instance, only select countries have adopted emissions targets. Energy-intensity sectors that compete on the world market typically face the prospect of 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 enhance energy security and create jobs. Climate policy is superimposed on energy and transport regulation and taxation.

The costs of emission reduction would also increases 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.[10]

There are only a handful of studies that estimate the economic impact of the EU emissions and energy targets for 2020 – roughly, the EU strives for a 20% reduction in

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

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

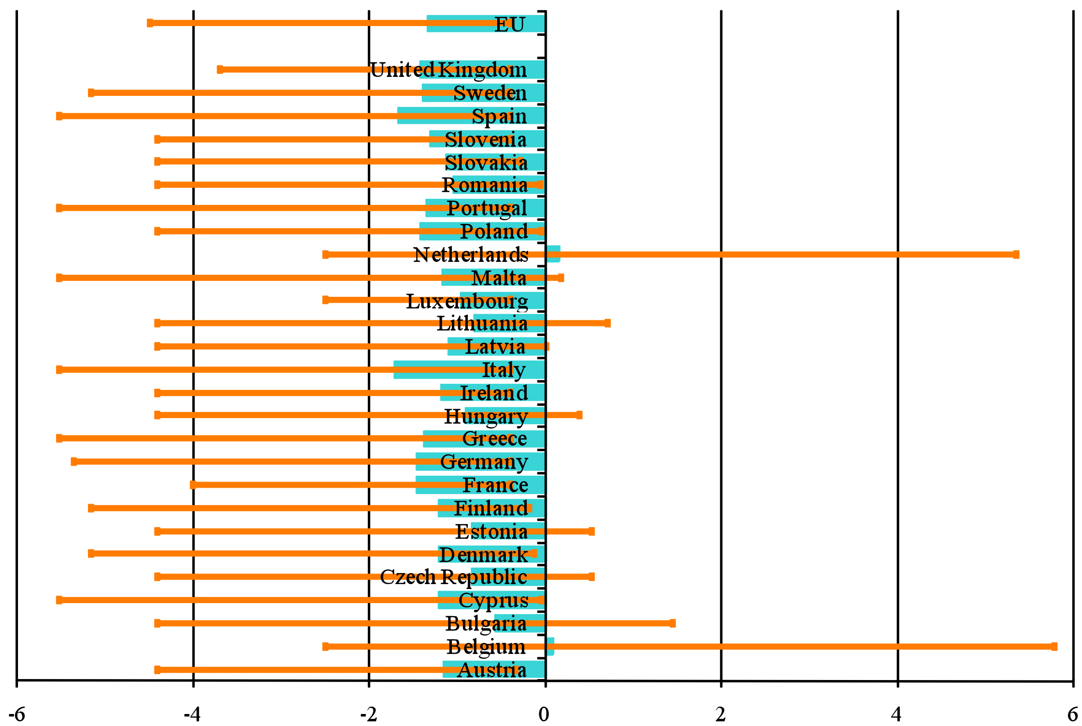
[10] Note that the rate of technological progress is largely beyond the control of policy makers, at least between now and 2020.

greenhouse gas emissions and a 20% share of renewables in total energy supply. The European Commission commissioned an impact assessment (Capros and Mantzos 2000), and the Energy Modeling Forum organised an independent review (Bernard and Vielle 2009; Böhringer et al. 2009a; Böhringer et al. 2009b; Kretschmer et al. 2009). To the best of my knowledge, no Member State ordered a separate impact assessment; and no academic (outside the EMF) studied the implications of the policies.

(Capros and Mantzos 2000) report cost estimates for every single country of the European Union. They report results for a large number of scenarios; I here use two, one that is slightly more economically sophisticated than the actual policy and one that is slightly less sophisticated. (Bernard and Vielle 2009; Kretschmer et al. 2009) and (Bernard and Vielle 2009) report estimates for a number of regions of the EU, while (Boeters and Koornneef 2010) and (Böhringer et al. 2009a) report for the EU as a single region. I assume homogeneity within the modelled regions, that is, every Member State within a region has the same impact as the region as a whole. Thus, there are six estimates for each country.

