# Peak and Decline Emissions Paths and the Global Warming Target

**Peter Sheehan, Roger Jones and Roger Bodman**

Victoria Institute of Strategic Economic Studies

Climate Change Working Paper No. 20

May 2015

Victoria Institute of Strategic Economic Studies
Victoria University
PO Box 14428
Melbourne VIC 8001 Australia
Telephone +613 9919 1340
Contact: peter.sheehan@vu.edu.au

# Peak and Decline Emissions Paths and the Global Warming Target

## Abstract

The global community is negotiating a new agreement to limit global warming to less than 2°C, and major countries have committed to emissions reductions to achieve that target. Yet greenhouse gas emissions continue to rise, reaching about 53 $GtCO_2e$ in 2013[1,2] and heading towards 54-58 Gt by 2020[3]. These facts imply that high peak, rapid decline emissions paths will be required, but little is known about their properties. We characterise a suite of high peak, rapid decline paths by drawing on the standard finding that the diffusion of new technologies starts slowly but accelerates as investment grows, learning develops, unit costs fall and networks expand. There is strong evidence of such processes at work now with clean energy technologies. Using a logistic model with a carbon constraint, we show that the less than 2°C target remains feasible for 2020 emissions levels of 54-58 $GtCO_2e$, but that every 1 $GtCO_2e$ rise in 2020 emissions raises the required rate of decline in emissions over 2020-50 by about 0.1 percentage points. These results indicate that, given high emissions to 2020, strong self-reinforcing emissions reduction paths after 2020 driven by the accelerating adoption of new technologies will be vital. International negotiations should give higher priority to such paths, recognising the powerful technological forces that are now at work. Indicative if not binding commitments might be sought from all countries to rates of decline of emissions after 2020. All nations should give renewed attention to ways of supporting and benefitting from the rapid development, diffusion and sharing of clean technologies now underway.

## Introduction

Climate scientists have studied a wide range of future emissions pathways out to or beyond 2100, with climate models of varying degrees of complexity used to assess the implied climate outcomes for each pathway. The prevailing approach in the literature to providing guidance on what future paths are consistent with a given temperature target is to infer the conditions that the paths must meet from the descriptive statistics of the pathway sample.

The consensus up until 2012 was that total emissions of Kyoto gases must be held to 44-48 $GtCO_2e$ in 2020, and to fall by 2.5-3.0% over 2020-50, for a 50% probability of limiting warming to <2°C.[4,5,6] These findings were influential in negotiations at Conference of the Parties (COP) meetings and are reflected in the current focus in the UNFCCC on closing the ‘emissions gap’ by 2020. More recently it has been argued[7] that a range of 2020 emissions up to 55 $GtCO_2e$ may preserve the option of meeting the <2°C target, but that a level of 47 $GtCO_2e$ or less in 2020 would allow the target to be achieved with less risk about the development and use of key technologies.

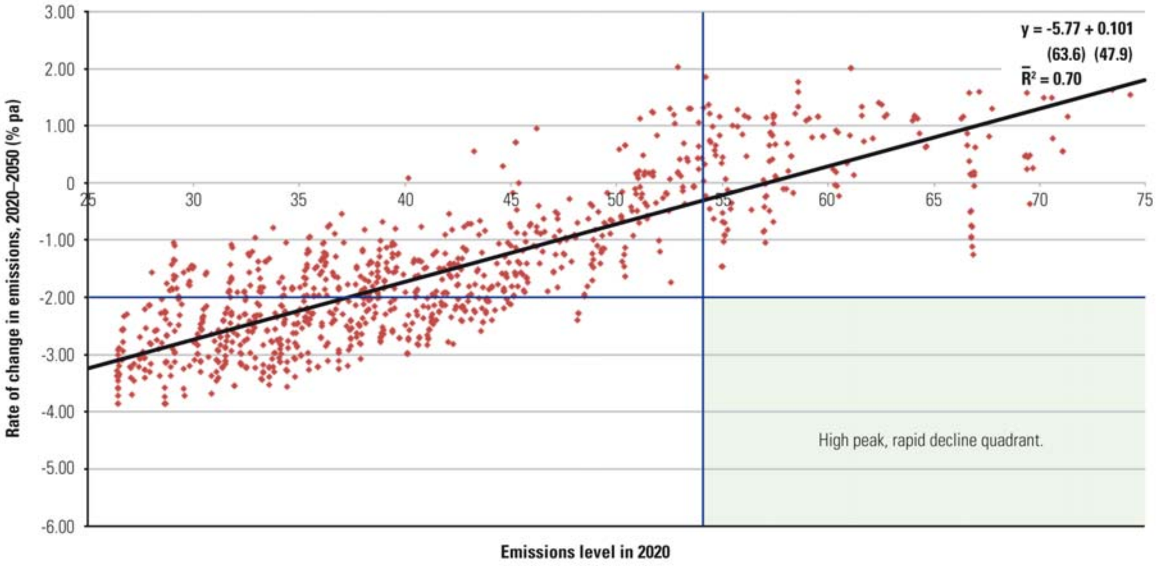
The IPCC Fifth Assessment Report (AR5) followed a similar methodology, based on a meta-analysis of a large sample of published scenarios in Working Group III (WGIII)[8] and of multiple model runs of the Representative Concentration Pathways (RCPs) in Working Group 1 (WGI).[9] As a result of these various forms of analysis, the AR5 Synthesis Report opted for more generalised guidance, noting that paths likely to hold warming to less than 2°C would require substantial emissions reductions over the next few decades, amounting to 40%-70% over 2010-2050, and near zero emissions by the end of the century.[10]

The key limitation of the meta-analytic approach is that the assembled scenarios are very diverse, in terms of whether or not policy mechanisms are employed, in the nature and extent of the modelling of new technologies and in many other respects. There is no justification for making general inferences from such a diverse but unrepresentative sample. In particular, for historical reasons the scenarios sets have few high peak, rapid decline scenarios, here defined as pathways with 2020 emissions at or over 54 GtCO$_2$e but with a rate of decline in emissions over 2020-50 of 2% per annum or more.

