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Abstract

Climate change is a small problem with a simple solution. A century of climate change causes as much damage as skipping a year, perhaps a decade of economic growth. Stabilizing the atmospheric concentrations of greenhouse gases can be achieved at a minimal cost, provided policy is smart and gradual. Current climate policy has been captured by rent-seekers and millennialists. Climate policy would be more effective if it would capitalize on the ongoing revolution in energy supply.

Keywords

Climate change; climate policy; climate economics

The problem

Greenhouse gas are transparent to visible light but not to infrared radiation. Energy from the sun thus easily enters the planet. Energy re-emitted by Earth finds it more difficult to leave: It is absorbed by greenhouse molecules in the atmosphere, and scattered in any direction – including back to the surface. This is the natural greenhouse effect. Planet Earth is warmer than it would have been without greenhouse gases in the atmosphere. If greenhouse gas concentrations would increase, then you would expect from first principles that the planet would become hotter.

The concentrations of three of the main greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), have increased steadily since the start of the Second Industrial Revolution (1750 say). The increase is dramatic if we consider that greenhouse gas concentrations had been more or less stable since the last Ice Age and the Agricultural Revolution. The increase in concentrations is no surprise as greenhouse gas emissions are associated with fossil fuel combustion and deforestation (CO_2), with population growth and affluence via meat and rice production and waste generation (CH_4), and with artificial fertilizers (N_2O).
Over the course of the 20th century, a rise in temperature has been observed, as well as a decrease in snow cover and a rise in sea level (due to thermal expansion as water warms).

The impact of the enhanced greenhouse effect on the climate does not follow from first principles alone. The climate is a complex system. Any initial change sets in motion a cascade of feedback effects, some positive and some negative. The most powerful feedbacks relate to water. A warmer atmosphere contains more water vapour, and water vapour is a powerful greenhouse gas. Cloud formation would be affected. Clouds can either cool – e.g., on a summer day – or heat – e.g., in a winter night. Ice is white and reflects sunlight. Water is dark and absorbs energy. Climate is also affected by a range of other things, some natural – variations in solar radiation, volcanoes, ocean dynamics – and some human – aerosols, land use change, nutrients.

State of the art climate models include these feedbacks and many more. These models project that the warming observed in the 20th century will continue during the 21st century and beyond. Models differ on the detail, though, and the range of future projections is enlarged because emission projections are highly uncertain too. Besides warming, climate change would also entail changes in wind and precipitation patterns.

Impacts of climate change

Some people argue that climate change is bad, as all change is for the worse. This is an odd position. Universal education for girls would be a radical departure from the past, but is generally welcomed. Change itself is neutral. Some change is good; other change is bad; most change is good for some and bad for others.

The impacts of climate change are many and diverse. The question whether climate change is beneficial or detrimental, big or large, depends on sector, location and time. Aggregate indicators are needed to assess whether climate change is, on balance, a good thing or a bad thing, and whether it is small or large relative to the many other problems that we have.

Some people worry about the unique and the vulnerable, such as atoll islands or butterflies. If you are so inclined, climate change is a big concern. Local extinctions of butterfly species have been documented with climate change as the likely cause. Many butterflies have difficulty crossing open spaces and thus cannot migrate. If the limited climate change of the past century already caused such problems, the more rapid climate change of this century must be disastrous (from this perspective). Stringent climate policy is thus justified (Smith et al. 2001).

Other people only care about systemic impacts of climate change, such as changes in ocean currents and the melting of the polar ice caps. If you are so inclined, then climate policy can wait. The probability of these scenarios is minute, and it is not known how greenhouse gas emission reduction would affect those probabilities (Smith et al. 2001).

Yet other people may care about the impact of climate change on total economic welfare, or about the distribution of that welfare. Figure 1 shows the 17 published estimates of the total economic impact of climate change (Tol 2009;Tol 2013b). The numbers should be read as follows: A global warming of 2.5ºC would make the average person feels as if she had lost 0.9% of her income. (0.9% is the average of the 10 dots at 2.5ºC.)

Most of these estimates were derived as follows. Researchers used models to estimate the many impacts of climate change for all parts of the world, estimated the values of these impacts, multiplied the quantities and prices, and added everything up. This is the so-called enumerative method.
Other estimates involve regressions of some sort of a welfare measure on climate. Agricultural land prices, for instance, reflect the productivity of the land and hence the value of the climate that allows plants to grow. The main advantage of the statistical method is that is based on actual behaviour (rather than modeled behaviour as in the enumerative method). The main disadvantage is that climate *variations over space* are used to derive the impact of climate *change over time*.

Yet other estimates elicit the views of supposed experts, or use physical impact estimates to shock a computable general equilibrium model and derive a welfare estimate that takes all market interactions into account.

Figure 1 contains many messages. There are only 17 estimates, a rather thin basis for any conclusion. Statements that climate change is the biggest (environmental) problem on humankind are simply unfounded (that is to say, we do not know whether it is true or not).

The 10 estimates for 2.5ºC show that researchers disagree on the sign of the net impact. Climate change may lead to a welfare gain or loss. At the same time, researchers agree on the order of magnitude. The welfare change caused by climate change is equivalent to the welfare change caused by an income change of a few percent. That is, a century of climate change is about as good/bad as a year of economic growth.

Considering all 17 estimates, it is suggested that initial warming is positive on net, while warming further warming would lead to net damages. This does not imply that greenhouse gas emissions should be subsidized. In Figure 1, the total impacts turn negative at a global warming of 2.2ºC. More importantly, the incremental impacts turn negative at a global warming of 1.1ºC. Because of the slow workings of the climate system and the large inertia in the energy sector, a warming of 2.2ºC can probably not be avoided and a warming of 1.1ºC can certainly not be avoided. That is, the initial net benefits of climate change are sunk benefits. We will reap these benefits no matter what we do to our emissions.

The uncertainty is rather large, however. The error bars in Figure 1 depict the 67% confidence interval. This is probably an underestimate of the true uncertainty, as experts tend to be overconfident and as the 17 estimates were derived by a group of researchers who know each other well.

The uncertainty is right-skewed. Negative surprises are more likely than positive surprises of similar magnitude. This is true for the greenhouse gas emissions: It is easier to imagine a world that burns a lot of coal than a world that rapidly switches to wind and solar power. It is true for climate itself: Feedbacks that accelerate climate change are more likely than feedbacks that dampen warming. The impacts of climate change are more than linear: If climate change doubles, its impacts more than double. Many have painted dismal scenarios of climate change, but no one has credibly suggested that climate change will make us all blissful. In that light, the above conclusion needs to be rephrased: A century of climate change is no worse than losing a decade of economic growth.

