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The PAGE09 Integrated Assessment Model: A Technical Description

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The PAGE09 integrated assessment model: A technical description

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Abstract

The PAGE09 model is a greatly revised update of the PAGE2002 integrated assessment model of climate change. It calculates the impacts of climate change and the costs of abatement and adaptation policies under uncertainty for eight world regions and ten time periods. This paper describes the changes made to PAGE2002 to create PAGE09, and the reasons for making them, and fully documents the PAGE09 model.

Introduction

PAGE09 is a new integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. It is designed to help policy makers understand the costs and benefits of action and inaction.

PAGE09 is an updated version of the PAGE2002 integrated assessment model. PAGE2002 was used to value the impacts and calculate the social cost of CO2 in the Stern review (Stern, 2007) and the Asian Development Bank's review of climate change in Southeast Asia (ADB, 2009), and value the impacts and costs in the Eliasch review of deforestation (Eliasch, 2008). The PAGE2002 model is described fully in Hope, 2006, Hope, 2008a and Hope, 2008b.

The update to PAGE09 been made to take account of the latest scientific and economic information, primarily in the 4th Assessment Report of the IPCC (IPCC, 2007). This paper describes the updated treatment of the science, impact, abatement and adaptation costs in the latest default version of the model, PAGE09 v1.7. The full set of model equations and default inputs to the model are shown in two appendices. Initial results from the model are presented in a companion paper, 'The Social Cost of CO2 from the PAGE09 model'.

PAGE09 uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the profound uncertainty that exists around climate change. Calculations are made for eight world regions, ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities). As in PAGE2002, all calculations are performed probabilistically, using Latin Hypercube Sampling to build up probability distributions of the results. The results for two policies and the difference between them are calculated in a single run of the model, so that the incremental costs and benefits of different abatement and adaptation policies can be found.

The changes made to PAGE2002 to create PAGE09, and the reasons for making them, are described under the following headings: Science, Impacts, Abatement costs and Adaptation.

Science

Inclusion of all six gases in the Kyoto protocol

In PAGE2002, CO2, CH4 and SF6 are the only greenhouse gases whose emissions are explicitly modelled. In PAGE09, the number of gases whose emissions are explicitly modelled is increased to 4, with the 3rd gas being N2O and the 4th gas representing all the gases whose concentration is low enough that their contribution to radiative forcing is linear in their concentration: HFCs, PFCs and SF6. Thus all the gases included in the Kyoto protocol (UN, 1998) are explicitly modelled in PAGE09. The forcing from N2O takes the same form as for CH4, based on the square root of the

concentration. The overlap terms between CH4 and N2O are typically under 0.1 W/m2, and are now calculated explicitly.

In PAGE2002, the excess radiative forcing from greenhouse gases not explicitly modelled, and the emissions of sulphates that cause cooling, are input as single projections over time, which do not vary across abatement scenarios. In PAGE09 the excess forcing from gases not explicitly modelled, and the sulphate emissions, are now allowed to vary by abatement policy, so that, for instance, the possibly significant differences between the sulphate cooling and the radiative forcing from black carbon and tropospheric ozone in business as usual and aggressive abatement policies can be represented. These changes allow a richer and more accurate exploration of abatement policies that combine cutbacks in CO2 with restrictions on non-CO2 greenhouse gases.

Inclusion of transient climate response

In PAGE2002, the climate sensitivity is input directly as an uncertain parameter. The climate sensitivity in PAGE09 is derived from two inputs, the transient climate response (TCR), defined as the temperature rise at the end of 70 years of CO2 concentration rising at 1% per year, corresponding to a doubling of CO2 concentration, and the feedback response time of the Earth to a change in radiative forcing, otherwise known as the half-life of global warming, and abbreviated to FRT in the model equations (Andrews and Allen, 2008).

Default triangular probability distributions for the climate sensitivity in PAGE2002 do not allow for the possibility of a long right tail. Default triangular distributions for TCR and FRT in PAGE09 give a climate sensitivity distribution with a long right tail, consistent with the latest estimates from IPCC, 2007 and elsewhere (Weitzman, 2009).

Modification of the feedback from temperature to CO2 concentration

The PAGE2002 model contains an estimate of the extra natural emissions of CO2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Hope, 2006)).

Recent model comparison exercises have shown that the form of the feedback in PAGE2002 works well for business as usual emissions, but overestimates concentrations in low emission scenarios (van Vuuren et al, 2009).

In PAGE09 the carbon cycle feedback (CCF) is introduced as a linear feedback from global mean temperature to a percentage gain in the excess concentration of CO2, to simulate the decrease in CO2 absorption on land and in the ocean as temperature rises (Friedlingstein et al, 2006). This is applied each analysis year, and is not carried forward from one analysis year to the next. The additional feedback gain is capped (at CCFFmax) so that the concentration does not run away in higher emission scenarios, and business as usual scenarios can be adequately simulated. PAGE09 is

much better than PAGE2002 at simulating the carbon cycle feedback results in Friedlingstein et al, 2006, van Vuuren et al, 2009.

Land temperature patterns by latitude

In PAGE2002, regional temperatures vary from the global mean temperature only because of regional sulphate forcing. However, geographical patterns of projected warming show greatest temperature increases over land (IPCC, 2007, ch10, p749), and a variation with latitude, with regions near the poles warming more than those near the equator (IPCC, 2007, ch10, figure 10.8 and supplementary material).

In PAGE09 the regional temperature is adjusted by a factor related to the effective latitude of the region, and one related to the land-based nature of the regions. The adjustment is calculated for each region using an uncertain parameter of the order of 1.5 degC (between 1 and 2 degC in the default model)representing the temperature increase difference between equator and pole (IPCC, 2007, ch10, figure 10.8 and supplementary material), and the effective absolute latitude of the region, and an uncertain constant of the order of 1.4 (between 1.2 and 1.6 in the default model) representing the ratio between mean land and ocean temperature increases (IPCC, 2007, ch10, p749).

Explicit incorporation of sea level rise

In PAGE2002, sea level rise is only included implicitly, assumed to be linearly related to global mean temperature. This neglects the different time constant of the sea level response, which is longer than the surface air temperature response (IPPC, 2007, p823).

In PAGE09, sea level is modelled explicitly as a lagged linear function of global mean temperature (Grinsted et al, 2009). The IPCC has a sea level rise projection in 2100 of 0.4 – 0.7 m from pre-industrial times (IPCC , 2007, p409). A characteristic response time of between 500 and 1500 years in the default version of PAGE09 gives sea level rises compatible with the IPCC results: a 50% confidence interval of 0.5 and 0.75 metres, and a 90% confidence interval of 0.4 to 1.0 metres, by 2100, compared to model-based ranges of 0.4 to 0.8 metres by 2100 in IPCC, 2007, SPM, p13-14.

Impacts

Impacts as a proportion of GDP

In PAGE2002, economic and non-economic impacts before adaptation are a polynomial function of the difference between the regional temperature and the tolerable temperature level, with regional weights representing the difference between more and less vulnerable regions. These impacts are

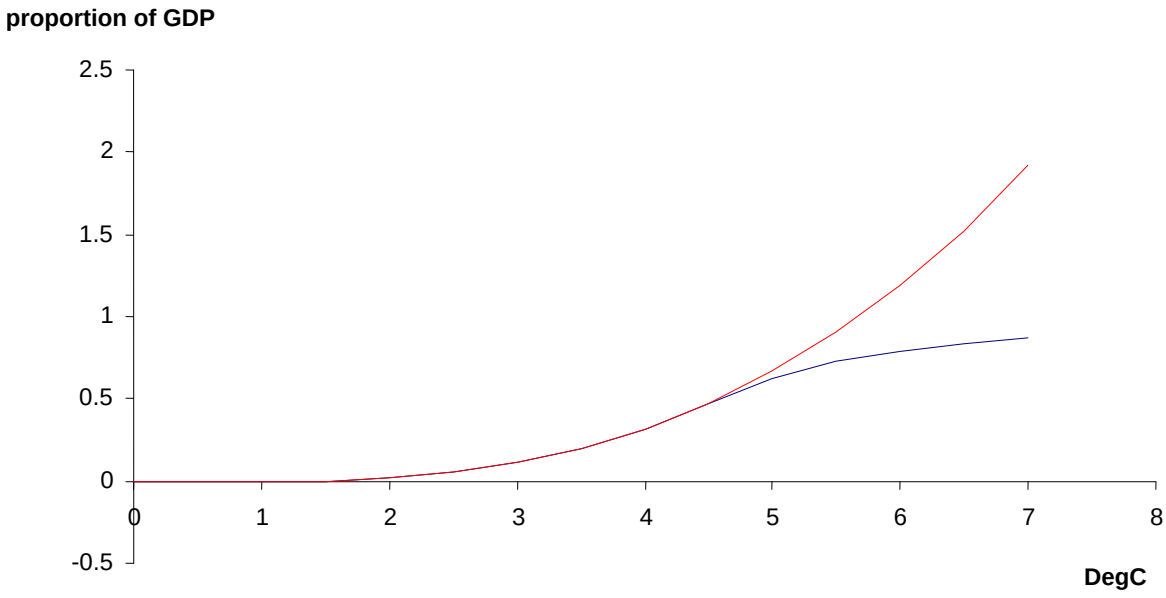
then equity weighted, discounted at the consumption rate of interest and summed over the period from now until 2200.