Figure 1a shows some characteristics of a set of 1004 scenarios assembled by Meinshausen et al (2009),[5] both from the literature and from their own scenario generation process (for details see Appendix). None of these is a high peak, rapid decline path in this sense. Figure 1b shows data on 846 paths assembled by the WGIII authors from the literature and from new modelling runs undertaken for the IPCC report.[8] This new set of scenarios is quite different, but in the IPCC data set only 16 of the 846 scenarios (1.9%) are high peak, rapid decline scenarios, and so have very little weight in any meta-analysis. Figure 1b also includes the RCP scenarios, none of which is high peak, rapid decline.

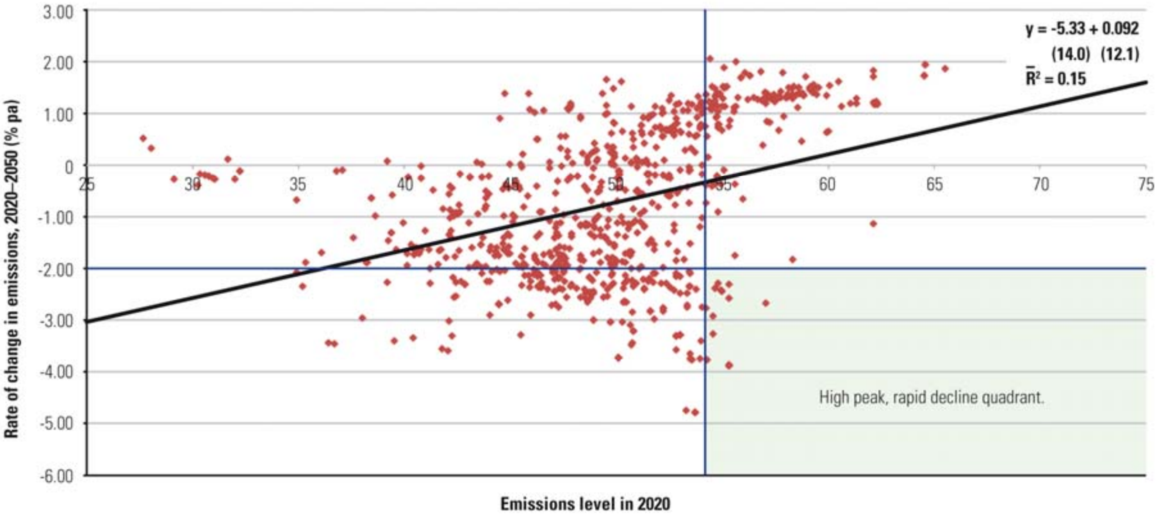
**Figure 1: Emissions levels in 2020 and rates of change in emissions over 2020-50: Two sets of scenarios**

**Panel a. 1004 emissions pathways assembled and analysed in Meinshausen et al. (2009)**



Source: See endnote 5.

**Panel b. 846 scenarios assembled and analysed in the IPCC Fifth Assessment Report**



Source: See endnote 10.

This effective exclusion of high peak, rapid decline paths is not because the required reductions over 2020-50 are atypical – in the two data sets 42.8% and 24.1% respectively show reductions of 2.0% per annum or more. These meta-analyses do not show by complex empirical modelling that paths with emissions of over 54 $GtCO_2e$ in 2020 are incompatible with a reasonable chance of holding 2100 warming to <2°C. They in effect assume that this is the case through the specification of the envelope of pathways that is analysed.

One reason for the exclusion of high peak paths is that many scenarios seriously underestimated the growth in emissions in countries such as China and India after about 2000.[11] It has also been common to study climate change under higher and lower scenarios, determined by different story lines, assumptions and degrees of mitigation action. This has resulted in smooth trajectories with a strong positive correlation between the emissions level and the future rate of change in emissions (as evident in the regression lines in Figure 1), hence precluding high peak, rapid decline paths.

## The diffusion of innovation and the logistic function

Here we apply a specific functional form, drawn from the literature on innovation and technology diffusion, to emissions paths from 2020, together with a carbon budget, to study the conditions under which high peak, rapid decline paths are consistent with less than 2°C warming.

Many processes of change – such as technology diffusion, industrial change or a new social movement – exhibit self-reinforcing path dependency. Change takes place slowly at first but accelerates as investment or activity grows and the path dependent benefits start to build. Learning develops, unit costs fall, networks and complementarities expand, firms and individuals respond and adoption rises rapidly. But as adoption reaches a saturation level the rate of further adoption slows. Many of the factors known to generate path dependency are central to the energy system and to the path of emissions. For example, sunk costs[12,13] – whether in physical capital, technology, education and reputation – are widespread. Learning by doing and scale economies are substantial in many clean technologies.[14,15] Technological and production complementarities between industries are likely to be strong as new technologies are developed and diffused, as are other externalities.[16] Path dependent social dynamics[17]can also be relevant to the social systems underpinning emissions trajectories.