The right extreme of Figure 1 is interesting too. At 3.0ºC of warming, impacts are negative, deteriorating, and accelerating. It is likely that the world will warm beyond 3.0ºC. Yet, at that point, estimates stop. After that, there is extrapolation and speculation.

From a policy perspective, the marginal impact is more relevant than the total impact. This is because optimal climate policy requires equating the marginal costs of greenhouse gas emission reduction to its marginal benefits. Intuitively, climate change is a long-term, global problem. A single policy maker can only hope to change climate change by a little bit. The benefits of that are measured at the margin.

The marginal impact of greenhouse gas emissions is the damage done by emitting an additional tonne of, say, carbon dioxide. It is known as the marginal damage cost, and as the social cost of carbon. It is the change in the net present value of the monetized impacts due to a small change in emissions, normalized by those emissions. Because of symmetry, the marginal damage of a small increase in emissions equals the marginal benefits of a small reduction in emissions. If the emissions trajectory is optimal, then the social cost of carbon equals the Pigou tax: The price we should put on greenhouse gas emissions if we wish to optimize net present welfare. Estimates of the social cost of carbon thus tell us what to do, how intensive climate policy should be, how much energy rises should be raised. It is a normative concept.

There have been many estimates of the marginal damage cost of carbon dioxide, the latest count standing at 759 (Tol 2009;Tol 2013b). At first sight, this is strange. Figure 1 shows only 17 estimates of the total impact of climate change. With 17 estimates of the total, how can there be 759 estimates of its first partial derivative? The answer is that there are 17 *comparative-static* estimates of the total impact of climate change *on the current economy* and *for a particular scenario*. The static results in Figure 1 need to be turned into dynamic ones by assuming a particular scenario for emissions and climate change, by assuming a scenario for development and the evolution of adaptive capacity, and by assuming functional forms of the relationship between impacts on the one hand and climate and development on the other. Furthermore, impacts need to be aggregated over time, over space, and over states of the world. This introduces many additional degrees of freedom, which explains the proliferation of estimates of the marginal damage cost of carbon dioxide.

Figure 2 summarizes the many estimates in a cumulative density function (CDF). The CDF shows that, if all published estimates are considered, there is 42% chance that the marginal damage cost is less that \$200/tC and a 58% chance that it is greater.

Figure 2 also illustrates the power of one of the most important parameters: The pure rate of time preference (PRTP). The pure rate of time preference is the utility discount rate. It measures how much we care about the future for the sake of it being then not now. The sample is split into four: Estimates that use a pure rate of time preference of 0%, 1% or 3% are shown, while other estimates (a handful only) are ignored. The lower the discount rate you use, the more you care about the future, the more you care about climate change, and the higher the marginal damage cost. The median estimate, for instance, is \$35/tC for a 3% pure rate of time preference, \$156/tC for 1% rate, and \$471/tC for 0% rate.

The discount rate has another effect. The CDF for all estimates does not reach unity, that is, there is a chance that the carbon tax should be greater than \$1,000/tC. This is entirely driven by the estimates that use a pure rate of time preference of 0%. For a higher rate, the CDF rapidly converges to one. This means that the discount rate not only discounts the impacts of climate change, but also the uncertainty about the impacts. This is intuitive. As we look further into the future, the uncertainty becomes ever larger. The discount rate curtails how far we look into the future, and thus how much uncertainty we have to contend with.

Impacts of emission reduction

Figure 3 shows global carbon dioxide emissions between 1970 and 2008 CO_2 emissions rose by 2.1% per year. The Kaya identity allows us to interpret past trends. Population growth was 1.5% per year over the same period. Emissions per capita thus rose by 0.6% per year. Per capita income rose by 1.5% per year, again slightly slower than the emissions growth rate. Total income thus rose by 3.0% per year, much faster than emissions. This is primarily because the energy intensity of production fell by 0.9% per year. The carbon intensity of the energy system also fell, but only by 0.01% per year.
The Kaya identity also allows us to assess how emissions can be cut. We would need to reduce population or income, or improve energy or carbon efficiency.

Some murderous regimes in Africa actively seek to reduce the population of their countries. Few democratic countries would seek to emulate this in the name of climate policy. Indeed, population policy is controversial in most democracies. China, however, has often put forward its one-child policy as one of its major contributions to climate policy.

The collapse of the former Soviet Union and its aftermath has shown that reducing the level of per capita income is an effective way of cutting greenhouse gas emissions. The Great Recession further demonstrated the power of economic growth over emissions growth. Promoting slower economic growth is not recommended to a politician seeking re-election.

That leaves us with just two of the four terms in the Kaya identity. Energy efficiency improvements have kept the rise of carbon dioxide emissions in check. Energy efficiency is likely to further improve in the future regardless of climate policy. This is because energy is a cost. A gadget that is the identical to its competitor but uses less energy is more appealing to customers. Companies therefore invest in improving the energy efficiency of their products.

Energy efficiency improvement does not necessarily imply reduced energy use. For instance, the fuel efficiency of the US car fleet was roughly constant between 1980 and 2010. This is a remarkable feat of engineering as, over the same period, the size and weight of cars increased considerably. The gains in fuel efficiency were used not to reduce energy use, but rather to increase comfort. This is known as the rebound effect. Better energy efficiency means lower energy costs means higher energy use. Improving the insulation of homes, for instance, often leads to higher indoor temperatures at the expense of reduced energy use.

Emission reduction costs money. There are various ways to look at this. Without climate policy, greenhouse gas emissions are free. With climate policy, emissions are not. What used to be free is no longer. Therefore, costs have gone up. Alternatively, you can look at this mathematically. Climate policy imposes a new constraint on a maximization problem. If the constraint bites – that is, if emissions are lower than they otherwise would have been – the objective function must fall. Put yet another way, climate policy forces people and companies to use different technologies and different fuels than they would have without climate policy. Without climate policy, these technologies and fuels are available, but people chose not to use them, or not to the same extent. More specifically, climate policy gets people and companies to invest more in energy savings than they would of their own volition, and gets them to switch to more expensive energy sources. That costs money.