There are several issues with this representation, including the lack of an explicit link from GDP per capita to the regional weights, and the possibility that impacts could exceed 100% of GDP with unfavourable parameter combinations.

In PAGE09, extra flexibility is introduced by allowing the optional possibility of initial benefits from small increases in regional temperature (Tol, 2002, Stern, 2007), by linking impacts explicitly to GDP per capita and by letting the impacts drop below their polynomial on a logistic path once they exceed a certain proportion of remaining GDP to reflect a saturation in the vulnerability of economic and non-economic activities to climate change (as some activities, such as primary extraction, education and computer gaming are clearly not so vulnerable to climate change), and ensure they do not exceed 100% of GDP. The saturation level can be set as high as 100% of GDP if the user does not think saturation will actually occur below this level.

Figure 1 shows such an impact function expressing impacts as a proportion (not a %) of GDP, with initial benefits (IBEN) of 1% of GDP per degree, with impacts (W) of 4% of GDP at a calibration temperature (TCAL) of 2.5 degC, with a polynomial power (POW) of 3, and an exponent with income (IPOW) of -0.5. The impact function has a saturation(ISAT) starting at 50% of GDP, which keeps the impacts (blue line) below 100% of GDP even for the high temperatures shown. The red line shows what the impacts would be if they continued to follow the polynomial form without saturation. If the saturation level were set at 100% of GDP, the impacts would follow the red line until they reached 100% of GDP, at about 6 degC, and would then remain at that level for higher temperature rises.

Figure 1. The impact of climate change by temperature rise in PAGE09



Discontinuity impacts

As in PAGE2002, there is a risk of a large-scale discontinuity, such as the Greenland ice sheet melting, if climate change continues. In PAGE2002 all the losses from the discontinuity are assumed to be felt as soon as the discontinuity is triggered. In PAGE09 the losses associated with a discontinuity do not all occur immediately, but instead develop with a characteristic lifetime after the discontinuity is triggered, which is more realistic (Lenton et al, 2008).

Equity weighting of impacts

In PAGE2002, impacts are equity weighted in a rather ad-hoc way, so that for region r at date t the total impact is the change in consumption multiplied by a factor E(r,t), where

E(r,t)= (Gworld(t)/G(r,t))^ EMUC

where G is the GDP per capita and EMUC is the negative of the elasticity of the marginal utility of consumption . The equity weighted damage is then discounted at the consumption rate of interest

PTP + EMUC*g(r,t)

and summed over the period from now until the final analysis year, usually 2200, where g(r,t)= (dG(r,t) /dt)/G(r,t) , the instantaneous per capita GDP growth rate.

In PAGE09, as in PAGE2002, PTP and EMUC can be input as probability distributions. PAGE09 uses the equity weighting scheme proposed by Anthoff et al (2009) which converts changes in consumption to utility, and amounts to multiplying the changes in consumption by

E(r,t) = (G(fr,0)/G(r,t))^ EMUC

where G(fr,0) is today's GDP per capita in some focus region (which could be the world as a whole, but in PAGE09 is normally the EU). This equity weighted damage is then discounted at the utility rate of interest, which is the PTP rate. As EMUC is always greater than zero, the effect is to increase the valuation of impacts in regions that are poorer than the focus region in the base year, and decrease the valuation of impacts in regions that are richer.

Abatement costs

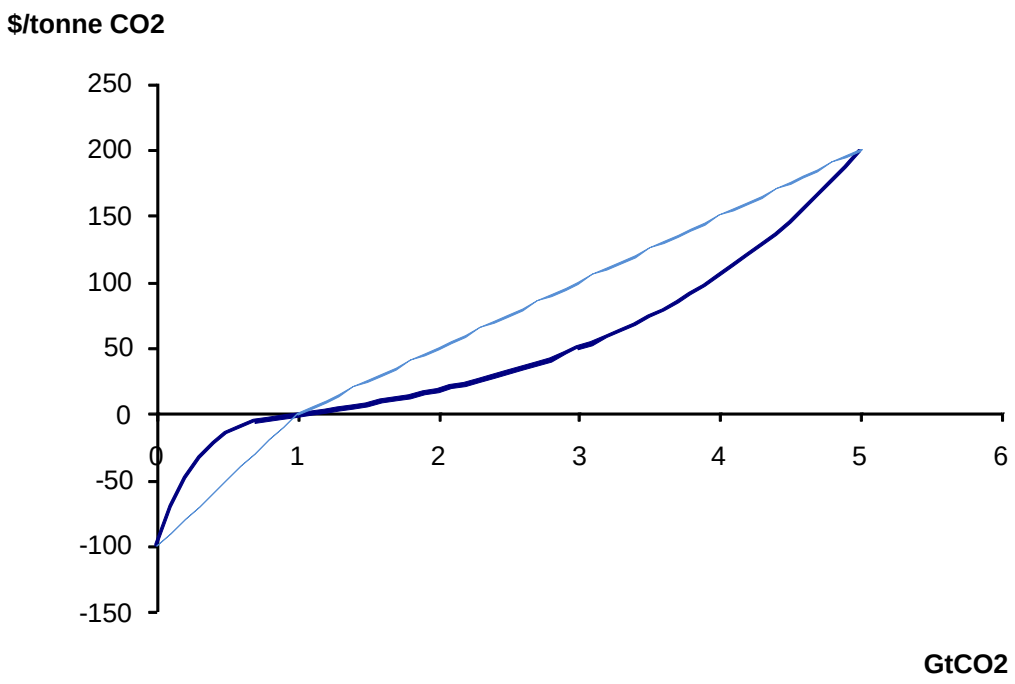
In PAGE2002, a simple stepwise marginal abatement cost (MAC) curve with two segments is used to model abatement costs. Cost parameters in all regions except the focus region differ from the values for the focus region by a regional multiplier.

This approach is clearly inferior in its form to recent continuous abatement cost curves generated by McKinsey, 2007, Bllomberg, 2010, Rose and Wei, 2008, and others. The PAGE2002 form makes it difficult to represent abatement that initially has a negative cost (for measures such as home insulation), and which has a positive cost, perhaps quite a high cost, for large amounts of abatement. It also does not allow for the abatement costs to be reduced by learning or technical progress, although Alberth and Hope, 2007 did make a first attempt to introduce these reductions.

In PAGE09 marginal abatement costs for each gas in each region are represented by a continuous curve, with an optional possibility of negative costs for small cutbacks, with marginal costs becoming positive for larger cutbacks. The curve is specified by three points, and by two parameters describing the curvature of the MAC curve below and above zero cost respectively. The three points are the (possibly negative) marginal abatement cost of the first unit of abatement, the proportion of BAU emissions that can be cutback before the marginal abatement costs become positive, and a high level of cutback where the marginal abatement costs are high.

Figure 2 shows a typical marginal abatement cost curve in PAGE09. The light blue line shows what the curve would be with both curvature parameters set to zero. The thicker, dark blue, line shows the curve with a curvature of 0.7 below zero cost, and 0.5 above zero cost.

Figure 2. Marginal abatement cost by amount of abatement in PAGE09



Changes in the shape of the curve over time are modelled by introducing annual proportional growth rates for the proportion of cutbacks at negative costs, and the maximum possible cutbacks. Learning and technical progress are also allowed, by applying the form from Alberth and Hope, 2007 to the marginal abatement cost at the maximum cutbacks.

The stipulation in PAGE2002 that cutbacks can never reduce over time is removed in PAGE09.

Adaptation

In PAGE2002, adaptation can increase the tolerable level of temperature change, and can also mitigate any climate change impacts that still occur. The costs involved in adapting to climate change are represented by uncertain adaptive cost parameters for the focus region. The corresponding adaptive cost factors in the non-focus regions are assumed to be proportional to those of the focus region. The multiplicative cost factor for each region is modelled as an uncertain parameter.

The total cost of adaptation depends on the change in the slope and plateau of the function representing tolerable temperature increase over time, and on the percentage reduction in weighted impacts that occur as a result of temperature increase above the tolerable level.