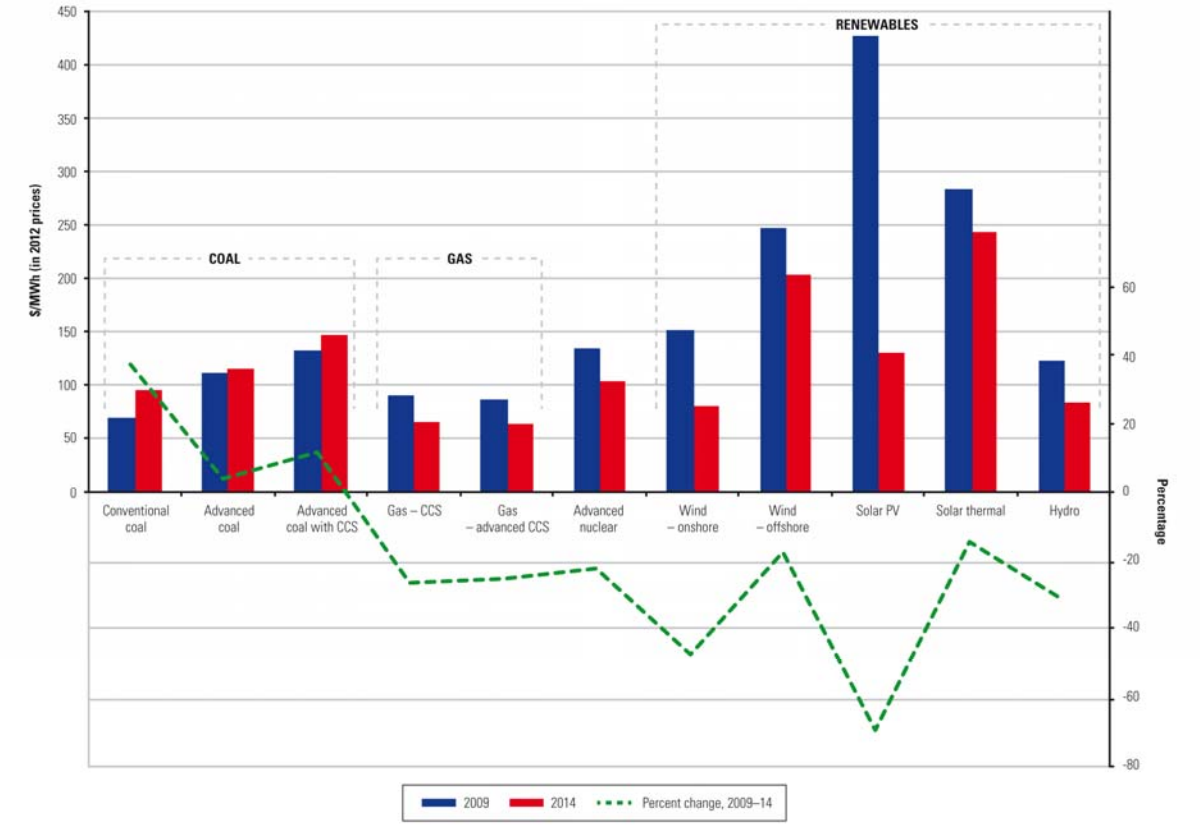
There is a substantial body of literature in economics (dating from Griliches 1957[18] and Mansfield 1961[19]), industrial sociology (dating from Rogers 1962[20]) and in energy studies[21,22] using the logistic function to model such self-reinforcing path dependent processes of technology diffusion over time. Recent work[23] has shown that the pace of diffusion across countries accelerated significantly over the 20th Century, but some have queried the relevance of the asymptotic properties of the logistic function[24] to describing the process of diffusion. Here we model the path of global emissions after 2020 consistent with a given carbon constraint by using a simple logistic function, with the asymptotic properties truncated (see methods).

There is no guarantee that emissions after 2020 will follow a logistic path, but there are growing signs that the underlying forces are being put in place. For example, Figure 2 shows estimates of the future levelised cost of electricity in the USA, for new plants being planned in 2009 and 2014 respectively, in $/MWh at 2012 prices.[25] The expected cost of generation has fallen sharply for all of the renewable sources shown, especially for onshore wind and solar PV, while rising for power from coal. By 2014 the projected cost level was lower for both hydro and onshore wind generation than for coal, with combined cycle gas plants as the cheapest option. Similar results are evident for the world as a whole.[26] As a result, global investment in renewable energy sources of US$214 billion in 2013 was about double that in new fossil fuel power plants excluding investment in replacement capacity.[27]

Many recent studies have reported on the overall carbon budget constraint consistent with <2°C global warming, in terms of the allowable level of cumulative emissions of $CO_2$ since the industrial revolution (see Appendix for details). Ignoring outliers, the studies imply a total carbon budget, for a 50% probability or higher of holding warming to <2°C, in the 965-1300 GtC range. With about 515 GtC emitted up to 2010, this gives a post-2010 carbon budget of 450-785 GtC. For the few studies using a 66% probability of holding warming to <2°C the post-2010 range is 460-590 GtC. WGI of AR5 concluded that the post-2010 budget constraints for $CO_2$ alone, for a 66% and 50% probability of holding warming to <2°C, were 480 GtC and 680 GtC respectively.[9]

These estimates generally presume that, over the future as in the past, the warming effects of Kyoto gases other that $CO_2$, such as $CH_4$ and $N_2O$, will be offset by the cooling effects of $SO_2$ and other aerosols. This is consistent with the well-established finding of a relationship between cumulative emissions of $CO_2$ only and temperature change, and with the historical record of radiative forcing from $CO_2$ and all other factors on a net basis. But the issues are complex, and new scientific work on aerosols reviewed in WGI[10] throws doubt on whether the net forcing from all factors other than $CO_2$ will be approximately zero in the future.

**Figure 2. Estimated levelised cost of electricity for new power projects under consideration in the USA, by fuel type, 2009 and 2014 ($/MWh in constant 2012 prices)**



Source: See endnotes 30 and 31.

Here we examine the implications of three post-2010 carbon budget constraints – 450, 550 and 650 GtC – to take account of this and other uncertainties, and also provide results for the 480 GtC and 680 GtC constraints. We apply the logistic path to all Kyoto gases, holding the contribution of warming gases other than $CO_2$ at 25% of the total. As non-$CO_2$ Kyoto emissions fall in line $CO_2$ emissions it seems reasonable to assume that their contribution is offset by other cooling factors, but we test sensitivities in which this is not the case.