Figure 2 shows the average of the five estimates for the welfare loss per country in 2020. Table 3 has all the results. The EU as a whole would lose 1.3% of welfare, with a range of 0.4% to 4.5%. Spain and Italy would be hit hardest with a mean loss of 1.7%. Belgium and the Netherlands would see positive impacts (when average across the five studies) of 0.1% and 0.2%. Note that 4 out of 5 models estimate a negative effect for these countries. (Bernard and Vielle 2009) are the exception, predicting a substantial improvement in the competitive position of these countries. The Netherlands particularly benefits from a lower oil price (the feedstock for its export-oriented

Figure 2. The 2020 welfare impact (percentage) of the EU 20/20/2020 package per Member State and for the EU as a whole; the bars show the average of six published estimates; the lines indicate the range of results.



chemical industry) and higher (absolute) margins on transport and re-export. For the EU as a whole, however, climate policy is costly. A loss of 1.3% is of course not dramatic, but it is projected to occur over the space of only eight years (2013-2020), so that roughly one in every ten years of growth is lost. I'll discuss below whether this investment is justified.

Table 3. The impact of the EU 20/20/2020 package on welfare (%) in 2020.

	Mean	StDev	PACE	DART	GEMINI-E3	WorldScan	PRIMES	PRIMES
Austria	-1.2	1.6	-0.8	-4.4	-0.5	-0.4	-0.6	-0.3
Belgium	0.1	2.9	-0.8	-2.5	5.8	-0.4	-0.9	-0.7
Bulgaria	-0.6	2.1	-0.8	-4.4	-0.5	-0.4	1.4	1.2
Cyprus	-1.2	2.1	-0.8	-5.5	-0.5	-0.4	-0.1	-0.1
Czech Republic	-0.8	1.8	-0.8	-4.4	-0.5	-0.4	0.5	0.5
Denmark	-1.2	1.9	-0.8	-5.2	-0.5	-0.4	-0.4	-0.1
Estonia	-0.8	1.8	-0.8	-4.4	-0.5	-0.4	0.5	0.5
Finland	-1.2	1.9	-0.8	-5.2	-0.5	-0.4	-0.3	-0.2
France	-1.5	1.5	-0.8	-4.0	-2.6	-0.4	-0.5	-0.5
Germany	-1.5	1.9	-0.8	-5.4	-1.0	-0.4	-0.7	-0.6
Greece	-1.4	2.0	-0.8	-5.5	-0.5	-0.4	-0.5	-0.6
Hungary	-0.9	1.8	-0.8	-4.4	-0.5	-0.4	0.2	0.4
Ireland	-1.2	1.6	-0.8	-4.4	-0.5	-0.4	-0.6	-0.5
Italy	-1.7	1.9	-0.8	-5.5	-1.9	-0.4	-1.1	-0.7
Latvia	-1.1	1.6	-0.8	-4.4	-0.5	-0.4	-0.6	0.0
Lithuania	-0.8	1.9	-0.8	-4.4	-0.5	-0.4	0.5	0.7
Luxembourg	-1.0	0.8	-0.8	-2.5	-0.5	-0.4	-1.0	-0.7
Malta	-1.2	2.2	-0.8	-5.5	-0.5	-0.4	0.2	0.0
Netherlands	0.2	2.7	-0.8	-2.5	5.3	-0.4	-0.5	-0.3
Poland	-1.4	1.8	-0.8	-4.4	-2.9	-0.4	-0.1	-0.1
Portugal	-1.4	2.0	-0.8	-5.5	-0.5	-0.4	-0.5	-0.5
Romania	-1.0	1.7	-0.8	-4.4	-0.5	-0.4	-0.1	-0.1
Slovakia	-1.1	1.6	-0.8	-4.4	-0.5	-0.4	-0.4	-0.3
Slovenia	-1.3	1.5	-0.8	-4.4	-0.5	-0.4	-1.0	-0.8
Spain	-1.7	2.0	-0.8	-5.5	-2.1	-0.4	-0.9	-0.4
Sweden	-1.4	1.9	-0.8	-5.2	-0.5	-0.4	-0.8	-0.8
United Kingdom	-1.4	1.5	-0.8	-3.7	-2.8	-0.4	-0.4	-0.4
EU	-1.3	1.6	-0.8	-4.5	-1.3	-0.4	-0.6	-0.5
First best	-0.7	0.6	-0.5	-2.0	-0.7	-0.3	-0.6	-0.5
EU (30%)	-2.9	2.7	-1.7	-7.5	-2.7		-1.1	-1.4