The adaptive costs in PAGE2002 are scale dependent, as they are expressed in $million per unit of adaptation bought. This makes it hard to specify regional factors, as the scale of economic activity in the region comes into the specification. For instance, in the default PAGE2002 model the modal cost

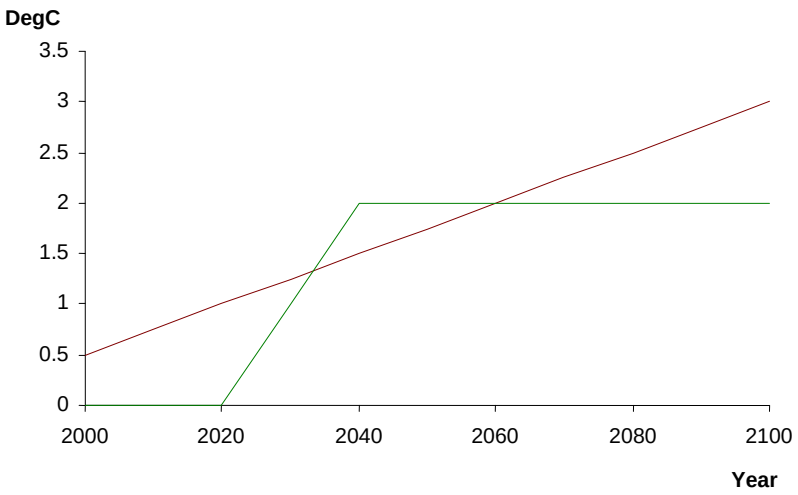
of adaptation in the EU economic sector to raise the tolerable temperature by 1 degC is $12bn per year. If a region, such as Africa, has only one-third of the economic activity of the EU, the user needs to remember to specify a regional cost factor for Africa of one-third, even if, relative to each unit of economic activity, it is just as hard to adapt in Africa as in the EU.

In PAGE09, adaptation policy is specified by seven inputs for each impact sector. The increase in tolerable temperature is represented by the plateau, the start date of the adaptation policy and the number of years it takes to have full effect. The reduction in impacts is represented by the eventual percentage reduction, the start date, the number of years it takes to have full effect and the maximum sea level or temperature rise for which adaptation can be bought; beyond this, impact adaptation is ineffective. Both types of policy are assumed to take effect linearly with time.

An adaptation policy in PAGE09 is thus 7 inputs for 3 sectors (sea level, economic and non-economic) for 8 regions, giving 168 inputs in all. This is a simplification compared to the 480 inputs in PAGE2002.

As an illustration of how adaptation is modelled in PAGE09, the green line in figure 3 shows the tolerable temperature in an impact sector that results from an adaptation policy to increase the tolerable temperature by 2 degC, starting in 2020 and taking 20 years to implement fully. If the temperature rise is shown by the red line, there will be 0.5 degC of impacts in 2000, increasing to 1 deg C by 2020, then reducing to 0 from 2030 to 2060 after which time the impacts start again, reaching 1 deg C by 2100. The user is free to specify the start date, the plateau and the number of years to take full effect, to try to reduce the impact from climate change.

Figure 3 Temperature and tolerable temperature by date in PAGE09



In PAGE09 the adaptive costs are specified as a % of GDP per unit of adaptation bought. This is scale independent (like the impacts measure). Regional factors then become about factors like the length of the coastline, and not about the amount of economic activity in a region, much like regional

factors for the impacts. Adaptive costs benefit from autonomous technical change in the same way as abatement costs.

Equity weighting of costs

In PAGE2002, abatement and adaptation costs are not equity weighted. This is logically incorrect, and has been criticised by Anthoff etal (2009).

In PAGE09, abatement and adaptation costs can be fully equity weighted in the same way as impacts, partially equity weighted or not equity-weighted. The latter options are provided in case the user wishes to evaluate policies in which the costs to poor countries are actually paid by transfers from rich countries.

When costs are fully equity-weighted, the changes in GDP from the costs are converted to utility in exactly the same way as the changes in GDP from impacts, by multiplying the changes in GDP by

E(r,t) = (G(fr,0)/G(r,t))^ EMUC

where G(fr,0) is today's GDP per capita in some focus region (which could be the world as a whole, but in PAGE is normally the EU). The equity weighted costs are then discounted at the utility rate of interest, which is the PTP rate.

Conclusion

The PAGE09 model represents the climate change impacts, abatement costs and adaptation costs that result from two abatement and adaptation policies specified by the user, one of which may be, but does not have to be, a business as usual policy. All results are presented as probability distributions and changes in utility, so that risks can be fully considered. Net present values are calculated, so that the total effects of the policies, and the net benefit of changing from one policy to the other, can be found. The functional forms inside the model are appropriate for policy analysis in the second decade of the third millennium. Future papers will present the results from using the PAGE09 model to address the remaining major open question concerning climate change: the total and marginal impacts of business as usual and abatement scenarios, the costs and benefits of abatement at different times in different regions, and the costs and benefits of adaptation.

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Appendix 1: PAGE09 equations

Introduction

This appendix describes all the equations in PAGE09 that differ from their counterparts in PAGE2002. The current version is PAGE09 v1.7.

Throughout, the equations use the convention that a variable which is the same across policies is in uppercase, while one that differs between policies is in lower case.

Climate

The climate module of PAGE09 is based closely on the existing PAGE2002 model, described fully in Hope, 2006 and Hope, 2008.

The equations are as in Hope, 2006 and Hope, 2008, with the following alterations.

Inclusion of Nitrous Oxide

The number of gases is increased from 3 to 4, with indices as follows.

g	Gas
1	Carbon dioxide (CO2)
2	Methane (CH4)
3	Nitrous oxide (N2O)
4	Linear gas

Equations 1 to 12 from Hope, 2006 apply to N2O as to CH4. The forcing from N2O takes the same form as for CH4, based on the square root of the concentration. Equation 14 is now

f(2,i)= F(2,0) + FSLOPE(2) *(sqrt(c(2,i))−sqrt((C(2,0)))) + over(2,i) – OVER(2,0) W/m2

f(3,i)= F(3,0) + FSLOPE(3) *(sqrt(c(3,i))−sqrt((C(3,0)))) + over(3,i) – OVER(3,0) W/m2

where c is concentration.

The overlap terms between CH4 and N2O are typically under 0.1 W/m2, and are now calculated explicitly, using the equation from IPCC, 2001,p358.

over(2,i)=- 0.47 ln[1+2.01E-5*(c(2,i)*C(3,0))^0.75+5.31E-15*c(2,i)*(c(2,i)*C(3,0))^1.52]

OVER(2,0) =- 0.47 ln[1+2.01E-5*(C(2,0)*C(3,0))^0.75+5.31E-15* C(2,0)*(C(2,0)*C(3,0))^1.52]

over(3,i) =- 0.47 ln[1+2.01E-5*(C(2,0)*c(3,i))^0.75+5.31E-15* C(2,0)*(C(2,0)*c(3,i))^1.52]

OVER(3,0) = OVER(2,0) all in W/m2

The linear gas now becomes gas 4; the equations for this are the same as for gas 3 in PAGE2002, as it represents any gas, or combination of gases, whose concentration is low enough (typically less than 1 ppb) that the radiative forcing is linear in the concentration.

f(4,i) = F(4,0) + FSLOPE(4) *(c(4,i)– C(4,0)) W/m2

Inclusion of transient climate response

In PAGE2002, the climate sensitivity is input directly as an uncertain parameter. In PAGE09, the climate sensitivity, SENS, in degC is calculated from two other uncertain inputs, the transient climate response TCR in degC and the half-life of global warming, FRT in years (Andrews and Allen, 2008).

SENS = TCR/(1-(FRT/70)*(1-EXP(-70/FRT))) degC

Modification of the feedback from temperature to CO2 concentration

The standard PAGE2002 model contains an estimate of the extra natural emissions of CO2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Hope, 2006)).

In PAGE09, equation 3 from Hope, 2006 is not applied to CO2; instead a linear feedback is introduced from global mean temperature to a percentage gain in the excess concentration of CO2. This is applied each analysis year, and is not carried forward from one analysis year to the next. The additional feedback gain is capped at CCFFmax so that the concentration does not run away in higher emission scenarios.

gain(i) = min(CCF*rt_g(i-1), CCFFmax) %

where gain is the Climate-Carbon Feedback Factor, CCF is an uncertain input representing the Climate-Carbon Feedback in % per degree C, and CCFFmax is an uncertain input in %.

The remaining emissions of CO2 in any analysis year are given by the existing equation 11 of Hope, 2006, now called renoccff, increased by the gain for that year

re(1,i)= REnoccff(1,i)*(1+gain(i)/100) Mtonne

The existing equation 12 from Hope, 2006 is used to convert remaining emissions to concentration.

Since the base year concentration of CO2 contains some gain, it needs to be adjusted downwards to give the correct base year remaining emissions to be carried forward

GAIN(0) = CCF*RT_G(0) %

REnoccff(1,0) = RE(1,0)/(1+GAIN(0)/100) Mtonne

Sulphates and excess forcing vary by policy

In PAGE09, pse(i,r) and exf(i) are allowed to vary by policy, and so are located in the Policy worksheet. They have no abatement costs associated with them.

Better units for direct sulphate forcing input

The input in PAGE2002 is not easily understandable. In PAGE09 we make the input D the level of mean base year direct sulphate forcing in W/m2.

The first term of equation 18 from Hope, 2006 is replaced by

fsd(i,r) = FSD(0,r)* sfx(i,r)/SFX(0,r) W/m2

Where

SFX(0,r) = SE(0,r)/AREA(r)

FSD(0,r) = D*SFX(0,r)/ SFX_G(0) W/m2

Where SFX_G(0) is the area weighted average of the regional base year sulphate fluxes.