As with any other policy, it is difficult to estimate the costs of climate policy. Most policy analysis is done ex ante – before the fact. We study a hypothetical situation, or rather, as a cost estimate is the difference in welfare with and without the policy, two hypothetical situations. If we evaluate past policy, we observe only one history. The “history” without policy is a counterfactual – what would have happened if. Cost estimates therefore must rely on models. We compare two models for ex ante policy analysis, and we compare a model run to reality for ex post policy evaluation. Cost estimates are only as good as the models used.

Not all models are equally good. Some analysts claim that all investments in energy savings are because of climate policy – although in fact energy efficiency has always been improving, well before the advent of climate policy. George W Bush once promised to improve energy efficiency by 14% over a decade – even though the historical trend is 18%/decade in the USA. Similarly, other people claim that all investment in renewable energy can be ascribed to climate policy. Truth is, renewable energy is commercially viable in a number of niche applications. Solar power, for instance, beats other source of electricity if the distance to the grid is sufficiently large.

Estimates of emission reduction costs vary widely, partly because all estimates are model based, and partly because there is little existing climate policy to calibrate models to. Most studies agree, however, that a complete decarbonization of the economy can be achieved at a reasonable cost if policies are smart, comprehensive and gradual.

Models disagree, however, on how much emission reduction would cost. This is illustrated in Table 1 (Clarke et al. 2009): Emission reduction costs vary by an order of magnitude. There are various reasons for this. Modellers make different assumptions about what options are available to reduce greenhouse gas emissions, and at what cost. Obviously, if a model omits an option – say, hydrogen fuel-cells for private transport – or assumes that its costs are high, then that model will find that emission reduction is more expensive. Vice verse, if a model assumes that an option exists – say, unlimited capacity for carbon storage – or puts its costs at a lower level than what is commonly believed, then that model will find that emission reduction is less expensive.

The rate of technological change is a key determinant of future emission reduction costs. The difference in the costs between carbon-neutral energy (solar, wind, nuclear) and carbon-emitting energy (coal, oil, gas), for instance, is a key assumption: Emission reduction would be cheap if solar is only slightly more expensive than coal. That cost difference is known for the present and past, but has to be assumed for the future. If technology progresses faster in carbon-neutral energy than in carbon emitting-energy – say, solar is getting cheaper faster than coal – abatement cost are lower. Different models make different assumptions about the rates of technological progress.

Some models even assume that progress in carbon-saving technologies accelerates in response to climate policy. Other models do not have such a response. This further explains the wide range in cost estimates.

If a model assumes high price elasticities, high substitution elasticities, and rapid depreciation of capital, its cost estimates will be lower than those of a low with low price elasticities, low substitution elasticities, and slow turnover of the capital stock. The latter model assumes that the world of energy use is set in its carbon-intensive ways, which makes it hard and expensive to change course.
Finally, some models assume that, in the scenario without climate policy, greenhouse gas emissions will not grow very fast. Consequently, emission targets are within easy reach. Other models assume rapidly rising emissions, so that a large effort is needed to meet emissions targets.

Table 1 shows results for different policy scenarios. There is one minor variation: Is the long-term target an upper bound for the concentrations in all years, or only in the final year? This makes a difference in any model, as the latter case has fewer constraints than the former case. However, there is so much momentum in both the carbon cycle and the energy system that the difference is small. Besides, you would have to rely on the natural processes in the carbon cycle to remove the excess carbon dioxide from the atmosphere. That puts a limit on the extent of the overshoot: In most cases, it is optimal to approach the target from below.

Some of the models in Table 1, however, assume that biomass power plus carbon capture and storage is a viable option at scale. This is negative-carbon-energy: Plants take up carbon dioxide when growing. In a normal biomass power plant, roughly the same amount of carbon dioxide is released again. But if the carbon is captured and stored, the net effect is that you remove carbon dioxide from the atmosphere. This implies that you can correct excess emissions from earlier years towards the end of the century. In this case, you can overshoot the target in the intermediate years to a larger extent, and costs are saved.

Participation of poorer countries in climate policy is another variation in the policy scenarios shown in Table 1. In some scenarios, every country starts to reduce its emissions from 2015 onwards. In other scenarios, only rich countries do, and poorer countries start considerable later. This has a large impact on the estimated cost of emission reduction. If a fraction of emission is excluded from abatement, the rest will have to be reduced more to meet the same target. As emission reduction costs are more than linear in emission reduction effort, this necessarily drives up the total costs. Furthermore, many of the cheaper emission reduction options can be found in poorer countries, partly because these economies tend to rely on older, less efficient technology, and partly because money buys more in poorer countries.

The concentration target is the third policy variation in Table 1. The more stringent the target, the higher the cost – and costs rise very rapidly from the more lenient to the more ambitious targets. For the most stringent targets, a number of models do not report. That can be for one of three reasons. First, the representation of the carbon cycle disallows the model to meet the target. Second, the representation of emissions and emission reduction disallows the target. Third, the model can meet the target, but the costs are so exorbitant that the modeler refused to report the results. Whatever the reason – physical, technical or political – the most stringent target inTable 1 may well be beyond reach. This is as expected: There are always things than cannot be done. However, the 450 ppm CO_2e target in Table 1 corresponds to a 50-50 chance of meeting the 2ºC target of the European Union and the United Nations.

Figure 4 (Tavoni and Tol 2010;Tol 2013b) complements Table 1. It shows results for the same set of models and the same set of scenarios, but now for the marginal abatement costs. This is best thought of as the carbon tax imposed on all greenhouse gas emissions from all economic activities in all (participating) countries in 2020. Per policy scenario, the models again disagree by an order of magnitude. The initial carbon tax required for meeting the least stringent target is modest, but this escalates with increased stringency.

Figure 4 shows the required carbon tax in 2015. The carbon tax is assumed to increase over time. There are four reasons why money is saved if emission reduction targets are lenient at first. Emission reduction requires changes in behaviour and technology. Behaviour and technology, however, are constrained by durable consumption goods and invested capital. A carbon tax does not reduce the emissions of those households and companies that continue to use the same cars, live and work in the same place and in the same building, and operate the same machinery. In those cases, a carbon tax simply imposes a penalty on investment decisions made in earlier, pre-climate-policy times. This is a deadweight loss to the economy. This deadweight loss falls over time as capital turns over, so that the carbon tax can increase with inducing excessive costs.