Sources: PACE (Böhringer et al. 2009a), DART (Kretschmer et al. 2009), Gemini-E3 (Bernard and Vielle 2009), WorldScan (Boeters and Koornneef 2010), PRIMES (Capros et al. 2008); PRIMES appears twice as it published estimates based on an overly optimistic and an overly pessimistic interpretation of the rules on CDM.

Table 4. The cost of carbon (€/tCO_2) inside and outside the EU ETS in 2020.

	Mean	StDev	PACE	DART	GEMINI-E3	WorldScan	PRIMES	PRIMES
Austria	42	33	106	33	15	44	22	30
Belgium	175	281	106	103	743	44	22	30
Bulgaria	42	33	106	33	15	44	22	30
Cyprus	59	51	106	137	15	44	22	30
Czech Republic	42	33	106	33	15	44	22	30
Denmark	79	94	106	259	15	44	22	30
Estonia	42	33	106	33	15	44	22	30
Finland	79	94	106	259	15	44	22	30
France	120	128	106	158	357	44	22	30
Germany	72	48	106	83	145	44	22	30
Greece	59	51	106	137	15	44	22	30
Hungary	42	33	106	33	15	44	22	30
Ireland	42	33	106	33	15	44	22	30
Italy	63	48	106	137	35	44	22	30
Latvia	42	33	106	33	15	44	22	30
Lithuania	42	33	106	33	15	44	22	30
Luxembourg	53	41	106	103	15	44	22	30
Malta	59	51	106	137	15	44	22	30
Netherlands	116	139	106	103	389	44	22	30
Poland	39	36	106	33	0	44	22	30
Portugal	59	51	106	137	15	44	22	30
Romania	42	33	106	33	15	44	22	30
Slovakia	42	33	106	33	15	44	22	30
Slovenia	42	33	106	33	15	44	22	30
Spain	86	63	106	137	174	44	22	30
Sweden	79	94	106	259	15	44	22	30
United Kingdom	126	143	106	151	400	44	22	30
EU	75	52	106	95	155	44	22	30
ETS	32	22	15	35	71	7	30	30
First best	44	22	37	68	72	17	30	39

Sources: PACE (Böhringer et al. 2009a), DART (Kretschmer et al. 2009), Gemini-E3 (Bernard and Vielle 2009), WorldScan (Boeters and Koornneef 2010), PRIMES (Capros et al. 2008) ; PRIMES appears twice as it published estimates based on an overly optimistic and an overly pessimistic interpretation of the rules on CDM.