The second term of equation 18 from Hope, 2006 gives fsi(i,r) in W/m2, so that

fs(i,r) = fsd(i,r) + fsi(i,r) W/m2

Land temperature patterns by latitude

In PAGE09 the regional temperature is adjusted by a factor related to the effective latitude of the region, and one related to the land-based nature of the regions. Equations 13 to 20 from Hope, 2006 are used to calculate the unadjusted realised temperature.

OCEAN_PROP, the proportion of the Earth covered by ocean, is calculated from the sum of the land areas in the regions and the total surface area of the Earth, 510 million km2.

OCEAN_PROP = 1-(AREA_G/510000000)

The adjustment is calculated for each region using

RT_ADJ(r) = POLE/90 *(LAT(r) – LAT_G) degC

where POLE is an uncertain parameter of the order of 1 degC representing the temperature increase difference between equator and pole, LAT(r) is the effective absolute latitude of the region, LAT_G is the area weighted mean latitude of the land mass of the Earth.

rtl is the regional temperature adjusted for latitude and land. Equation 20 from Hope, 2006 is used to find rt(i,r) (with FRT in place of OCEAN), and then

rtl(i,r) = rt(i,r)/(1+(OCEAN_PROP/RLO)-OCEAN_PROP) + RT_ADJ(r) degC

where RLO is an uncertain constant of the order of 1.4 representing the ratio between mean land and ocean temperature increases.

RT(0,r) must be calculated by subtracting the adjustment from the reported regional base year temperatures, which are RTL(0,r)

RT(0,r) =(RTL(0,r) - RT_ADJ(r))* (1+(OCEAN_PROP/RLO)-OCEAN_PROP) degC

Equation 21 from Hope, 2006 is now applied to find the global mean land temperature, rtl_g(i). The global mean ocean temperature is given by

rto_g(i) = rtl_g(i) /RLO degC

and the global mean temperature is given by

rt_g(i) =OCEAN_PROP*rto_g(i)+(1-OCEAN_PROP)*rtl_g(i) degC

Explicit incorporation of sea level rise

In PAGE09, sea level is modelled explicitly using very simple equations that link sea level rise to temperature rise

es(i) = SLTEMP*rt_g(i) + SLA metres

YP(1) = Y(1) –Y0

YP(i) = Y(i) – Y(i-1) i = 2 to 10.

EXPFS(i) = EXP(-YP(i)/SLTAU)

s(i) = s(i-1) + (es(i) – s(i-1))*(1-EXPFS(i)) metres

where s is sea level, es is equilibrium sea level, and SLTEMP, SLA and SLTAU are uncertain parameters representing the sensitivity of sea level to temperature, the asymptotic sea level rise with no temperature change and the characteristic time for sea level to respond to temperature rise respectively.

To initialise, we also need to specify S(0) giving four uncertain sea level parameters in all.

Abatement costs

Inputs for each gas, g, g=1 to 4 are

EMIT(g,1) Uncertainty in BAU emissions in focus region in final analysis year %

Q0_PROP_INIT(g,1) Cutbacks at negative cost in focus region in base year % of BAU emissions

C0_INIT(g) Most negative cost cutback in base year $/tonne

QMAX_MINUS_Q0_PROP_INIT(g) Max cutbacks at positive cost in base year % of BAU emissions

CMAX_INIT(g,1) Maximum cutback cost in focus region in base year $/tonne

IES(g) Initial experience stock of cutbacks Million tonne

(assuming EMIT_NAME = Million tonne)

Inputs for each region, r, except the focus region, r=2 to 8, applied to all gases

EMITF(r) Uncertainty in BAU emissions factor

Q0F(r) Negative cost percentage factor

CMAXF(r) Maximum cost factor

Inputs with single, uncertain, values

Q0PROPMULT Cutbacks at negative cost in final year as multiple of base year

QMAX_MINUS_Q0_PROPMULT Maximum cutbacks at positive cost in final year as multiple of base year

C0MULT Most negative cost in final year as multiple of base year

CURVE_BELOW Curvature of MAC curve below zero cost, specified as 1 minus the cost midway between 0 and Q0 as a proportion of the cost if the curve were linear. As CURVE_BELOW approaches zero, this portion of the MAC curve approaches a linear curve. Must stay above zero and below 1.

CURVE_ABOVE Curvature above zero cost, specified as 1 minus the cost midway between Q0 and QMAX as a proportion of the cost if the curve were linear. As CURVE_ABOVE approaches zero, this portion of the MAC curve approaches a linear curve. Must stay above zero and below 1.

CROSS Experience crossover ratio

LEARN Learning rate

There are also two inputs applied to both abatement and adaptive costs

AUTOMULT Autonomous technical change (costs in final year as multiple of base year)

EQUITY_PROP Equity weights proportion

The regional factors are applied to give EMIT(g,r), Q0_PROP_INIT(g,r) and CMAX_INIT(g,r) in regions 2 to 8

EMIT (g,r)= EMIT(g,1)*EMITF(r) %

Q0_PROP_INIT (g,r)= Q0_PROP_INIT(g,1)* Q0F(r) % of BAU emissions

CMAX_INIT(g,r) = CMAX_INIT(g,1)* CMAXF(r) $/tonne

Zero-cost emissions (ZC(i,g,r)) as a percent of base year emissions are calculated for each gas, region and analysis year, as in PAGE2002 (Hope, 2006).

Cutbacks are the reductions from the zero-cost emissions. Unlike PAGE2002, cutbacks are allowed to decrease in later years.

cb(i,g,r) = max(ZC(i,g,r)-er(i,g,r),0) %

Absolute cutbacks in emissions are calculated from cb

cbe(i,g,r) = cb(i,g,r)*e0(g,r)/100 Mtonne

Cumulative cutbacks since the base year are required for the experience curves

cumcbe(1,g,r) = 0

cumcbe(i,g,r)= cumcbe(i-1,g,r)+cbe(i-1,g,r) *YAGG(i-1) i = 2 to 10 Mtonne

cumcbe_g(i,g) = cumcbe(i,g,r) summed over r Mtonne

Learning and autonomous technical change reduce the maximum marginal costs

learnfac(i,g,r) = ((CROSS*cumcbe_g(i,g)+(1-CROSS)*cumcbe(i,g,r)+IES(g))/IES(g))^- (LN(1/(1-LEARN))/LN(2))

AUTO = (1-AUTOMULT^(1/(Y_LAST-Y0)))*100 % per year

AUTOFAC(i)=(1-AUTO/100)^(Y(i)-Y0)

The most negative marginal abatement cost, the maximum cutbacks at positive cost, and the cutbacks at negative cost all change over time.

C0G = (C0MULT^(1/(Y_LAST-Y0))-1)*100 % per year

C0(i,g) = C0_INIT(g)*(1+C0G/100)^(Y(i)-Y0) $/tonne

QMAX_MINUS_Q0_PROPG = (QMAX_MINUS_Q0_PROPGMULT^(1/(Y_LAST-Y0))-1)*100 % per year

QMAX_MINUS_Q0_PROP(i,g) =
QMAX_MINUS_Q0_PROP_INIT(g)*(1+QMAX_MINUS_Q0_PROPG/100)^(Y(i)-Y0)
% of BAU emissions

Q0PROPG = (Q0PROPMULT^(1/(Y_LAST-Y0))-1)*100 % per year

Q0_PROP(i,g,r) = Q0_PROP_INIT(g,r)*(1+Q0PROPG/100)^(Y(i)-Y0) % of BAU emissions

Absolute cutbacks at negative cost and the maximum reference cutbacks are calculated.

Q0(i,g,r) = (Q0_PROP(i,g,r)/100)*(ZC(i,g,r)/100)*e0(g,r) Mtonne

QMAX(i,g,r) =(QMAX_MINUS_Q0_PROP(i,g)/100)*(ZC(i,g,r)/100)*e0(g,r)+Q0(i,g,r)
Mtonne

Learning and autonomous change are applied to the maximum marginal cost

cmax(i,g,r)=CMAX_INIT(g,r)*learnfac(i,g,r)*AUTOFAC(i) $/tonne

The parameters in the MAC curves are calculated

BLO(i,g,r)=-2*LN((1+CURVE_BELOW)/(1-CURVE_BELOW))/Q0(i,g,r)) per Mtonne

ALO(i,g,r)=C0(i,g)/(EXP(-BLO(i,g,r)*Q0(i,g,r))-1) $/tonne

BHI(i,g,r)=2*LN((1+CURVE_ABOVE)/(1-CURVE_ABOVE))/(QMAX(i,g,r)-Q0(i,g,r)) per Mtonne

ahi(i,g,r)=cmax(i,g,r)/(EXP(BHI(i,g,r)*(QMAX(i,g,r)-Q0(i,g,r)))-1) $/tonne

For each gas, region and analysis year, the marginal abatement cost (MAC) curve for cutback Q is given by

If Q>Q0

MAC(Q) = AHI*(exp(BHI*(Q-Q0))-1) $/tonne

else

MAC(Q) = ALO*(exp(BLO*(Q-Q0))-1) $/tonne

This differs from the technical specification, where MAC(Q) was specified as the sum of the two terms. The summed form proved intractable and unreliable in practice. This alternative gives the same flexibility, while allowing an intuitive way of specifying the curvature of the cost curve below and above Q0.