## Logistic paths consistent with the budget constraints

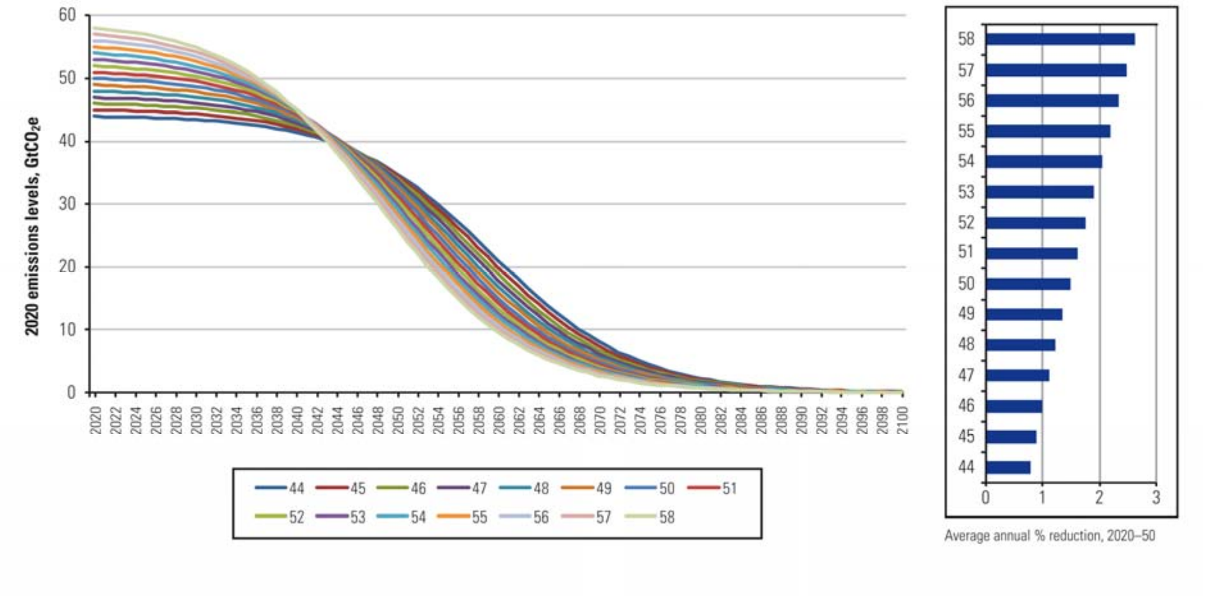
Panel (a) of Figure 3 shows, for the 450 GtC carbon budget constraint, the estimated logistic paths for total $CO_2e$, starting from 2020 emissions levels of 44-58 $GtCO_2e$. For the 44-58 $GtCO_2e$ range and the 450 GtC constraint, the required reduction in total emissions over 2020-50 is 0.7% to 2.6% per annum, and for the 52-58 $GtCO_2e$ part of this range is 1.7% to 2.6% per annum.

Panel (b) of Figure 3 shows, for 2020 emissions from 52-58 $GtCO_2e$, the paths consistent with three post 2010 carbon budget constraints, and the rates of reduction in emissions over 2020-50. For the higher carbon budgets (550 GtC and 650 GtC) the emissions paths are relatively flat after 2020, with rapid declines emerging only after 2040 (550 GtC constraint) and after 2050 (650 GtC constraint). As a result, the implied average annual rates of reduction in emissions over 2020-50 are modest – being 0.6-1.0% and 0.2-0.3% respectively. For the IPCC's central estimate of the carbon constraint for a

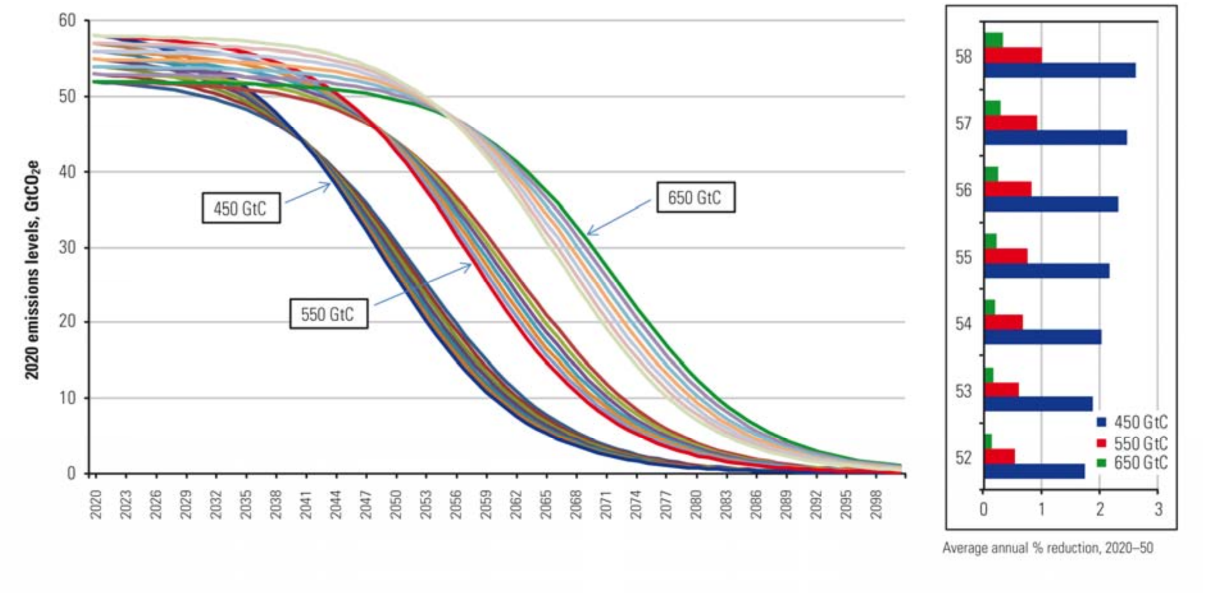
66% probability of achieving <2°C (480 GtC) the required reduction range is 1.3-2.0%, while for its 50% probability constraint (680 GtC) the required reductions are less than for 650 GtC constraint.

**Figure 3. Emissions paths consistent with holding warming to <2°C, for different 2020 emissions levels and carbon budget constraints. Panel (a): paths consistent with a carbon constraint of 450 GtC, for emissions in 2020 at 44-58 GtCO$_2$e, and rates of change over 2020-50. Panel (b): paths consistent with 450, 550 and 650 560 GtC constraints and 2020 emissions levels of 52-58 GtCO$_2$e, and the average annual rate of change over 2020-50 as a percentage of the 2010 level. Estimates of the authors.**

**Panel a: Post-2010 budget constraints of 450 GtC, for 2020 emissions levels for all Kyoto gases from 44-58 GtCO$_2$e**



**Panel b: Post-2010 budget constraints from 450-650GtC, for emissions levels from 52-58 GtCO$_2$e**



We report on three sensitivities around these results. First, for the 450 GtC constraint each 1 $GtCO_2e$ rise in 2020 emissions increases the required rate of reduction by 0.15 percentage points. This sensitivity falls as the budget constraint rises, being only 0.08 percentage points for the 550 GtC constraint and 0.03 points for the 650 GtC constraint.