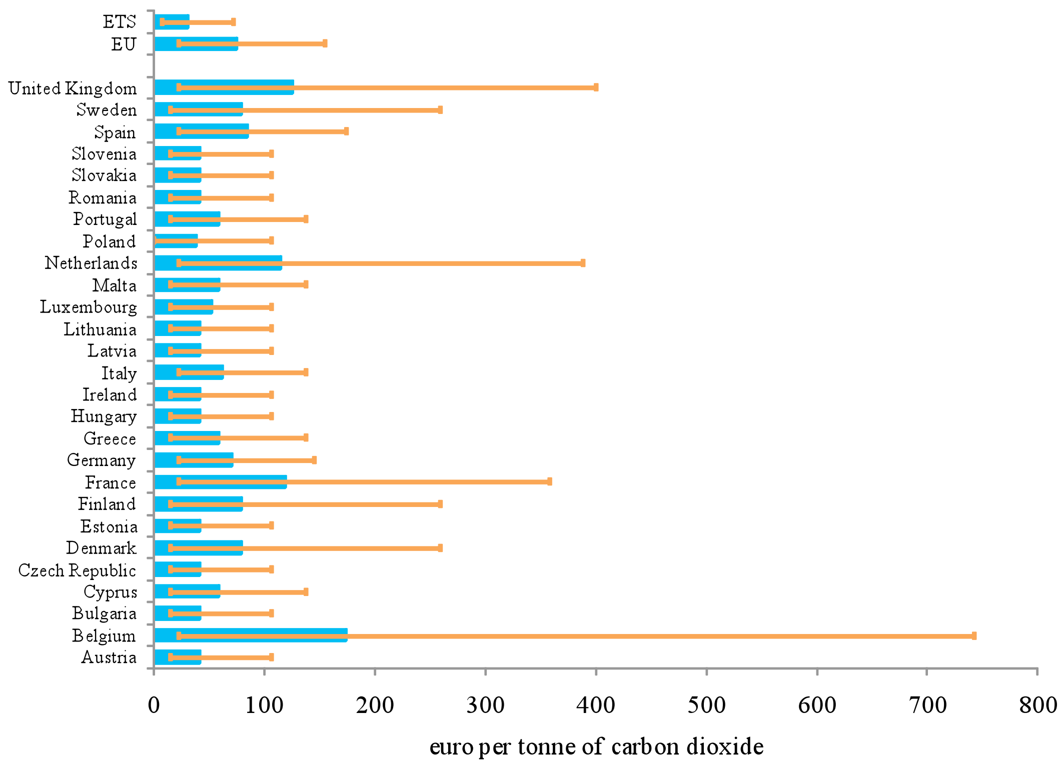
Böhringer et al. (2009b) show that the 1.3% loss is at least a factor two higher than it could be.

This is because of the EU pays lip service only to cost-efficacy in the regulation of greenhouse gas emissions. Particularly, instead of one price for carbon, there are at least 28 prices: one in the ETS, and at least one per Member State for non-ETS emissions. Furthermore, climate policy is also used to serve other policy targets, particularly on renewables and energy security. Besides, climate policy is placed on top of pre-existing regulations.

Table 3 also shows an estimate of the costs if the target is raised to 30%. No primary estimates, so I extrapolate from the 20% assuming a quadratic cost function.[11] The costs more than double, to 2.9% of GDP in 2020, with a range of 1.1-7.5% of GDP. These results are illustrative only, but they do indicate the potential costs of adopting a more stringent target.

Figure 3 shows the price of carbon in 2020. Table 4 shows the detailed results. The price in the EU Emissions Trading System (ETS) is some €32/tCO_2, with a range from €7/tCO_2 to €71/tCO_2. The (unweighted) average price outside the ETS is much higher: €75/tCO_2. The non-ETS carbon price exceeds €32/tCO_2 in four countries: Belgium (€175/tCO_2), UK (€126/tCO_2), France (€120/tCO_2) and the Netherlands (€116/tCO_2). Although some Eastern and Southern European countries have been allocated more non-ETS emission rights than they will likely need, the non-ETS price of carbon is zero in one country (Poland) in one model (Bernard and Vielle 2009) only. This is because there is a restricted trade in non-ETS allowances. The non-ETS market price settles on €42/tCO_2; this creates a scarcity in all countries and scenarios but one.

Figure 3. The 2020 price of carbon (2005 euro per tonne of carbon dioxide) for the EU 20/20/2020 package per Member State (non-ETS), for the EU one average (non-ETS) and for the Emissions Trading System (ETS); the bars show the average of six published estimates; the lines indicate the range of results.



[11] Note that WorldScan did not publish sufficient information to allow such extrapolation.