Technological change is another reason why emission reduction is expensive in the short term but cheaper in the medium to long term. Carbon-neutral energy is still immature technology. Although fossil fuel technology continues to progress, it is well developed and all the easy improvements have been made. In contrast, we can still expect major technological breakthroughs with solar power and bioenergy. Furthermore, the easily accessible sources of fossil fuels are getting exhausted. So, over time, we expect the costs of fossil fuels to rise and the costs of renewables to fall. As the costs of emission reduction are driven by the difference in costs between fossil and renewable energy, abatement costs should fall over time.

Political economy of climate policy

I argue above that climate change is a relatively small problem that can easily be solved. A casual observer of climate policy and the media would have a different impression. Five things stand in the way of simple solution.

Firstly, there is a demand for an explanation of the world in terms of Sin and Final Reckoning. Although many Europeans are nominally secular, fewer are in practice. The story of climate change is often a religious one: emissions (sin) lead to climate change (eternal doom); we must reduce our emissions (atone for our sins). This sentiment is perhaps stronger in Germanic cultures. It has lead to an environmental movement (a priesthood) that thrives on climate alarmism, often devoid of a factual basis. In order to maximize their membership and income, environmental NGOs meet the demand for scaremongering and moral superiority.

Secondly, climate policy is perfect for politicians. Climate change is a problem that spans centuries. Substantial emission reduction requires decades and global cooperation. A politician can thus make grand promises about saving the world while shifting the burden of actually doing something to her successor and blaming some foreigner for current inaction.

Thirdly, climate policy allows bureaucrats to create new bureaucracies. Climate policy has been a political priority for about two decades. Emissions have hardly budged, but a vast amount of civil servants and a larger amount of consultants and do-gooders have occupied themselves with creating a bureaucratic fiction that something is happening.

Fourthly, besides expanded bureaucracies, climate policy can be used to create rents in the form of subsidies, grandparented emission permits, mandated markets and tax breaks. Climate policy thus serves the interests of rent seekers and of policy makers who use rent creation to reward allies.
Fifthly, climate policy requires government intervention at the global scale. This antagonizes many, and feeds the fears of right-wing conspiracy theorists. This had led to a movement that attacks climate policy at every opportunity, and extends those attacks to the climate science that underpins that policy, and the scientists who conduct the research. Alarmists have retaliated in kind, and the result is polarization.

Sixthly, greenhouse gas emission reduction is a global public good. The costs of emission abatement are borne by the country that reduces the emissions. The benefits of emission reduction are shared by all of humankind. It is thus individually rational to do very little, and hope that others will do a lot. As every country reasons the same way, nothing much happens. There is no solution to this short of installing a world government.

Optimal climate policy

Figure 2 shows the marginal impacts of greenhouse gas emissions. Figure 4 shows the carbon tax needed to meet a particular target – or, vice versa, the 2100 concentration of greenhouse gases as a function of the near-term carbon tax. Figure 5 (Tol 2013b) results from combing the two: The probability density function of the greenhouse gas concentration if carbon is priced at the Pigou tax. One result is as expected: The higher the discount rate, the less we care about the future, the higher the greenhouse gas concentration.

Another result may come as a surprise. Concentrations are probably greater than 450 ppm CO_2eq, even if for a very low pure rate of time preference. The European Union and the United Nations have agreed that the global mean surface air temperature should not exceed 2°C above pre-industrial times. An even chance on this requires that greenhouse concentrations stay below 450 ppm CO_2eq.
In other words, EU and UN policy does not pass the benefit-cost test. This may be because our estimates of the costs of emission reduction are too high. This is unlikely as the models assume first-best policy implementation. It may be because our estimates of the impacts of climate change are incomplete. This is more likely, but the PDF covers a wide range of estimates.

Alternatively, the EU and UN target may be wrong (Tol 2007). The 2°C target on UN was adopted from the EU. The EU target was adopted from Germany. And the Germany government adopted the 2°C target at the advice of the Scientific Advisory Committee on Global Environmental Change (WBGU 1995). The WBGU is a small body of academics. In 1995, they wrote a report on climate

policy. There are three lines of argument. First, the IPCC estimated that the total impact of a doubling of the atmospheric concentration of carbon dioxide would be 1-2% of GDP. WBGU argued that this was an underestimate because extreme weather events were omitted, and raised the number to 5%. Extreme weather costs on average much less than 1% of GDP per year, and climatologists have abandoned a rapid increase in extreme weather due to climate change. Second, the WBGU argued that *homo sapiens* had not experienced temperatures higher than 1.5°C above pre-industrial, so 2°C would be safe. Presumably, the WBGU would also argue that China has never experienced democracy, so autocracy is best for China. Thirdly, the WBGU argues that the 2°C target would safeguard creation. Recall that the W stands for scientific. The Basic Law defines Germany as a secular country.
Despite its flaws, when the EU was looking for a long-term target for its climate policy, Germany was the only Member State to suggest one. Similarly, when UN was looking for a target, the EU was the only one to recommend one.

There is another UN target. Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), ratified by almost all countries, states that

> “the ultimate objective of [...] 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.“

Anyone can read anything into the second sentence. It is waffle. Appealing but vapid language is what makes great diplomacy. The first sentence seems to be of a similar nature. How can anyone object to avoiding (otherwise unspecified) danger? The word “stabilization”, however, is all but innocuous. However, atmospheric degradation of carbon dioxide is partly by a geological process (rock weathering), and at a geological time scale. At a human time scale, there is no degradation at all. About 13% of anthropogenic carbon dioxide emissions stay in the atmosphere forever. That means that, in order to stabilize concentrations, carbon dioxide emissions must go to zero. Almost all countries are thus under a legal obligation to reduce their emissions by 100%.

There is no evidence that suggests that the people who drafted Article 2 were aware of this. The people who ratified the UNFCCC probably did not realize the implications either. Indeed, politicians regularly refer to an 80% emission reduction goal in the long run, with the greener ones opting for 90%. International law says it is 100%.

In a benefit-cost analysis, marginal costs are equated to marginal benefits. Two insights follow. First, if there are damages from emissions, then it is optimal to reduce emissions. In fact, it is relatively cheap to reduced emissions by the first bit while the benefits of the first bit of emission reduction are relatively high. Therefore, benefit-cost analysis calls for action that goes beyond token emission reduction. Second, it is relatively expensive to reduce the final bit of emissions while the benefits of reducing the final bit are relatively low. Therefore, benefit-cost analysis rarely calls for a complete elimination of emissions.