Secondly, for the 450 GtC constraint, the impact on the required rate of reduction in emissions over 2020-50 of a 10% change in the 2020 emissions level and in the carbon budget constraint is broadly similar. For example, for a 2020 emissions level of 52 $GtCO_2e$ and a carbon constraint of 450 GtC the required annual reduction is 1.7%; for a 10% increase in both variables (to 57 $GtCO_2e$ and 495 GtC) the required rate of reduction is still about 1.7%.

Thirdly, we tested the sensitivity of these results for less than complete offsetting of the warming effects of non-$CO_2$ gases by the cooling effects of aerosols and other factors. At the IPCC 66% probability constraint (480 GtC), for every 10% of non-$CO_2$ warming not offset by aerosols the required reduction over 2020-50 rises by about 0.25 percentage points, while at the 50% constraint (680GtC) the effect is only about 0.05 percentage points.

These results show that high peak, rapid decline paths to achieve the <2°C target for peak warming remain feasible in a specific sense, that the required reduction in emissions over 2020-50 are consistent with those generated in many model runs. At the IPCC 66% probability carbon constraint the required annual reduction in emissions over 2020-50 is 1.3-2.0%, and about one-third of the model runs summarised in Figure 1 show reductions of 2% or more. While the required 2020-50 rate of reduction falls as the carbon constraint rises, for a given carbon constraint it increases with the 2020 level of emissions and with the proportion of future warming from non-$CO_2$ gases not offset by aerosol effects.

## Conclusions

These results have implications for both global and national climate policy. At COP17 in Durban in 2011 the Parties determined that they will sign, by 2015, a legal instrument binding on all Parties and to be effective from 2020.[28] As a result processes have been underway within the UNFCCC both to reduce 2020 emissions and to obtain commitments about emissions beyond 2020. Our results show that, while the <2°C target remains feasible for quite high 2020 emissions levels, the key requirement is to achieve an accelerating, path dependent process of emissions reductions. With evidence of such processes underway for many technologies and being driven by powerful economic forces, the proposed 2015 agreement should give a central place to commitments about the pace of emissions reductions after 2020. It is also important that the agreement does not limit the incentives for countries to pursue more rapid reductions than they are willing to include in binding agreements.

In terms of national policies, a renewed emphasis on making use of self-reinforcing, market-based processes to drive emissions down will involve greater use of carbon pricing, to reflect true economic costs, and strong support for innovation in both energy-use and energy-supply technologies. Much is being achieved in terms of renewable energy production, but investment in geosequestration technologies is subdued and much greater effort is needed to realise the potential of efficient end-use energy technologies.[29]

## Methods

Consider the non-linear differential equation for technology diffusion:

$$dy/dt = k(y(t)-a)*(b-y(t)) \tag{1}$$

where the rate of growth of *y* (the proportion of firms adopting the technology at time *t*) is a function of the number of new adopters *y(t)-a* (where *a* is the starting point of diffusion) and the number yet to adopt *y(t)-b* (where *b* is the end point of diffusion) and a constant *k* influencing the overall rate of growth. Equation (1) defines a bell-shaped path for the rate of adoption (*dy/dt*) between *a* and *b,* and an S-shaped curve for the total level of adoption between *a* and *b.* For a starting point with no diffusion (*a = 0*) the solution to this differential equation is the logistic function:

$$y(t) = b/1+e^{-(c+\alpha t)} \tag{2}$$

where *c* is a constant of integration and $\alpha = kb$. The cumulative level of adoption *y* follows the logistic curve, with *y* going to *0* as *t* goes to -∞ and going to *b* as *t* goes to +∞. The long asymptotic tails create a problem for applications to actual adoption practices, and here those tails are truncated.

In this application we assume that the uptake of emissions-reducing technology and practices follow the logistic forms, that global emissions after 2020 follow a (declining) logistic form. Here *y* represents the cumulative uptake of those technologies and practices after 2020, and hence *y* is given by:

$$y(t) = (1 - \frac{1}{(1+e^{-(c+\alpha t)})}) \tag{3}$$

where *t* = 0 at 2020, and total emissions at year *t* are given by:

$$E_t = E_{2020}*\beta* y(t) \tag{4}$$

In equation (4) $\alpha$, the coefficient of *t,* influences the shape of the curve over time; *c* influences the position of the curve in the adoption space and β is an alignment parameter which we use to ensure that the emissions curve aligns close to the 2020 level in 2021. The first ten years of the logistic curve are truncated, with 2021 being the 11th year of the logistic functions used. Logistic curves chosen are required to give emissions close to zero by 2100, but a residual element is used to account for spillovers, equal to five times the level of emissions in the 2100 year. No allowance is made for negative emissions, or for an irreducible component of total emissions. Total emissions from 2020 onwards, for a given emissions path, are thus the sum of total annual emissions for each year 2020-2100 inclusive, plus five times the 2100 level of emissions.

Equation (4) is applied to total Kyoto emissions, and paths consistent with various 2020 emissions levels and the post 2010 carbon budget constraint are calculated. While the policy debate is mainly conducted in terms of emissions of all Kyoto gases, and hence in $GtCO_2e$, the budget constraints in the literature are for carbon and in GtC. Emissions of all Kyoto gases are assumed to be 50 $GtCO_2e$ in 2010. From this base, total emissions from 2010 to 2020 are calculated, for a range of 2020 emissions levels from 44-60 $GtCO_2e$ by straight line interpolation. Total emissions over this period and in 2020, as well as the residual budget constraint from 2020, are expressed in $GtCO_2e$ by assuming that non-carbon sources provide 25% of all emissions of Kyoto gases.