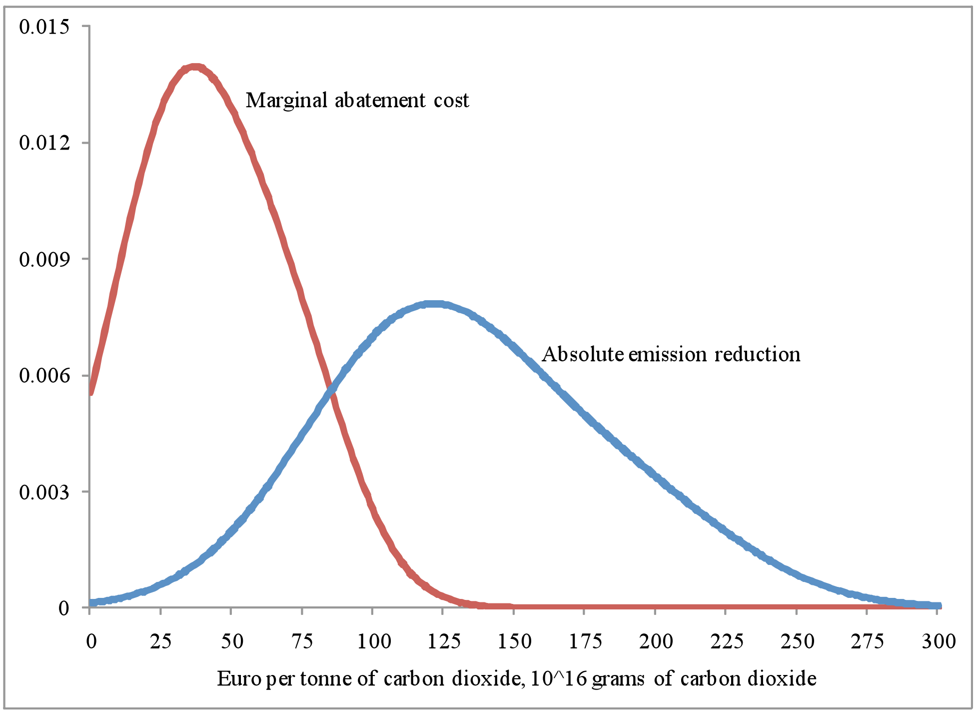
4. A benefit-cost analysis of EU climate policy for 2020

To a first approximation, a benefit-cost analysis of greenhouse gas emission reduction policy requires that the marginal costs of emission reduction be equal to the marginal benefits of emission reduction. When evaluating climate policy for a single continent over an eight year period, the approximation is in fact fairly accurate.

Note that EU emissions are a small and shrinking fraction of global emissions. Therefore, emission reduction in the EU only, and only between 2013-2020 can have a minimal effect on climate change and its impacts. This argument is irrelevant, however, as it militates against any long-term investment programme. For example, by the same reasoning, it is pointless to teach children how to write the letter "a" as it is useless without the rest of the alphabet, or if no other children would learn how to read and write. Emission reduction by any jurisdiction in any legislative period necessarily has a small effect. That is no reason not to do it. It is a reason to evaluate costs and benefits at the margin.

Section 2 estimates the marginal damage costs of climate change. Section 3 estimates the marginal costs of emission reduction in the EU. The question whether EU policy passes the benefit-cost test is, at first sight, simply a matter of comparing the two estimates. However, there are three complications. Firstly, EU policy is not cost-effective. The same target can be met at a much lower cost (Böhringer et al. 2009b). As cost-effectiveness is a condition for efficiency, this alone means that EU policy fails the benefit-cost test. I therefore compare the marginal damage costs of climate change (Table 2) to the marginal abatement costs for the *ideal* policy (Table 4, bottom row) rather than for the *actual* policy.

Figure 4. The probability density functions of the marginal abatement costs and the absolute emission reduction in the EU in 2020.