so

mc(i,g,r)=IF(cbe(i,g,r)<Q0(i,g,r),ALO(i,g,r)*(EXP(BLO(i,g,r)*(cbe(i,g,r)-Q0(i,g,r)))-1),
ahi(i,g,r)*(EXP(BHI(i,g,r)*(cbe(i,g,r)-Q0(i,g,r)))-1)) $/tonne

Total costs (TC) are given by the integral of the MAC curve up to Q

TC(Q) = (a2/b2)*(exp(b2*(Q-Q0))-exp(b2*(-Q0))) – a2*Q if Q<Q0 $million

TC(Q0) = (a2/b2)*(1-exp(b2*(-Q0)))– a2*Q0 $million

TC(Q) = TC(Q0) + (a1/b1)*(exp(b1*(Q-Q0))-1) – a1*(Q – Q0) if Q>Q0 $million

so

TCQ0(i,g,r)=IF(Q0(i,g,r)=0,0,(ALO(i,g,r)/BLO(i,g,r))*(1-EXP(-BLO(i,g,r)*Q0(i,g,r)))-ALO(i,g,r)*Q0(i,g,r))
$million

tc(i,g,r)=IF(cbe(i,g,r)<Q0(i,g,r),(ALO(i,g,r)/BLO(i,g,r))*(EXP(BLO(i,g,r)*(cbe(i,g,r)-Q0(i,g,r)))-EXP(-BLO(i,g,r)*Q0(i,g,r)))-ALO(i,g,r)*cbe(i,g,r),(ahi(i,g,r)/BHI(i,g,r))*(EXP(BHI(i,g,r)*(cbe(i,g,r)-Q0(i,g,r)))-1)-ahi(i,g,r)*(cbe(i,g,r)-Q0(i,g,r))+TCQ0(i,g,r)) $million

Total abatement costs of all gases

tct(i,r)= tc(i,g,r) summed over g

tct_per_cap(i,r)=tct(i,r)/POP(i,r) $

If costs are completely equity weighted, the weighted cost per capita would be given by

wtct_per_cap (i,r)= (((CONS_PER_CAP_FOCUS_0)^EMUC)/(1-EMUC))*((CONS_PER_CAP)^(1-EMUC) - (CONS_PER_CAP-tct_per_cap(i,r)) ^(1-EMUC)) $

Costs can be not equity-weighted (EQUITY_COSTS=0), partially equity weighted (EQUITY_COSTS=1, EQUITY_PROP<1), or fully equity-weighted (EQUITY_COSTS=1, EQUITY_PROP=1).

pct_per_cap(i,r)= IF(EQUITY_COSTS=0,tct_per_cap(i,r),(1-EQUITY_PROP)*tct_per_cap(i,r)+EQUITY_PROP*wtct_per_cap(i,r)) $

Total costs are given by

pct(i,r) = pct_per_cap(i,r)*POP(i,r) $million

pct_g(i) = pct(i,r) summed over r $million

If EQUITY_COSTS=0, a discount factor from the consumption discount rate (DFC) is used, otherwise the utility discount factor (DF) is used

DR(i,r)=PTP+(EMUC*(GRW(i,r)-POP_GRW(i,r))) % per year

DFC(1,r)=(1+(DR(1,r)/100))^(-(Y(1)-Y0))

DFC(i,r)=DFC(1-i,r)*(1+(DR(i,r)/100))^(-YP(i)) for i = 2 to 10

Discounted costs are

pcdt(i,r) = IF(EQUITY_COSTS=0,pct(i,r)*DFC(i,r),pct(i,r)*DF(i)) $million

pcdt_g(i) = pcdt(i,r) summed over r $million

Costs are aggregated and then summed over r and i to give total abatement costs

pcdat(i ,r)= pcdt(i,r)*YAGG(i) $million

tpc = pcdat(i,r) summed over r and i $million

Adaptation costs

Unit costs of adaptation are calculated for each region, for all impact categories except discontinuity, where there is no adaptation.

CP(d,r) = CP(d,1) * CF(r) for d = s,1,2, r=2 to 8 %GDP per degC or metre

CI (d,r) = CI(d,1)* CF(r) for d = s,1,2, r=2 to 8 %GDP per % drop in impact

Adaptive costs benefit from autonomous technical change. Impact reduction costs are input per metre or degC

acp(i,d,r) = atl(i,d,r)*CP(d,r)*GDP(i,r)/100*AUTOFAC(i) $million

aci(i,d,r) = imp(i,d,r)*CI(d,r)*GDP(i,r)/100*impmax(d,r)*AUTOFAC(i) $million

Adaptive costs are the sum of plateau and impact adaptive costs

ac(i,d,r) = acp(i,d,r)+aci(i,d,r) $million

act(i,r) = ac(i,d,r) summed over d $million

act_per_cap(i,r) = act(i,r)/POP(i,r) $

If costs are completely equity weighted, the weighted cost per capita would be given by

eact_per_cap(i,r) = (((CONS_PER_CAP_FOCUS_0)^EMUC)/(1-EMUC))*((CONS_PER_CAP)^(1-EMUC) - (CONS_PER_CAP-act_per_cap(i,r)) ^(1-EMUC)) $

Adaptive costs can be equity weighted or not, the same as abatement costs

wact_per_cap(i,r)= IF(EQUITY_COSTS=0,act_per_cap(i,r),(1-EQUITY_PROP)*act_per_cap(i,r)+EQUITY_PROP*eact_per_cap(i,r)) $

wact(i,r) = IF(EQUITY_COSTS=0,act_per_cap(i,r),wact_per_cap(i,r))*POP (i,r) $million

If EQUITY_COSTS=0, a discount factor from the consumption discount rate (DFC) is used, otherwise the utility discount factor (DF) is used

wacdt(i,r) = IF(EQUITY_COSTS=0,act(i,r)*DFC(i,r),wact(i,r)*DF(i)) $million

Costs are aggregated and then summed over r and i to give total adaptive costs

aact(i,r) =wacdt(i,r)*YAGG(i) $million

tac = aact(i,r) summed over r and i $million

Impacts

The number of impact categories is increased from 3 to 4, with indices as follows.

d	Impact category
s	sea level impact
1	first impact based on regional temp rise (economic by default)
2	second impact based on regional temp rise (non-economic by default)
dis	discontinuity impact

There are eight regions, r, with the focus region given the index 1.

Impact is specified as % loss of GDP, subtracted from consumption, and saturation applies if more than a certain percent of consumption is lost. SAVE is the savings rate, assumed constant over regions and time.

CONS(i,r)=GDP(i,r)*(1-SAVE/100) $million

(assuming CURRENCY_NAME=$million, and POP_UNIT_NAME=million)

GDP_PER_CAP(i,r)=GDP(i,r)/POP(i,r) $

CONS_PER_CAP(i,r)=CONS(i,r)/POP(i,r) $

Abatement and adaptive costs are subtracted from consumption before impacts are calculated

cons_per_cap_after_costs(i,r)= CONS_PER_CAP(i,r)-(tct_per_cap(i,r)-act_per_cap(i,r)) $

gdp_per_cap_after_costs(i,r)= cons_per_cap_after_costs(i,r)/(1-SAVE/100) $

WINCF(1) = 1

WINCF(r) =WF(r) r= 2 to 8

So for sea level the impact calculation is:

Tolerable sea level rise and reduction in impact per metre rise in each region are calculated from the adaptive policy in that region. There is no tolerable sea level rise unless adaptation is bought.

atl(i,s,r)=IF(Y(i)-pstart_a(s,r)<0,0,IF(((Y(i)-pstart_a(s,r))/pyears_a(s,r))<1,((Y(i)-pstart_a(s,r))/pyears_a(s,r))*plateau_a(s,r),plateau_a(s,r))) metre

imp(i,s,r)=IF(Y(i)-istart_a(s,r)<0,0,IF(((Y(i)-istart_a(s,r))/iyears_a(s,r))<1,((Y(i)-istart_a(s,r))/iyears_a(s,r))*impred_a(s,r),impred_a(s,r))) %

Sea level rise impact is the difference between the sea level rise and the tolerable sea level rise.

i(i,s,r)=IF((s(i)-atl(i,s,r))<0,0,s(i)-atl(i,s,r)) metre

The impact at reference GDP per capita, including plateau adaptation

iref(i,s,r)=WINCF(r)*((W(s)+IBEN(s)*SCAL)*(i(i,s,r)/SCAL)^POW(s)-i(i,s,r)*IBEN(s)) %

The impact at actual GDP per capita without saturation

igdp(i,s,r)=iref(i,s,r)*(gdp_per_cap_after_costs(i,r)/GDP_PER_CAP_FOCUS_0)^IPOW(s) %

Impact including saturation and impact adaptation

Modify ISAT to apply to GDP and ensure impact never exceeds 100% of consumption per capita

ISATG=ISAT*(1-SAVE/100)

Impact adaptation is bought for impmax metres or degC; beyond this, impact adaptation is ineffective

isat(i,s,r)=IF(igdp(i,s,r)<ISATG,igdp(i,s,r),ISATG+((100-SAVE)-ISATG)*((igdp(i,s,r)-ISATG)/(((100-SAVE)-ISATG)+(igdp(i,s,r)-ISATG))))*(1-imp(i,s,r)/100*if(i(i,s,r)<impmax(s,r),1,impmax(s,r)/i(i,s,r))) %

Impact per capita

isat_per_cap(i,s,r)=(isat(i,s,r)/100)* gdp_per_cap_after_costs(i,r) $

Remaining consumption per capita after the impact

rcons_per_cap(i,s,r)= cons_per_cap_after_costs(i,r)- isat_per_cap(i,s,r) $

Remaining GDP per capita after the impact is based on remaining consumption and the savings rate

rgdp_per_cap(i,s,r) = rcons_per_cap(i,s,r)/(1-SAVE/100) $

(this may appear to overestimate the impact on gdp, but it does not, as impacts are always subtracted from consumption, and rgdp is only used as the starting point for impacts for the next impact category. Any other form for this equation would lead to errors as remaining consumption would no longer be (1-SAVE/100) times remaining GDP, and so ISATG would no longer ensure impacts never exceeded remaining consumption).