There is clearly no single set of values of the parameters $c$, $\alpha$ and $\beta$ in equation (4) consistent with a given level of post 2020 total emissions, that is with a given carbon constraint. The results shown are arrived at by numerical methods rather than by algebraic solution. No claim is made that the paths shown in Figure 3 are the only logistic paths consistent with the constraints. These paths are those in which the positioning variable $c$ is held fixed (at 0.14) but a search is undertaken over the shape variable $\alpha$ (subject to appropriate alignment with the 2020 values) for the value consistent with the specific constraint. If different values of c are used and $\alpha$ is again used as the search variable a different but closely related family of paths are derived. Figure A1 shows such paths for a range of values of $c$ from 0.11 to 0.16, for the 450 GtC and 650 GtC constraints and for a 2020 level of emissions of 56 $GtCO_2e$**.** There resulting variations are minor and have no impact on the central argument put here.

## Endnotes

1. Le Quére, C. *et al*. Global carbon budget 2014. *Earth Syst. Sci. Data Discuss*. 7, 521–610 (2014).
2. Montzka, S.A., Dlugokencky, E.J. & Butler, J.H. Non-$CO_2$ greenhouse gases and climate change. *Nature* 476, 43–50 (2011).
3. Friedlingstein, P. et al. Persistent growth of CO2 emissions and implications for reaching climate targets. *Nat. Geosci.* doi:10.1038/NGEO2248 (2014).
4. Allen, M.R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458, 1163–1166 (2009).
5. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458, 1158–1163 (2009).
6. Rogelj, J. et al. Emission pathways consistent with a 2°C global temperature limit. *Nature Clim. Change* 1, 413–418 (2011).
7. Rogelj, J. et al. 2020 emissions levels required to limit warming to below 2°C', *Nature Clim. Change* 3, 405–412 (2013).
8. IPCC. *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Edenhofer, O., et al.). (Cambridge University Press, 2014).
9. IPCC Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis*. (eds Stocker, T. et al.) 3-29 (Cambridge University Press, 2013).
10. IPCC *Climate Change 2014: Synthesis Report*. Fifth Assessment Report (IPCC November 2014).
11. Sheehan, P. The new global growth path: Implications for climate change analysis and policy. *Climatic Change* 91, 211–231 (2008).
12. Arrow, K.J. in *History Matters: Essays on Economic Growth, Technology, and Demographic Change* (eds Guinnane, T.W. *et al*) 23-35 (Stanford University Press, 2004).
13. David, P.A. Path dependence: A foundational concept for historical social science. *Cliometrica* 1, 91–114 (2007).
14. IEA *World Energy Outlook 2012* (2012).
15. Qui, Y. & Anadon, L. The price of wind power in China during its expansion: Technology adoption, learning-by-doing, economies of scale, and manufacturing localization. *Energ. Econ.* 34, 772–785 (2012).
16. Durlauf, S.N. Nonergodic economic growth. *Rev. Econ. Stud.* 60, 349–366 (1993).

17. Durlauf, S.N. & Young, H.P. (eds), *Social Dynamics: Economic Learning and Social Evolution* (MIT Press, 2001).
18. Griliches, Z. Hybrid corn: An exploration in the economics of technical change. *Econometrica* 25, 501–522 (1957).
19. Mansfield, E. Technical change and the rate of imitation. *Econometrica* 29, 741–766 (1961).
20. Rogers, E.M. *Diffusion of Innovations* (Free Press, 1962).
21. Grubler, A. *The Rise and Fall of Insfrastructures: Dynamics of Evolution and Technological Change in Transport* (Physica-Verlag, 1990).
22. Pan, H. & Köhler, J. 2007, 'Technological change in energy systems: Learning curves, logistic curves and input–output coefficients', *Ecol. Econ.* 63, 749–758.
23. Comin, D., Hobijn, B. & Rovito, E. Five Facts You Need to Know About Technology Diffusion (NBER WP No. 11928, 2006).
24. Comin, D. & Hobijn, B. An exploration of technology diffusion. *Am. Econ. Rev.* 100, 2031–2059 (2010).
25. World Energy Council *World Energy Perspective: Cost of Energy Technologies* (2013).
26. Fraunhofer Institute for Solar Energy Systems *Levelised Cost of Electricity Renewable Energy Technologies* (2013).
27. UNFCCC Advancing the Platform: Draft Decision -/CP.18. Conference of the Parties, 17th Session, Durban (2012).
28. Wilson, C. et al. Marginalization of end-use technologies in energy innovation for climate protection. *Nature Clim. Change*, 2, 780–788 (2012).
29. EIA *Annual Energy Outlook 2009.*
30. EIA *Annual Energy Outlook* 2014.

# Appendix

## *Meta-analysis of emissions pathways*

Meta-analytic studies of emissions pathways have been widely used in the literature to provide information about the level of emissions in 2020 consistent with holding warming to <2°C. Such methods have been applied both to ensembles of synthetic pathways and to a wide range of pathways studied by Integrated Assessment Models (IAMs), with the descriptive statistics over sets of pathways used to provide evidence about the required conditions for 2020 emissions.

Studies undertaking a meta-analysis of a wide range of stylised emissions pathways generated by a synthetic process include Meinshausen et al.,[1] Bowen and Ranger,[2] and Rojelj et al.[3,4,5] Several of these use the SiMCaP EQW model[6] to generate a set of emissions paths for analysis, and here we concentrate on Meinshausen et al.[1] as a representative case of this approach. They develop a set of 1004 emissions pathways for analysis and use a simple climate model to estimate the probability of the global mean temperature exceeding 2°C by 2100. In terms of emissions levels in 2020, they find that the 50% probability level is about 45 $GtCO_2e$, but that the probability of warming being >2°C by 2100 rises to 75% if emissions are not lower than 50 $GtCO_2e$ in 2020. Bowen and Ranger[2] also use the SiMCaP EQW model to generate scenarios and find that emissions need to be held to 40-48 $GtCO_2e$ for a 50% probability of achieving the >2°C target.