Applied to climate change, greenhouse gas emissions can be reduced by a little bit without much of a bother. Energy use is often wasteful or the result of perverse incentives. Eliminating all emissions is disruptive. While technical but costly alternatives have been identified for most applications of carbon dioxide, this is not (yet) the case for every niche application (e.g., in space travel and the military). Alternative energy sources are relatively cheap when applied at a small scale, but much more expensive at a large scale. Photovoltaic panels can be mounted on roofs (that is, with a zero opportunity cost for space) but roofs are finite. A little wind power can be easily integrated into an electricity network, but grid reinforcement, back up capacity, and frequency regulators are necessary when wind penetration is more than a few percent.

Vice versa, uncontrolled climate change can do a lot of damage and the initial emission reductions thus bring substantial benefits. However, as climate change is reduced further and further, those benefits fall. The benefits from reducing global warming from 0.1ºC per century to 0.01ºC are small. Therefore, a benefit-cost analysis will not recommend a 100% emission reduction. Yet, a 100% emission reduction is required by international law.

A solution

Any solution to the climate problem (Tol 2013a) should start with acknowledging that we live in a world of many countries, the majority of which jealously guard their sovereignty. That means that climate policy should serve a domestic constituency. Opinion polls in democratic countries have consistently shown over a period of 20 years that a majority is in favour of greenhouse gas emission reduction, even if that means more expensive energy.

Unilateral climate policy is expensive, however. If a country raises its price of energy, but its trading partners do not, business will shift abroad. A country that is confident that its neighbours will adopt roughly the same climate policy, will be more ambitious. The United Nations Framework Convention on Climate Change (UNFCCC) foresees an annual meeting at which countries can indeed pledge their near-term abatement plans and review other countries' progress against previous pledges. This is facilitated by internationally agreed standards on emissions monitoring and reporting. As the actions of trading partners matter most, regional trade organizations should play a bigger role in this process.

The costs of emission reduction vary greatly. It therefore makes sense if countries were allowed to reduce emissions by investing in abatement in other countries. The Kyoto Protocol of the UNFCCC establishes exactly this. Unlike the emissions targets of the Kyoto Protocol, its flexibility mechanisms do not expire.
Therefore, three crucial ingredients to a successful climate policy are already in place.

Carbon dioxide is the main anthropogenic greenhouse gas. Fossil fuel combustion is the main source of carbon dioxide emissions. The world would not warm by much if we burn all reserves of conventional oil and gas, the mainstays of the current energy system. Substantial warming requires that we burn considerable amounts of unconventional oil and gas, or use more coal, also in unconventional ways.

The availability of fossil fuels is crucial part of any scenario of future carbon dioxide emissions. Figure 6 shows estimates of the reserves and resources of fossil fuels by type (WEC 2010) from 2010, when the shale gas revolution was tentatively reaching beyond the borders of the USA and the shale oil revolution was in its infancy. Reserves can be profitably exploited with current technology at current prices and costs. Resources are known or suspected to be there, and may become commercial in the future. Figure 6 reveals that conventional oil and gas reserves are relatively small: 317 billion tonnes of oil equivalent. In 2009, total primary energy use was 11.6 GTOE. There is therefore enough conventional oil and gas to cover energy demand for another 27 years. Figure 6 also reveals, however, that there are plenty of other types of fossil fuels, including coal of course but also large resources of unconventional liquids and gases.

The second panel of Figure 6 shows the carbon dioxide emissions that would result if these fossil fuels were burned. For comparison, global 2008 emissions were 30 billion tonnes of CO_2. We can keep up current emissions for 100 years or more. The third panel shows the impact on the atmospheric concentration, should all available fossil fuels be burned at once. Conventional oil and gas can contribute only about 100 ppm. Other fossil fuels, reserves and resources, are worth another 1500 ppm.

This implies that the climate problem is not driven by conventional oil and gas, but rather by what will replace conventional oil and gas when they run out. The future energy sector will look radically different from today. The revolution in energy has already begun in the form of tar and shale. Instead of riding the waves of the ongoing revolution, climate policy has focused on creating another energy revolution, hitherto without success. Instead, climate policy should seek to harness the forces of creative destruction that are sweeping the energy sector.

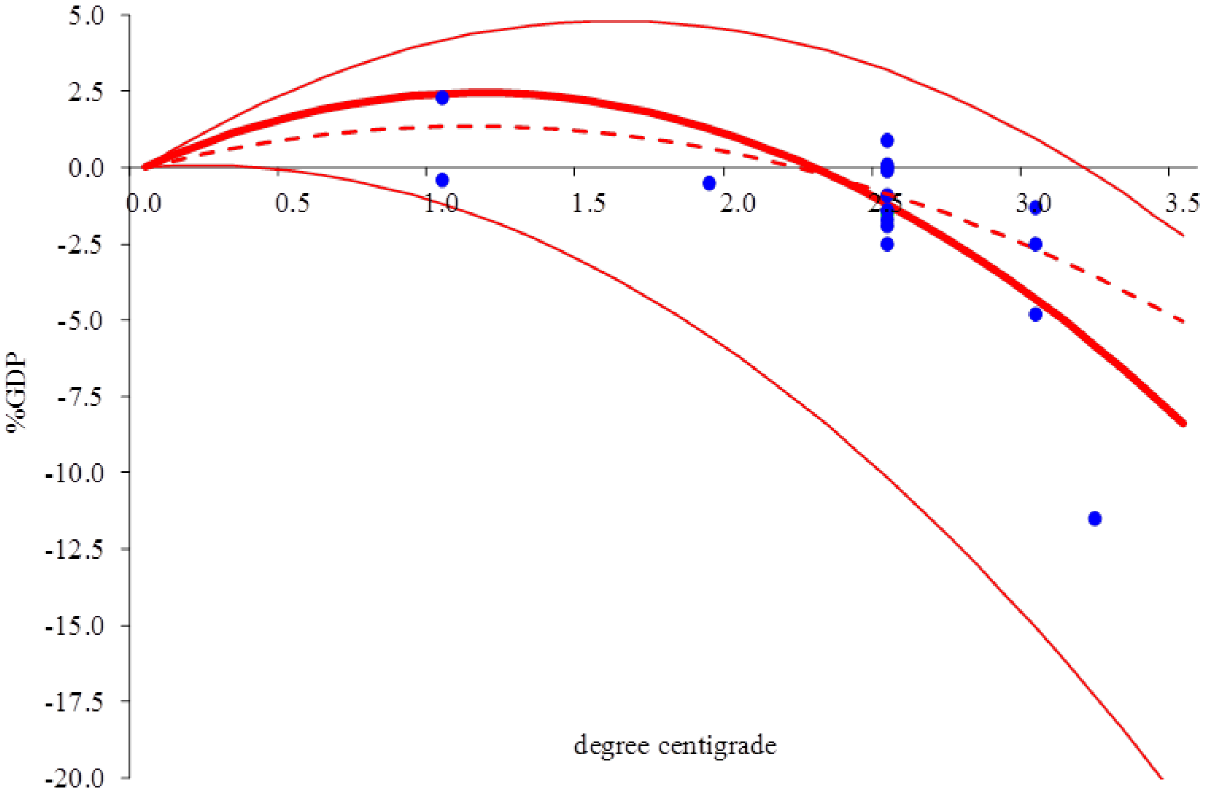
Table 1. The total costs of greenhouse gas emission reduction.