The same calculation is performed for impacts 1 and 2. For impact 1 replace metres by degC, cons_per_cap_after_costs(i,r)and gdp_per_cap_after_costs(i,r)by rcons_per_cap(i,s,r) and rgdp_per_cap(i,s,r), and for impact 2 replace them with degC, rcons_per_cap(i,1,r) and rgdp_per_cap(i,1,r). Unlike PAGE2002, there is no tolerable temperature rise unless adaptation is bought.

Discontinuity has a different procedure as far as isat(i,dis,r), as it either occurs or doesn't, and if it occurs it takes time to reach its full effect.

The equilibrium impact from a discontinuity is

IREFEQDIS(r)=WINCF(r)*W(dis) %

The equilibrium impact at actual GDP per capita without saturation

igdpeqdis(i,dis,r)=IREFEQDIS(r)*(rgdp_per_cap(i,2,r)/GDP_PER_CAP_FOCUS_0)^IPOW(dis) %

The realised impact at actual GDP per capita without saturation is

igdp(1,dis,r)=occur_dis(1)*(1-EXPFDIS(1))*igdpeqdis(1,dis,r) %

igdp(i,dis,r) =igdp(i-1,dis,r)+occur_dis(i)*(1-EXPFDIS(i))*(igdpeq(i,dis,r)-igdp(i-1,dis,r)) %

i = 2 to 10.

where

EXPFDIS(i)=EXP(-(Y(i) – Y(i-1))/DISTAU)

and

occur_dis(i)=1 if i_dis(i)*PDIS/100>rand[0,1] or occur_dis(i-1)=1

occur_dis(i)=0 otherwise

Impact including saturation is

isat(i,dis,r)=IF(igdp(i,dis,r)<ISATG,igdp(i,dis,r),ISATG+(100-ISATG)*((igdp(i,dis,r)-ISATG)/((100-ISATG)+(igdp(i,dis,r)-ISATG)))) %

(there is no adaptation for discontinuity impacts).

The calculation of isat_per_cap(i,dis,r), rcons_per_cap(i,dis,r) and rgdp_per_cap(i,dis,r) follow the same form as for impact 2 with rcons_per_cap(i,1,r) and rgdp_per_cap(i,1,r) replaced by rcons_per_cap(i,2,r) and rgdp_per_cap(i,2,r).

Equity weighted impact uses the integrated form of equity weighting

wit(i,r) = (((CONS_PER_CAP_FOCUS_0)^EMUC)/(1-EMUC))*((cons_per_cap_after_costs(i,r)^(1-EMUC) – (rcons_per_cap(i,dis,r)) ^(1-EMUC))*POP(i,r) $

Impacts are first discounted using the utility discount factor, which is calculated from the constant PTP rate

DF(i) =(1+PTP/100)^(-(Y(i)-Y0))

widt (i,r)= wit(i,r)*DF(i) $million

And then aggregated

YAGG(i) = YHI(i) – YLO(i) years

where YHI and YLO are defined as in Hope(2006).

addt(i,r) = widt(i,r)*YAGG(i) $million

And then summed over r and i to give total impacts.

addt_gt = addt(i,r) summed over r and i $million

Impacts are capped at CIV_VALUE

td = min(addt_gt, CIV_VALUE) $million

Total impacts and costs

The total effect of climate change is the sum of impacts, abatement costs and adaptive costs

If total effect exceeds the statistical value of civilisation, it is capped at this level

te = min(td + tpc + tac, CIV_VALUE) $million

This is the quantity that optimal climate policy would seek to minimise.

Appendix 2: Full set of inputs for the calculations

PAGE09	version	1.7		Run	1		Date	14/05/10				
Base Year:	2008											
Analysis Years:		2009	2010	2020	2030	2040	2050	2075	2100	2150	2200	
Impacts:												
EN	Economic											
CU	Non-econ											
ptp rate	1.033333	<0.1,1, 2>			%/ year							
Equity weighted costs	1											
Elasticity of utility	1.166667	<0.5,1,2>										
	CO2	CH4	N2O	Lin								
Pre-industrial conc	278000	700	270	0	ppb							
Density	7.8	2.78	7.8	100000	Mt/ppb							
Forcing slope	5.5	0.036	0.12	0.2								
Stimulation		0	0	0	Mt/ppb							
Stay in air	30				%	<25,30,35>						
Emit to air		100	100	100	%							
Half life		10.5	114	1000	years							
Base year conc	395000	1860	322	0.11	ppb							
Cumulative emissions	2050000				Mtonnes							
Base year forcing	1.735	0.550	0.180	0.022	W/m2							

Regions & baseyear:		Area:	GDP	Pop	CO2 emit	CH4 emit	N2O emit	Lin emit	S emit	Natural S	RT	Latitude	
EU	EU	4.50E+06	1.39E+07	496	4400	24	1.400109	73.61871	4.1	7.0E-08	1	45	(Focus region)
USA	US	9.36E+06	1.30E+07	315	6183	29	1.234923	191.6451	5.5	7.0E-08	1	40	
Other OECD	OT	1.42E+07	7.32E+06	273	2438	22	0.66379	69.02367	1.7	7.0E-08	1.2	40	

FSU & ROE	EE	2.29E+07	3.10E+06	304	3216	38	0.448255	24.67513	11.9	7.0E-08	1.4	55
China & CP Asia	CA	1.17E+07	7.83E+06	1536	5040	56	2.436778	79.08005	32.2	7.0E-08	0.6	30
India & SE Asia	IA	8.90E+06	7.82E+06	2123	8286	71	1.02158	55.24011	6.6	7.0E-08	0.8	15
Africa & ME	AF	3.63E+07	4.69E+06	1219	4656	66	1.951801	33.74054	11.2	7.0E-08	0.7	20
Latin America	LA	3.47E+07	5.62E+06	581	3971	58	1.889284	30.18799	7.4	7.0E-08	0.85	20
		Km2	$million	million	Mtonne	Mtonne	Mtonne	Mtonne	TgS	Tg/Km2	degC	

GDP growth rates:	start	2008	2009	2010	2020	2030	2040	2050	2075	2100	2150	
	end	2009	2010	2020	2030	2040	2050	2075	2100	2150	2200	
	EU	1.9	1.9	1.9	1.9	1.9	1.7	1.7	1.7	1.7	1.7	%/year
	US	1.9	1.9	1.9	1.9	1.9	1.7	1.7	1.7	1.7	1.7	%/year
	OT	1.9	1.9	1.9	1.9	1.9	1.7	1.7	1.7	1.7	1.7	%/year
	EE	3.4	3.4	3.4	3.4	3.4	3.0	3.0	3.0	1.7	1.7	%/year
	CA	4.3	4.3	4.3	4.3	4.3	2.6	2.6	2.6	1.7	1.7	%/year
	IA	4.4	4.4	4.4	4.4	4.4	2.6	2.6	2.6	1.7	1.7	%/year
	AF	5.0	5.0	5.0	5.0	5.0	3.0	3.0	3.0	1.7	1.7	%/year
	LA	5.0	5.0	5.0	5.0	5.0	3.0	3.0	3.0	1.7	1.7	%/year

Pop growth rates	start	2008	2009	2010	2020	2030	2040	2050	2075	2100	2150	
	end	2009	2010	2020	2030	2040	2050	2075	2100	2150	2200	
	EU	0.3	0.3	0.3	0.3	0.2	-0.1	-0.2	-0.2	0.0	0.0	%/year
	US	0.8	0.8	0.8	0.8	0.6	0.4	0.4	0.3	0.0	0.0	%/year
	OT	0.4	0.4	0.4	0.1	0.0	-0.2	-0.3	-0.3	0.0	0.0	%/year
	EE	0.2	0.2	0.2	0.1	0.0	-0.3	-0.4	-0.5	0.0	0.0	%/year
	CA	0.5	0.5	0.5	0.4	-0.1	-0.7	-1.0	-1.5	0.0	0.0	%/year
	IA	1.6	1.6	1.6	1.2	0.7	0.1	-0.5	-1.1	0.0	0.0	%/year
	AF	2.5	2.5	2.5	2.1	1.3	0.7	0.0	-0.5	0.0	0.0	%/year
	LA	1.3	1.3	1.3	1.1	0.6	0.1	-0.3	-0.7	0.0	0.0	%/year
Excess forcing	0.65										W/m2	