Figure 1a shows the 1004 paths studied by Meinshausen et al.,[1] with the annual rate of change in emissions over 2020-50 plotted against level of emissions in 2020. The data are divided into four quadrants, defined by a 2020 emissions level of 54 $GtCO_2e$ and a rate of reduction in emissions of 2.0% per annum over 2020-50. Most of the paths studied (85%) have 2020 emissions less than 54 $GtCO_2e$, and 68% of all paths have 2020 emissions of less than 45 $GtCO_2e$. Of the paths with 2020 emissions over 54 $GtCO_2e$ the majority are high emissions paths over the long term, with most of them having 2050 emissions above or equal to the 2020 level. There is no path with 2020 emissions at 54 GtCO2e or higher and a rate of reduction over 2025 of 2% per annum or more.

The other approach is to undertake a meta-analysis of the emissions pathways analysed by IAMs in recent years. UNEP (2010) collected and analysed a total of 223 emissions pathways analysed in the literature from 2006 onwards. This analysis was repeated in UNEP[7] and updated in Rogelj et al.,[5] which reanalyses 193 emissions pathways from the IAM literature. The historical emissions for each pathway are standardised to the historical multi-gas base established for the RCPs.[8] For each pathway a wide range of parameters are varied over 600 models runs with a reduced complexity climate model (MAGICC), and the fraction of these model runs over 2°C is interpreted as the probability of exceeding the target for this pathway.

Of the 193 standardised pathways in Rogelj et al.,[6] 39 were found to have a medium chance (probability of >50%) of limiting warming to <2°C (Table A1). For these pathways the median level of emissions in 2020 was 44 $GtCO_2e$, with the 15/85 percentile range at 38-47 $GtCO_2e$, with no pathway over 50 $GtCO_2e$ in 2020. The median reduction in emissions over 2020-50 in these paths was 2.7% per annum (measured in terms of the average annual change on the common base 2000 emissions level) with the 15/85 percentile range at 1.5-3.5% per annum. The paths cluster mainly between 40-

50 $GtCO_2e$ in terms of 2020 emissions, but have widely different levels of emissions in 2100, with many having significant negative emissions by that date. There is no path with 2020 emissions over 50 $GtCO_2e$, in spite of the fact that half of the paths have reduction rates over 2020-50 of 2.7% per annum or more.

### *Carbon budget*

Several recent studies have reported on the overall carbon budget constraint consistent with <2°C global warming, in terms of the allowable level of cumulative emissions of $CO_2$ since the industrial revolution. Seven studies and eight estimates are reported in Table 1A, with the individual estimates (as described in the notes) converted into carbon budgets consistent with an even chance (but for studies 2 and 6 a 66% or greater chance) of holding peak warming to no more than 2°C. These studies used different methods and models, including different approaches to the treatment of other gases and to the treatment of various classes of uncertainty, and so the results must be interpreted with care. In particular several different approaches were used for other gases: studies 1-5 in effect assume that in the future, as in the past, the net warming effects of non-$CO_2$ Kyoto gases will be small; study 6 reports only a budget for all Kyoto gases; and studies 7 and 8 provide separate budgets for $CO_2$ only and for all Kyoto gases, with the $CO_2$ budget cited here. The central estimates of the carbon only budget constraint from AR5 WGIII for a 66% and 50% of holding warming to >2°C are also shown Table A1.

**Table 1A. Summary results from recent global carbon budget studies**

| *Study* | *Carbon budget consistent with<2°C warming (GtC)* | | *Post-2010 $CO_2$ emissions consistent with<2°C warming (GtC)* | |
|---|---|---|---|---|
| | *50% chance* | *66% chance* | *50% chance* | *66% chance* |
| 1. Allen et al. 2009(a)[10] | 1000 | | 480 | |
| 2. Zickfield et al. 2009(b)[11] | | 980 | | 460 |
| 3. Matthews et al. 2009 (i)(c)[12] | 1250 | | 730 | |
| 4. Matthews et al. 2009 (ii)(c)[12] | 1400 | | 880 | |
| 5. Friedlingstein et al. 2011z(d)[13] | 1300 | | 780 | |
| 6. Rogelj et al. (2013)(e)[14] | | | | |
| 7. Huntingford et al. (2013)(f)[15] | 965 | 1110 | 445 | 590 |
| 8. Meinshausen et al. 2009(g)[1] | 820+ | | 300+ | |
| 9. IPCC AR5 WGIII (2014)(h)[16] | 1210 | 1000 | 680 | 480 |

Notes: [a] Cumulative carbon emissions for most likely peak warming of 2°C, with 5-95% confidence interval of 1.3°-3.9°C. [b] Cumulative carbon emissions after 2000 of 550 GtC (range 300-770 GtC), for probability of exceeding 2°C in the unlikely range (probability of 0.1-0.33). [c] Model-based estimate (i) is for allowable carbon emissions of 1250 GtC (5-95% range 950-2000 GtC) for 2°C warming; observationally based estimate of 1400 GtC (range 1000-1900 GtC). [d] Cumulative carbon emissions to 2100 consistent with 2°C warming, no probability range given. [e] Cumulative emissions of 2500 $GtCO_2e$ (680 GtCe) over the 21st century, for all Kyoto gases, for probability of exceeding 2°C in the unlikely range (probability of 0.1-0.33). [f] Cumulative emissions of Kyoto gases over 2000-2500 of 2630 $GtCO_2e$ (717 GtCe) for a 50% probability of holding warming to <2°C, which is estimated to be equivalent to about 2000 $GtCO_2$ (545 GtC) for $CO_2$ only. [g] Limiting $CO_2$ emissions to 1440 $GtCO_2$ (392GtC) over 2000-50 gives a 50% probability of warming not exceeding 2°C. [h] Assessments based on the assessment of the transient climate response to cumulative carbon emissions.