Target	650 ppm		550 ppm				450 ppm			
Approach	below		above		below		above		Below	
Non OECD	now	later	now	later	now	later	now	later	Now	Later
Model 1	-0.2	0.5	4.8	6.4	5.1	7.4	36.2	78.6	54.4	X
Model 2	13.4	18.8	30.4	48.2	30.9	64.1	123.4	X	X	X
Model 3	23.8	18.9	33.9	26.3	38.0	X	56.7	X	X	X
Model 4	1.4	1.2	3.8	5.1	5.1	10.2	X	X	X	X
Model 5	15.6	17.3	29.7	X	32.7	X	X	X	X	X
Model 6	7.2	7.8	16.2	29.8	18.8	35.7	X	X	X	X
Model 7	2.2	6.5	4.4	9.1	10.9	X	11.9	X	X	X
Model 8	2.2	na	5.9	na	12.4	na	27.9	X	X	X
Model 9	2.4	3.1	5.3	6.7	6.5	X	15.5	32.8	25.7	X
Model 10	13.0	12.8	44.3	59.8	44.3	59.8	X	X	X	X
Model 11	1.9	2.6	27.9	39.7	32.1	64.5	X	X	X	X

Source: (Tol 2014)

Costs are the net present value of the abatement costs over the 21st century. Costs are given in trillions of dollar. Results are presented for 11 different models and model variants, and for 3x2x2 policy scenarios with different stabilization targets (in parts per million of carbon dioxide equivalent), different approaches to those targets (from below, that is the target caps concentrations at all times, or from above, that is the target holds for 2100 but may be exceeded in the interim), and for different participation (non-OECD countries start to reduce their emissions in the near future or later in the century). Infeasible scenarios are marked X.

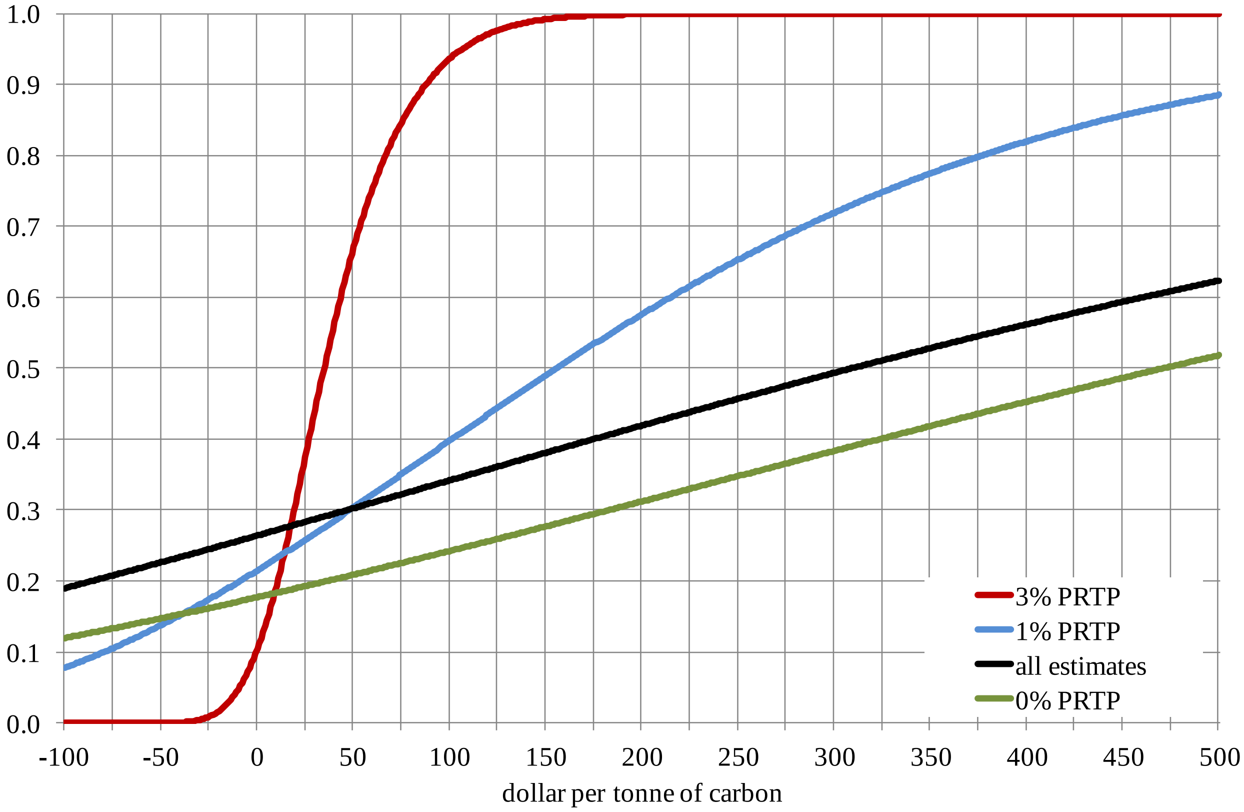
Figure 1.
The global total annual impact of climate change expressed in welfare-equivalent income change



Dots are primary estimates. The thick red curve is the best fit, the thin red curves its 95% confidence interval; the dashed line is an earlier best fit.