PAGE09	version	1.7				
Science			**min**	**mode**	**max**	
	Percent of CO2 emitted to air	62.00	57	62	67	%
	Half-life of CO2 atmospheric residence	73.33	50	70	100	years
	Transient climate response	1.70	1	1.3	2.8	degC
	Stimulation of CO2 concentration	9.67	4	10	15	%/degC
	CO2 stimulation limit	53.33	30	50	80	%
	Land excess temperature ratio to ocean	1.40	1.2	1.4	1.6	
	Poles excess temperature change over equator	1.50	1	1.5	2	degC
	Sulfate direct (linear) effect in 2008	-0.47	-0.8	-0.4	-0.2	W/m2
	Sulfate indirect (log) effect for a doubling	-0.40	-0.8	-0.4	0	W/m2
	Sea level rise in 2008	0.15	0.1	0.15	0.2	m
	Sea level rise with temperature	1.73	0.7	1.5	3	m/degC
	Sea level asymptote	1.00	0.5	1	1.5	m
	Half-life of sea level rise	1000.00	500	1000	1500	years
	Half-life of global warming	35.00	10	30	65	years
	Equilibrium warming for a doubling of CO2	2.99				degC
Tolerable						
	Tolerable before discontinuity	3.00	2	3	4	degC
	Chance of discontinuity	20.00	10	20	30	% per degC
Weights						
	Savings rate	15.00	10	15	20	%
	Calibration sea level rise	0.50	0.45	0.5	0.55	m
	Calibration temperature	3.00	2.5	3	3.5	degC
	Sea level initial benefit	0.00	0	0	0	%GDP per m
	Sea level impact at calibration sea level rise	1.00	0.5	1	1.5	%GDP
	Sea level impact function exponent	0.73	0.5	0.7	1	
	Sea level exponent with income	-0.30	-0.4	-0.3	-0.2	
	Economic initial benefit	0.13	0	0.1	0.3	%GDP per degC

Economic impact at calibration temperature	0.50	0.2	0.5	0.8	%GDP
Economic impact function exponent	2.17	1.5	2	3	
Economic exponent with income	-0.13	-0.3	-0.1	0	
Non-econ initial benefit	0.08	0	0.05	0.2	%GDP per degC
Non-econ impact at calibration temperature	0.53	0.1	0.5	1	%GDP
Non-econ impact function exponent	2.17	1.5	2	3	
Non-econ exponent with income	0.00	-0.2	0	0.2	
Loss if discontinuity occurs	15.00	5	15	25	%GDP
Discontinuity exponent with income	-0.13	-0.3	-0.1	0	
Half-life of discontinuity	90.00	20	50	200	years
Impacts saturate beyond	33.33	20	30	50	%consumption
Statistical value of civilisation	5.3E+10	1.00E+10	5.00E+10	1.00E+11	$million
US weights factor	0.80	0.6	0.8	1	
OT weights factor	0.80	0.4	0.8	1.2	
EE weights factor	0.40	0.2	0.4	0.6	
CA weights factor	0.80	0.4	0.8	1.2	
IA weights factor	0.80	0.4	0.8	1.2	
AF weights factor	0.60	0.4	0.6	0.8	
LA weights factor	0.60	0.4	0.6	0.8	

Adaptive costs

Adaptive costs sea level plateau	0.0233	0.01	0.02	0.04	%GDP per metre
Adaptive costs sea level impact	0.0012	0.0005	0.001	0.002	%GDP per %reduction per metre
Adaptive costs Economic plateau	0.0117	0.005	0.01	0.02	%GDP per degC
Adaptive costs Economic impact	0.0040	0.001	0.003	0.008	%GDP per %reduction per degC
Adaptive costs Non-econ plateau	0.0233	0.01	0.02	0.04	%GDP per degC
Adaptive costs Non-econ impact	0.0057	0.002	0.005	0.01	%GDP per %reduction per degC
US Adaptive costs factor	0.80	0.6	0.8	1	
OT Adaptive costs factor	0.80	0.4	0.8	1.2	
EE Adaptive costs factor	0.40	0.2	0.4	0.6	
CA Adaptive costs factor	0.80	0.4	0.8	1.2	
IA Adaptive costs factor	0.80	0.4	0.8	1.2	
AF Adaptive costs factor	0.60	0.4	0.6	0.8	
LA Adaptive costs factor	0.60	0.4	0.6	0.8	

Preventative costs

CO2					
Uncertainty in BAU emissions in 2200	8.33	-50	0	75	%
Cutbacks at negative cost	20.00	0	20	40	% of emissions
Most negative cost cutback	-233.33	-400	-200	-100	$million per Mtonne
Maximum cutbacks at positive cost	70.00	60	70	80	% of emissions
Maximum cutback cost	400.00	100	400	700	$million per Mtonne
Initial experience stock	150000.00	100000	150000	200000	Mtonne
CH4					
Uncertainty in BAU emissions in 2200	25.00	-25	0	100	%
Cutbacks at negative cost	10.00	0	10	20	% of emissions
Most negative cost cutback	-4333.33	-8000	-4000	-1000	$million per Mtonne
Maximum cutbacks at positive cost	51.67	35	50	70	% of emissions
Maximum cutback cost	6333.33	3000	6000	10000	$million per Mtonne
Initial experience stock	2000.00	1500	2000	2500	Mtonne

N2O					
Uncertainty in BAU emissions in 2200	0.00	-50	0	50	%
Cutbacks at negative cost	10.00	0	10	20	% of emissions
Most negative cost cutback	-7333.33	-15000	-7000	0	$million per Mtonne
Maximum cutbacks at positive cost	51.67	35	50	70	% of emissions
Maximum cutback cost	27333.33	2000	20000	60000	$million per Mtonne
Initial experience stock	53.33	30	50	80	Mtonne
Lin					
Uncertainty in BAU emissions in 2200	0.00	-50	0	50	%
Cutbacks at negative cost	10.00	0	10	20	% of emissions
Most negative cost cutback	-233.33	-400	-200	-100	$million per Mtonne
Maximum cutbacks at positive cost	70.00	60	70	80	% of emissions
Maximum cutback cost	333.33	100	300	600	$million per Mtonne
Initial experience stock	2000.00	1500	2000	2500	Mtonne
US uncertainty in BAU emissions factor	1.00	0.8	1	1.2	
OT uncertainty in BAU emissions factor	1.00	0.8	1	1.2	
EE uncertainty in BAU emissions factor	1.00	0.65	1	1.35	
CA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
IA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
AF uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
LA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
US negative cost percentage factor	1.08	0.75	1	1.5	
OT negative cost percentage factor	1.00	0.75	1	1.25	
EE negative cost percentage factor	0.70	0.4	0.7	1	
CA negative cost percentage factor	0.70	0.4	0.7	1	
IA negative cost percentage factor	0.70	0.4	0.7	1	
AF negative cost percentage factor	0.70	0.4	0.7	1	
LA negative cost percentage factor	0.70	0.4	0.7	1	
US maximum cost factor	1.00	0.8	1	1.2	
OT maximum cost factor	1.23	1	1.2	1.5	
EE maximum cost factor	0.70	0.4	0.7	1	

	CA maximum cost factor	1.00	0.8	1	1.2	
	IA maximum cost factor	1.23	1	1.2	1.5	
	AF maximum cost factor	1.23	1	1.2	1.5	
	LA maximum cost factor	0.70	0.4	0.7	1	
	Cutbacks at negative cost in 2200 as multiple of 2008	0.73	0.3	0.7	1.2	
	Cutbacks at negative cost growth rate	-0.16				% per year
	Maximum cutbacks in 2200 as multiple of 2008	1.27	1	1.3	1.5	
	Maximum cutbacks growth rate	0.12				% per year
	Most negative cost in 2200 as multiple of 2008	0.83	0.5	0.8	1.2	
	Most negative cost growth rate	-0.09				% per year
	Curvature below zero cost	0.50	0.25	0.45	0.8	
	Curvature above zero cost	0.40	0.1	0.4	0.7	
	Experience crossover ratio	0.20	0.1	0.2	0.3	
	Learning rate	0.20	0.05	0.2	0.35	
All costs						
	Costs in 2200 as multiple of 2008	0.65	0.5	0.65	0.8	
	Autonomous technical change	0.22				% per year
	Equity weights proportion	1.00	1	1	1	