Secondly, both marginal costs and marginal benefits are rather uncertain. I therefore compute the probability that EU policy meets the benefit-cost test. Furthermore, I show what the target would have been had the EU adopted an expected cost-benefit analysis.

I take the probability density function of the marginal damage costs of climate change from (Tol 2009a). Table 2 displays some of the characteristics. Note that, for this study, I converted the estimates of the social cost of carbon to 2007 Euro per tonne of carbon dioxide.

I derive the probability density function of the marginal abatement costs in the same manner as (Tol 2009a) derived the uncertainty about the social cost of carbon. Each of the six estimates of the marginal abatement costs in Table 4 is assumed to be the central estimate of a Normal distribution.[12] The standard deviation of each of the six estimates is assumed to be equal to the standard deviation between the six estimates. The joint probability density is the rescaled sum of the individual probability densities.[13] See Figure 4.

As the probability densities of the marginal abatement costs and the marginal damages costs are mutually independent, the bivariate probability density is the outer product of the two. The chance of meeting the benefit-cost test is then the integral over the bivariate probability density under the condition that the marginal abatement costs is less than or equal to the marginal damage cost.

If all estimates of the marginal damage costs are used, there is a chance of 43% that the benefit-cost test is met (cf. Table 5). If only estimates with a zero percent pure rate of time preference are used, this chance increases to 60%. It falls to 26% for a one percent pure rate of time preference, and to 4.5% for a three percent pure rate of time preference. EU climate policy can be justified by great care for the future (i.e., a low discount rate) and by substantial aversion to risk (i.e., accepting a low probability of passing the benefit-cost test).

Table 5 also shows the expected value of the benefits, which follows from the bivariate distribution of absolute abatement[14] (Figure 4) and social cost of carbon. The expected benefit varies between 7 and 102 billion euro, depending on the pure rate of time preference assumed (if any). The expected cost is 209 billion euro, 1.3% of projected GDP in 2020,[15] if emission abatement is implemented as planned. The benefit-cost ratio ranges between 0.03 and 0.49. If emission abatement is implemented in the cost-effective manner, expected costs fall to 116 billion euro, 0.7% of GDP. The benefit-cost ratio increases to between 0.06 and 0.88.

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[12] Unlike the impacts of climate change, there is no reason to believe that the uncertainty about the costs of emission reduction is asymmetric or fat-tailed.

[13] Vote-counting as used here, while not entirely appropriate, leads to a wider spread than using Bayes' rule.

[14] The distribution of absolute abatement is constructed as above: there are four best guesses, one each from the four models; the standard deviation of each best guess is assumed to be equal to the standard deviation between the best guesses; each individual estimate is assumed to be normally distributed; and the joint distribution is based on aggregating and rescaling the individual distributions.

[15] The models were all calibrated to the same scenario of economic and population growth.

Table 5. Cost-benefit analysis of the EU 20/20/2020 package: Four alternative estimates of the social cost of carbon (cf. Table 2), the probability of the EU policy meeting the benefit-cost test, the expected value of the benefit, and the benefit-cost ratio for planned and cost-effective implementation of the EU policy.

	All	0%	1%	3%
Social cost of carbon (€/tCO_2)	49	76	24	5
Probability of EU policy meeting the benefit-cost test	43.1%	60.0%	26.1%	4.5%
Expected benefit (bln €)	66.1	102.2	39.1	7.1
Benefit-cost ratio (policy as proposed @ 209.3 bln €)	.32	.49	.15	.03
Benefit-cost ratio (cost-effective policy @ 115.8 bln €)	.57	.88	.28	.06

At first sight, the benefit-cost ratios seem to be at odds with the estimated probabilities of meeting in the benefit-cost test, also displayed in Table 5. This illustrates the third problem with doing a benefit-cost analysis of a regional solution to a global problem. The results of the marginal/probability and total/expected cost analysis deviate from one another because the former assumes that the same carbon tax is applied outside the EU whereas the latter only considers the costs and benefits of emission reduction in Europe. Equating the marginal costs of emission reduction to the marginal benefits would increase welfare – if the Pigou tax is applied to all emissions. However, only European emissions are regulated. Therefore, the benefits are only a fraction of the benefits of a global abatement policy – but the costs to Europe are the same.[16]