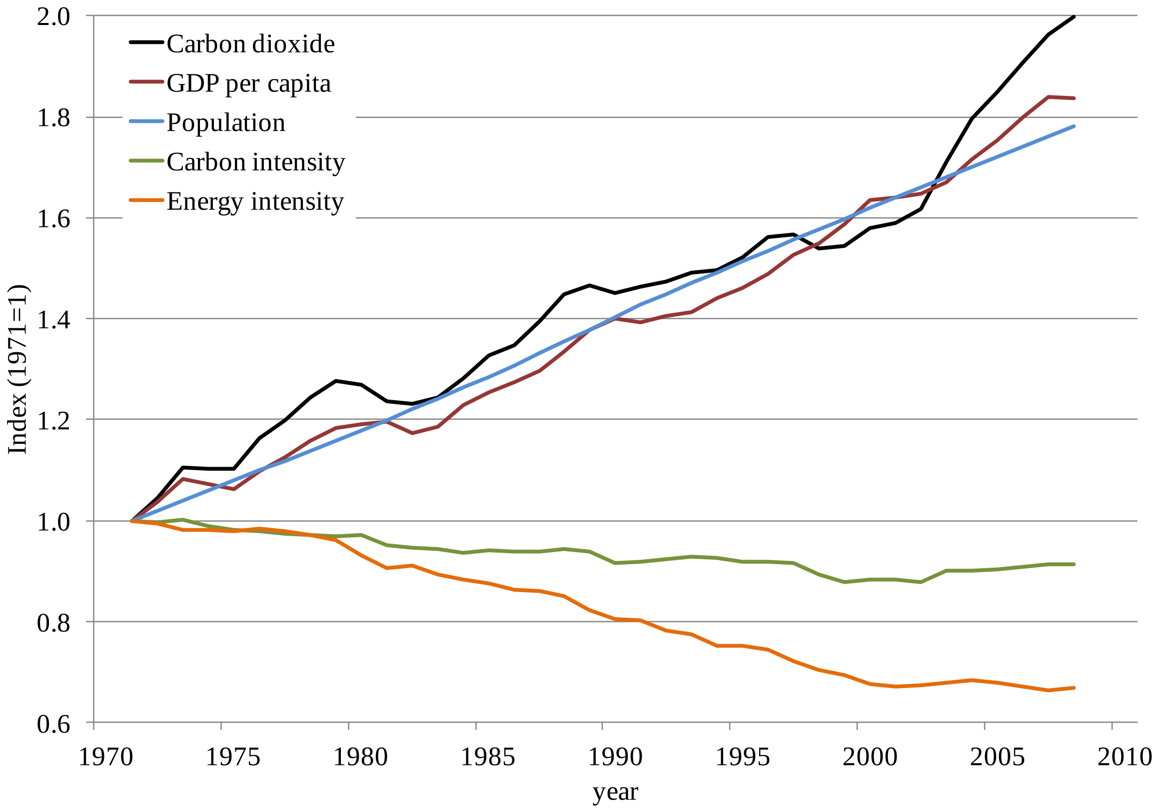
Source: (Tol 2014)

Figure 2. The cumulative distribution function of the social cost of carbon for all published studies and for all published studies that use a particular pure rate of time preference



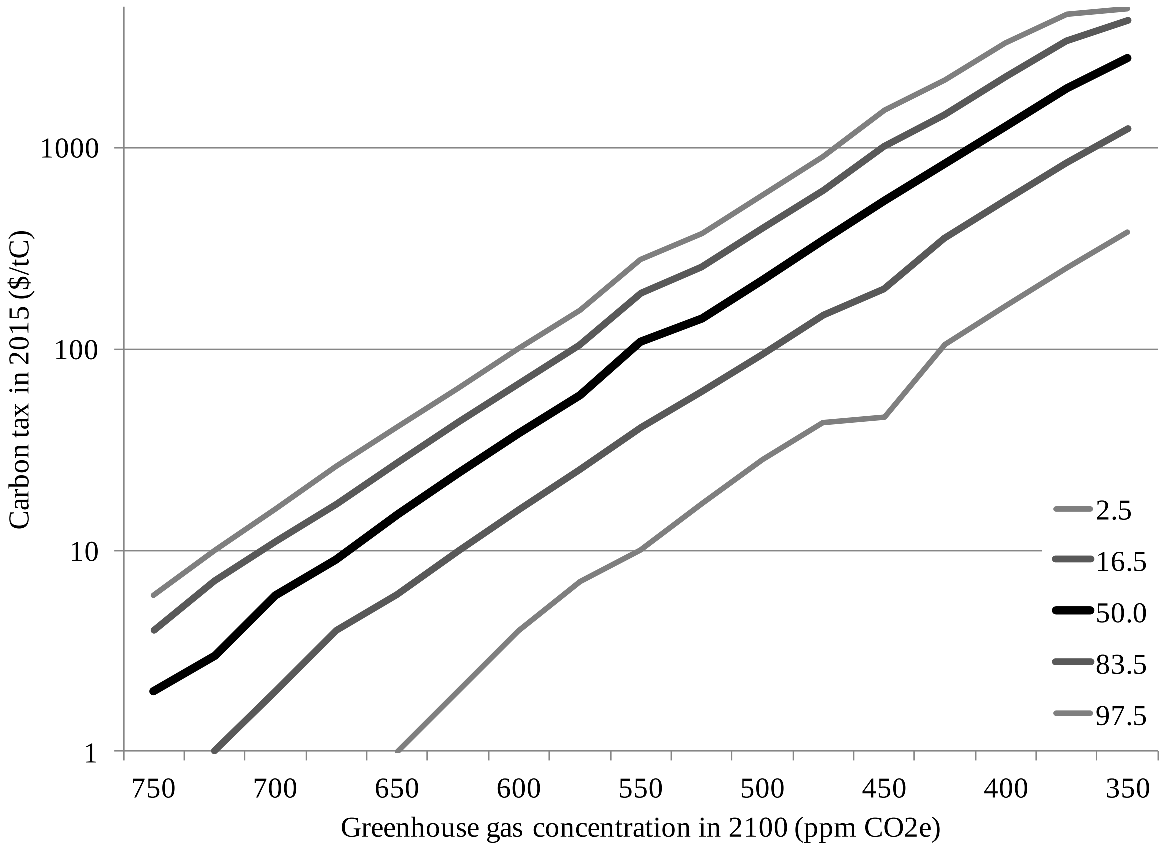
Source: (Tol 2014)