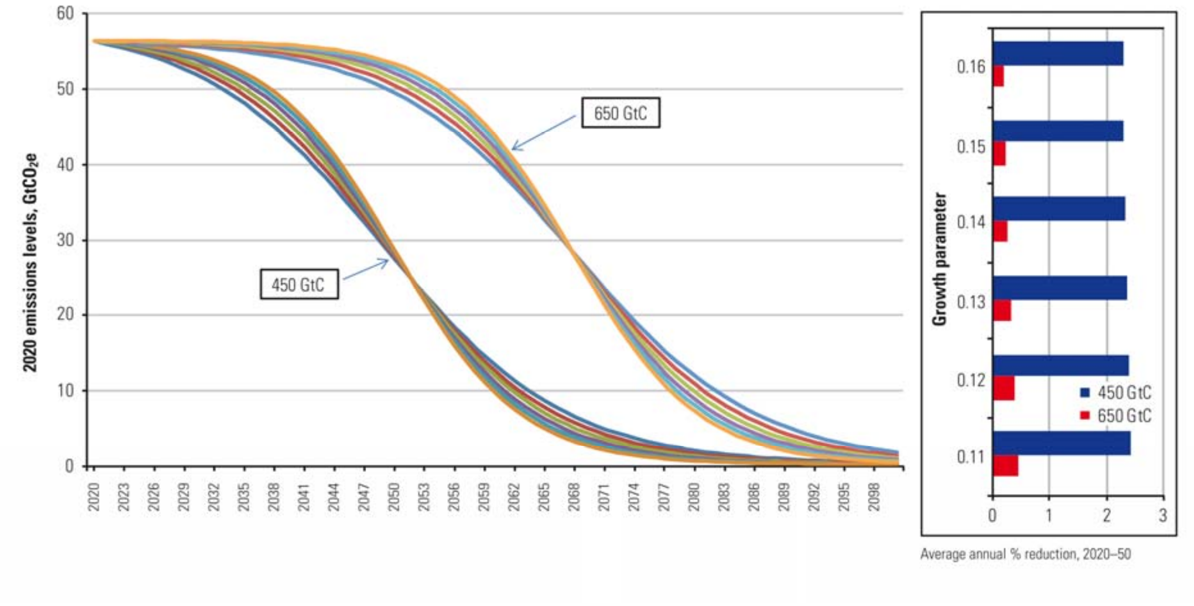
These estimates are converted to a common base using estimated carbon emissions to 2000 of 425 GtC and over 2001-10 of 90 GtC. All estimates are for carbon only, and exclude any allowance for warming due to non-$CO_2$ Kyoto gases (except for study 6) and for cooling due to $SO_2$ and other aerosols.

Ignoring the two outliers (study 8 because of the selection bias discussed above and because it covers emissions only to 2050, and study 4 which is not model-based), the six remaining estimates are fairly well constrained. They imply a total carbon budget, for a 50% probability or higher of holding warming to >2°C, in the 965-1300 GtC range, and a post-2010 carbon budget of 450-780 GtC.

### *Parameter variations with the logistic model*

As noted in the Methods section of the paper, there is not a single set of values of the parameters *c*, *α* and β in equation (4) consistent with a given level of post 2020 total emissions, that is with a given carbon constraint. The results shown are arrived at by numerical methods rather than by algebraic solution. No claim is made that the paths shown are the only logistic paths consistent with the constraints. The paths shown in Figure 3 are those in which the positioning variable *c* is held fixed (at 0.14) but a search is undertaken over the shape variable *α* (subject to appropriate alignment with the 2020 values) for the value consistent with the specific constraint. If different values of c are used and *α* is again used as the search variable a different but closely related family of paths are derived. Appendix Figure 1A shows such paths for a range of values of *c* from 0.11 to 0.16, for the 450 GtC and 650 GtC constraints and for a 2020 level of emissions of 56 $GtCO_2e$**.** The figure shows that the resulting variations are minor, both in terms of the overall shape of the paths and in the variations in the required rate of reduction in emissions over 2020-50. They are not of a magnitude such as to impact on the central argument put here.

**Figure A1. Alternative emissions paths and required rates of reduction in emissions over 2020-50, for different values of the positioning parameter, for 2020 emissions levels of 56 $GtCO_2e$ and carbon constraints of 450 GtC and 650 GtC**



## Appendix Endnotes

1. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458, 1158-1163 (2009).
2. Bowen, A. & Ranger, N. Mitigating Climate Change Through Reductions in Greenhouse Gas Emissions: The Science and Economics of Future Paths for Global Annual Emissions. (Grantham Research Institute on Climate Change and the Environment, London School of Economics, 2009).
3. Rogelj, J. et al. Opinion: Copenhagen Accord pledges are paltry. *Nature* 464, 1126–1128, doi:10.1038/4641126a (2010).
4. Rogelj, J. et al. Analysis of the Copenhagen Accord pledges and its global climatic impacts: A snapshot of dissonant ambitions. *Environ. Res. Lett.* 5, 1–9 (2010).
5. Rogelj, J. et al. Emission pathways consistent with a 2°C global temperature limit. *Nature Clim. Change* 1, 413–418, doi: 10.1038/NCLIMATE1258 (2011).
6. Meinshausen, M. et al. Multi-gas emissions pathways to meet climate targets. *Climatic Change*, 75, 151–194 (2006).
7. UNEP *Bridging the Emissions Gap: A UNEP Synthesis Report.* (Nairobi, 2011).
8. Meinshausen, M. et al. The RCP greenhouse gas concentration and their extensions from 1765 to 2300. *Climatic Change,* 109, 213–241 (2011).
9. Sheehan, P. The new global growth path: implications for climate change analysis and policy. *Climatic Change*, 91, 211–231 (2008).
10. Allen, M.R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458, 1163–1166, doi:10.1038/nature08019 (2009).
11. Zickfield, K. et al. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *PNAS* 106, 16129–16134 (2009).
12. Matthews, H.D. et al. The proportionality of global warming to cumulative carbon emissions. *Nature* 459, 829–832, doi:10.1038/nature08047 (2009).
13. Friedlingstein, P. et al. Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nature Clim. Change* 1, 457–461, doi: 10.1038/NCLIMATE1302 (2011).
14. Rogelj, J. et al. 2020 emissions levels required to limit warming to below 2°C. *Nature Clim. Change*, 3, 405–412, doi: 10.1038/NCLIMATE1758 (2013).
15. Huntingford, C. et al. The link between a global 2°C warming threshold and emissions in years 2020, 2050 and beyond. *Environ. Res. Lett.* 7, 1–8 (2012).
16. IPCC *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Edenhofer, O. et al.). (Cambridge University Press, 2014).