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Prevention	**A1B emissions**										
	2009	**2010**	**2020**	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	
EU CO2 emissions	100	100	102	104	98	97	80	66	66	66	%
US CO2 emissions	100	100	102	104	98	97	80	66	66	66	%
OT CO2 emissions	100	100	102	104	98	97	80	66	66	66	%
EE CO2 emissions	102	104	95	96	91	90	72	62	62	62	%
CA CO2 emissions	103	107	136	165	183	198	195	176	176	176	%
IA CO2 emissions	103	107	136	165	183	198	195	176	176	176	%
AF CO2 emissions	103	107	138	168	187	210	208	178	178	178	%
LA CO2 emissions	103	107	138	168	187	210	208	178	178	178	%
EU CH4 emissions	100	100	96	93	80	77	63	58	58	58	%
US CH4 emissions	100	100	96	93	80	77	63	58	58	58	%
OT CH4 emissions	100	100	96	93	80	77	63	58	58	58	%
EE CH4 emissions	104	107	113	109	92	86	69	62	62	62	%
CA CH4 emissions	101	103	121	142	147	143	103	81	81	81	%
IA CH4 emissions	101	103	121	142	147	143	103	81	81	81	%
AF CH4 emissions	102	103	124	141	142	146	125	97	97	97	%
LA CH4 emissions	102	103	124	141	142	146	125	97	97	97	%
EU N2O emissions	100	100	103	102	98	96	89	84	84	84	%
US N2O emissions	100	100	103	102	98	96	89	84	84	84	%
OT N2O emissions	100	100	103	102	98	96	89	84	84	84	%
EE N2O emissions	100	101	103	104	102	100	91	87	87	87	%
CA N2O emissions	100	101	102	107	110	111	108	108	108	108	%
IA N2O emissions	100	101	102	107	110	111	108	108	108	108	%
AF N2O emissions	100	100	101	105	107	109	109	109	109	109	%
LA N2O emissions	100	100	101	105	107	109	109	109	109	109	%

EU Lin emissions	103	107	97	101	105	109	117	126	126	126	%
US Lin emissions	103	107	97	101	105	109	117	126	126	126	%
OT Lin emissions	103	107	97	101	105	109	117	126	126	126	%
EE Lin emissions	104	107	184	266	349	361	368	334	334	334	%
CA Lin emissions	106	113	234	452	669	910	1108	1029	1029	1029	%
IA Lin emissions	106	113	234	452	669	910	1108	1029	1029	1029	%
AF Lin emissions	108	115	236	479	722	878	1007	952	952	952	%
LA Lin emissions	108	115	236	479	722	878	1007	952	952	952	%

EU sulphates	93	87	61	60	56	61	47	41	41	41	%
US sulphates	93	87	61	60	56	61	47	41	41	41	%
OT sulphates	93	87	61	60	56	61	47	41	41	41	%
EE sulphates	101	102	90	66	36	29	13	13	13	13	%
CA sulphates	104	109	140	99	51	39	17	16	16	16	%
IA sulphates	104	109	140	99	51	39	17	16	16	16	%
AF sulphates	104	108	136	201	191	192	89	65	65	65	%
LA sulphates	104	108	136	170	191	192	89	65	65	65	%

Excess forcing	0.70	0.71	0.80	0.83	0.81	0.80	0.69	0.55	0.55	0.55	W/m2

New adaptation

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU sea level	0.25	2000	20	50	2020	40	1
US sea level	0.25	2000	20	50	2020	40	1
OT sea level	0.25	2000	20	50	2020	40	1
EE sea level	0.25	2000	20	50	2020	40	1
CA sea level	0.20	2000	30	25	2020	40	1
IA sea level	0.20	2000	30	25	2020	40	1
AF sea level	0.20	2000	30	25	2020	40	1
LA sea level	0.20	2000	30	25	2020	40	1

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU Economic	1.0	2000	20	30	2010	20	2

US Economic	1.0	2000	20	30	2010	20	2
OT Economic	1.0	2000	20	30	2010	20	2
EE Economic	1.0	2000	20	30	2010	20	2
CA Economic	1.0	2010	30	15	2010	30	2
IA Economic	1.0	2010	30	15	2010	30	2
AF Economic	1.0	2010	30	15	2010	30	2
LA Economic	1.0	2010	30	15	2010	30	2

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU Non-econ	0	2000	100	15	2010	40	2
US Non-econ	0	2000	100	15	2010	40	2
OT Non-econ	0	2000	100	15	2010	40	2
EE Non-econ	0	2000	100	15	2010	40	2
CA Non-econ	0	2000	100	15	2010	40	2
IA Non-econ	0	2000	100	15	2010	40	2
AF Non-econ	0	2000	100	15	2010	40	2
LA Non-econ	0	2000	100	15	2010	40	2

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Prevention	**2016 r5 low emissions**										
	2009	**2010**	**2020**	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	
EU CO2 emissions	100	100	84	55	26	15	4	1	1	1	%
US CO2 emissions	100	100	76	47	18	10	3	1	1	1	%
OT CO2 emissions	100	100	80	51	21	12	3	1	1	1	%
EE CO2 emissions	102	104	86	58	32	19	5	1	1	1	%
CA CO2 emissions	103	107	130	93	58	33	8	2	2	2	%
IA CO2 emissions	103	107	135	103	71	44	13	3	3	3	%
AF CO2 emissions	103	107	130	99	70	44	14	4	4	4	%
LA CO2 emissions	103	107	114	78	43	25	6	2	2	2	%
EU CH4 emissions	100	100	90	59	32	30	30	34	34	34	%
US CH4 emissions	100	100	86	56	29	29	33	42	42	42	%
OT CH4 emissions	100	100	79	47	19	16	14	16	16	16	%
EE CH4 emissions	104	107	94	57	23	20	18	18	18	18	%
CA CH4 emissions	101	103	111	73	40	33	26	22	22	22	%
IA CH4 emissions	101	103	133	99	71	70	71	65	65	65	%
AF CH4 emissions	102	103	121	87	59	60	68	71	71	71	%
LA CH4 emissions	102	103	104	66	32	28	25	25	25	25	%
EU N2O emissions	100	100	111	114	111	108	89	68	68	68	%
US N2O emissions	100	100	111	114	111	108	89	68	68	68	%
OT N2O emissions	100	100	111	114	111	108	89	68	68	68	%
EE N2O emissions	100	101	111	116	115	112	92	71	71	71	%
CA N2O emissions	100	101	110	120	124	125	109	87	87	87	%
IA N2O emissions	100	101	110	120	124	125	109	87	87	87	%
AF N2O emissions	100	100	108	117	120	122	110	88	88	88	%
LA N2O emissions	100	100	108	117	120	122	110	88	88	88	%
EU Lin emissions	94	88	32	28	23	16	5	1	1	1	%

US Lin emissions	94	88	30	25	21	15	5	2	2	2	%
OT Lin emissions	94	88	25	19	12	8	2	1	1	1	%
EE Lin emissions	103	105	97	63	29	18	4	1	1	1	%
CA Lin emissions	104	108	160	121	82	54	12	2	2	2	%
IA Lin emissions	104	108	198	176	154	109	33	7	7	7	%
AF Lin emissions	106	111	138	108	77	54	16	4	4	4	%
LA Lin emissions	106	111	123	84	45	28	6	2	2	2	%
EU sulphates	94	87	50	36	25	15	6	2	2	2	%
US sulphates	94	87	50	36	25	15	6	2	2	2	%
OT sulphates	94	87	50	36	25	15	6	2	2	2	%
EE sulphates	101	102	74	43	16	8	2	1	1	1	%
CA sulphates	104	109	115	66	23	12	2	1	1	1	%
IA sulphates	104	109	115	66	23	12	2	1	1	1	%
AF sulphates	104	108	112	94	85	50	13	3	3	3	%
LA sulphates	104	108	112	94	85	50	13	3	3	3	%
Excess forcing	0.70	0.71	0.74	0.58	0.40	0.27	0.16	0.12	0.12	0.12	W/m2

New adaptation

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU sea level	0.25	2000	20	50	2020	40	1
US sea level	0.25	2000	20	50	2020	40	1
OT sea level	0.25	2000	20	50	2020	40	1
EE sea level	0.25	2000	20	50	2020	40	1
CA sea level	0.20	2000	30	25	2020	40	1
IA sea level	0.20	2000	30	25	2020	40	1
AF sea level	0.20	2000	30	25	2020	40	1
LA sea level	0.20	2000	30	25	2020	40	1

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU Economic	1.0	2000	20	30	2010	20	2
US Economic	1.0	2000	20	30	2010	20	2
OT Economic	1.0	2000	20	30	2010	20	2

EE Economic	1.0	2000	20	30	2010	20	2
CA Economic	1.0	2010	30	15	2010	30	2
IA Economic	1.0	2010	30	15	2010	30	2
AF Economic	1.0	2010	30	15	2010	30	2
LA Economic	1.0	2010	30	15	2010	30	2

	Plateau	Pstart	Pyears	Impred	Istart	Iyears	Impmax
EU Non-econ	0	2000	100	15	2010	40	2
US Non-econ	0	2000	100	15	2010	40	2
OT Non-econ	0	2000	100	15	2010	40	2
EE Non-econ	0	2000	100	15	2010	40	2
CA Non-econ	0	2000	100	15	2010	40	2
IA Non-econ	0	2000	100	15	2010	40	2
AF Non-econ	0	2000	100	15	2010	40	2
LA Non-econ	0	2000	100	15	2010	40	2