Figure 3. Global emissions of carbon dioxide and its constituents



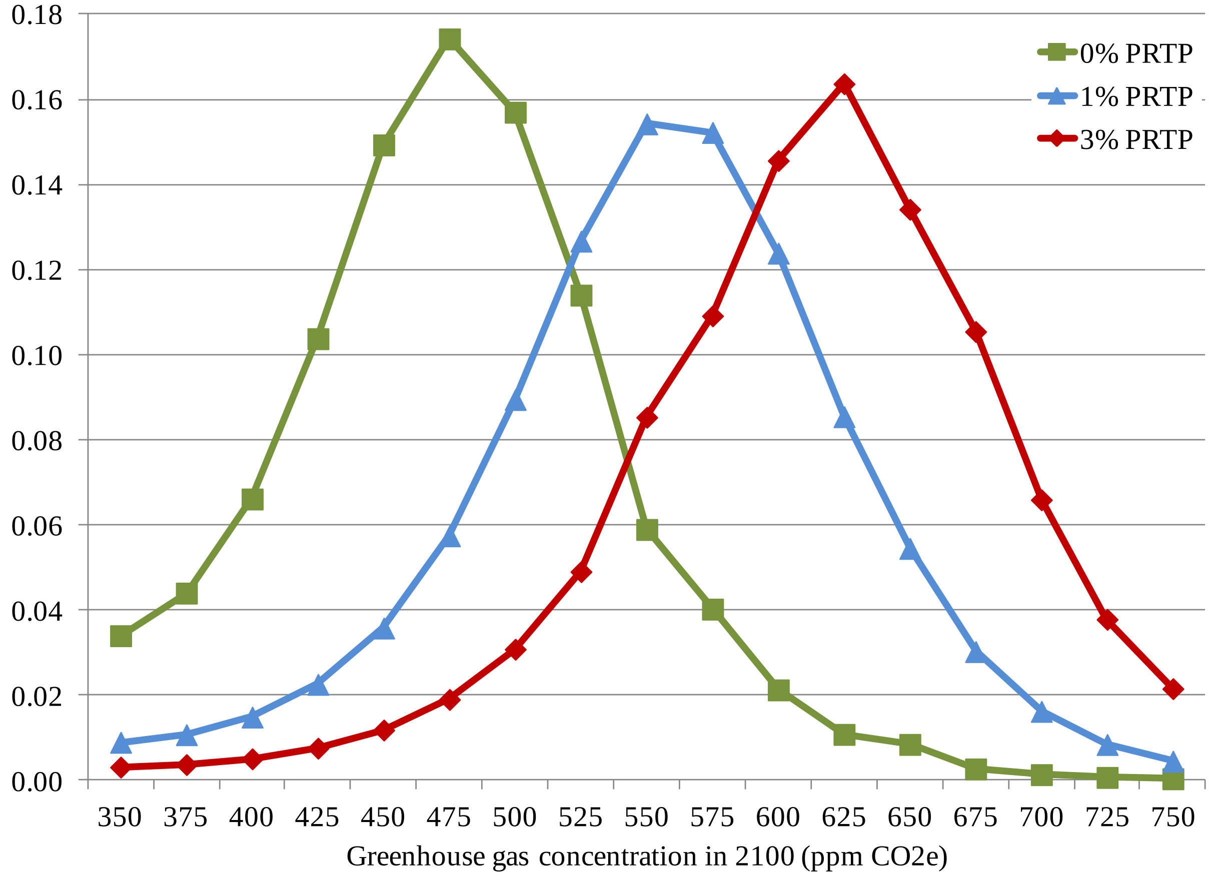
Source: (Tol 2014)

Figure 4. Selected percentiles of the initial carbon tax as a function of the target concentration



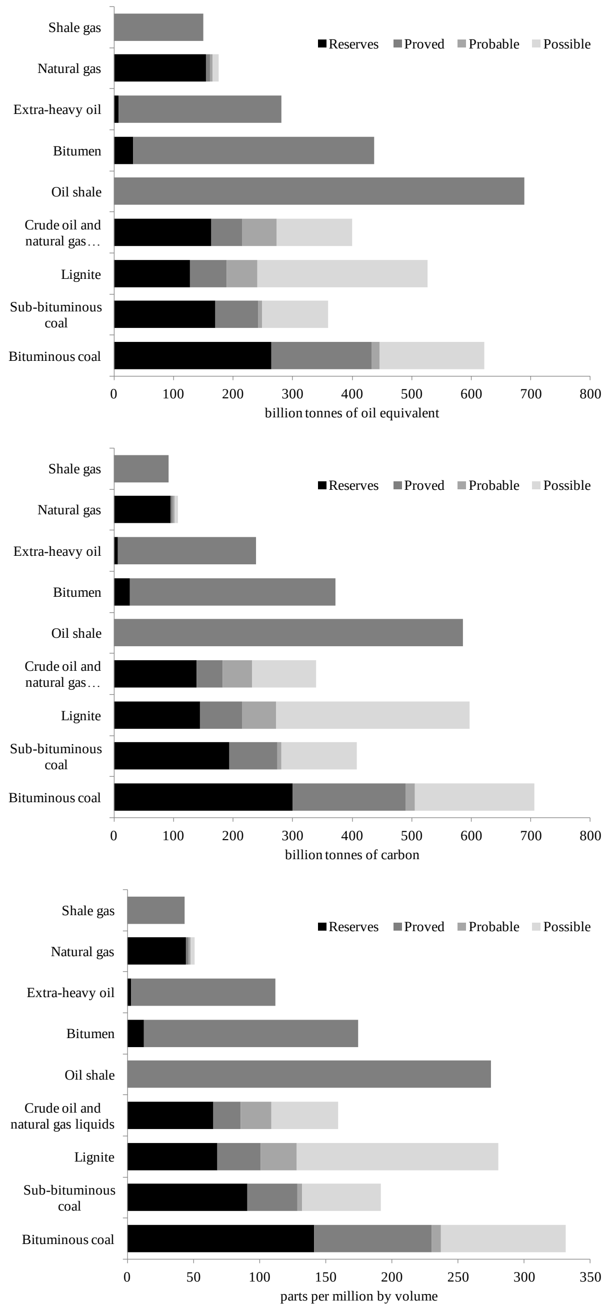
Source: (Tol 2014)

Figure 5. The probability density function for the optimal greenhouse gas concentration for three alternative pure rates of time preference



Source: (Tol 2014)

Figure 6. Fossil fuel reserves and resources as estimated for 2010 (top panel), their carbon content (middle), and implied carbon dioxide concentrations



Source: (Tol 2014)

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