Cost-benefit analysis would recommend that level of emission abatement for which the expected marginal damage cost equals the expected marginal abatement cost.[17] The latter is difficult to ascertain as much of the variation between my six estimates of the marginal abatement costs is explained by differences in the no-additional-climate-policy scenarios used by the models. Therefore, I do the cost-benefit analysis separately for each model. I assume that the abatement cost curve is quadratic in emission reduction from baseline. The marginal abatement cost curve is therefore linear, and the "optimal" abatement level follows from rescaling the abatement level used by each model.

Table 6 shows the results. The EU target is to cut 2020 emissions to 20% below 1990 emissions. This implies a cut of 19% to 30% below baseline emissions, depending on the model. If the pure rate of time preference is 3% per year, the target falls to 1.4-2.5% from the base year (1990), which is 1.6-2.7% from the baseline. For a 1% pure rate of time preference, the optimal target is 6.9 to 12% from base year (7.6 to 13% from baseline). For a 0% pure rate of time preference, the optimal target exceeds the EU target: 22% to 38% from base year (24% to 42% from baseline). If all estimates of the social cost of carbon are considered regardless of the discount rate, two models suggest that the EU target is too stringent and two models suggest that it is too lenient. The optimal target is 14% to 24% from base year (15% to 27% from baseline). As above, the EU emission reduction targets can be justified only with a low discount rate.

[16] In fact, costs are higher because of leakage (Bernard and Vielle 2009).

[17] Assuming, as above, that all emissions are regulated.

Table 6. Proposed and optimal emission reduction in 2020.

	Mean	StDev	PRIMES	PACE	DART	Gemini-E3
From base year (1990)						
EU	20.0%	-	20.0%	20.0%	20.0%	20.0%
All	20.7%	4.9%	24.4%	24.6%	19.6%	14.2%
0%	32.1%	7.6%	37.8%	38.2%	30.4%	22.0%
1%	10.1%	2.4%	11.9%	12.1%	9.6%	6.9%
3%	2.1%	0.5%	2.5%	2.5%	2.0%	1.4%
From base line (2020)						
EU	22.9%	4.9%	18.8%	20.3%	29.9%	22.7%
All	22.6%	5.4%	26.6%	26.9%	21.5%	15.5%
0%	35.1%	8.4%	41.3%	41.7%	33.3%	24.0%
1%	11.1%	2.6%	13.0%	13.2%	10.5%	7.6%
3%	2.3%	0.5%	2.7%	2.7%	2.2%	1.6%

5. Discussion and conclusion

This paper comes in three parts. I first survey the impacts of climate change. I next survey the impacts of greenhouse gas emission reduction, particularly in the European Union. I then bring the two strands together in a cost-benefit analysis of the EU targets for 2020.

There are positive and negative impacts of climate change. Positive impacts dominate in the short run (when climate change is largely beyond human control), but negative impacts dominate in the medium and long run. Impact estimates are uncertain, incomplete and controversial but the available evidence suggests that a century of climate change is most likely about as bad as losing one year of economic growth and probably less bad than losing a decade of growth.

Emission reduction can be done cheaply, but this requires that emissions gradually deviate from the baseline scenario and that policy is well-designed and takes account of previous regulations. I find that planned EU policy does not meet these conditions. It is twice as expensive as needed, and would cost the equivalent of one in ten years of economic growth.

Comparing the orders of magnitude of the costs of emission reduction and the impacts of climate change suggests that the EU targets are not like to meet the benefit-cost test. This is indeed the case. For a standard discount rate, the benefit-cost ratio is rather poor (1/30). The EU targets become more attractive if policy implementation would be improved or if substantial weight would be placed on the remote future, but one would need to take an extreme position to justify the 20% emission reduction target for 2020.

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