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Is it too late to stabilise the global climate?*

John Quiggin[†]

Assessment of the feasibility of stabilising the global climate requires consideration of trajectories for emissions of carbon dioxide and other greenhouse gases. This study presents a simple and robust analysis of feasible emissions trajectories. Consideration of feasible trajectories suggests that if the current pace of mitigation efforts is sustained, the likely outcome will be stabilisation at concentrations close to 500 parts per million. Such an outcome will imply a higher than 50 per cent probability of substantial damage from climate change and an enhanced risk of a catastrophic outcome.

Key words: climate change and greenhouse, environmental policy, environmental and ecological economics.

Climate change is one of the biggest problems facing the world today, and also one of the most complex. The most prominent attempts to synthesise the evidence on the central issues are the Assessment Reports of the Intergovernmental Panel on Climate Change (2007a,b,c), consisting of thousands of pages of text, linking to many more thousands of journal articles, books and reports. It is a challenging task to read the Report as a whole, and clearly impossible for any one person to read and understand more than a tiny fraction of the associated literature. Even the Summary for Policymakers (IPCC 2007d) consists of three densely written documents, which cannot easily be understood without following cross-references to the main report.

The scientific literature, consisting of thousands of journal articles and reports, is even less accessible. The crucial issues are typically addressed using large-scale models, each of which is the product of many researcher-years of effort, and each of which would require an intensive effort to understand.

Yet, decisions about responses to climate change must be made by policymakers with very limited time, and, in most cases, little background in science or economics. The policies must be communicated to a public audience with equally many competing demands.¹

* Presidential address presented at the 56th Annual Conference of the Australian Agricultural and Resource Economics Society, Fremantle WA, Australia, 8–10 February 2012.

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¹ The difficulties are exacerbated by the fact that the public is also being bombarded by a fraudulent anti-science campaign (Doyle 2011; McKnight 2012), driven primarily by a group of rightwing ideologues and media organisations, of which News Limited (including Fox News, the Wall Street Journal, the Times of London and the majority of Australian newspapers) are the most prominent. There is, unfortunately, little that can be done about this.

Quiggin (2012) argues that

What is needed to resolve these difficulties is a simple and robust analytical framework, in which policy responses to climate change can be assessed on the basis of a small number of input parameters. To take this a step further, the input parameters themselves must be derived from a comprehensible process.

Given the complexity of the standard models of climate, economic activity and energy use, this task might seem hopeless. However, long experience of modelling suggests that in any large and complex model, a small number of equations, parameters and closure conditions determine, up to a good approximation, the results of crucial interest. This subset can be used to generate a small version of the full model, which can be used as a basis for analysis.

Quiggin (2012) presents a simple and robust benefit–cost analysis for the determination of a globally optimal target for atmospheric concentrations of carbon dioxide and for the associated carbon price path. The simple benefit–cost framework yields an optimal pair consisting of a carbon price (or marginal abatement cost) and an optimal target level for atmospheric concentrations of CO₂ and other greenhouse gases.

The crucial observation is that given a quadratic loss function from uncontrolled climate change and a quadratic abatement cost curve, the optimal pair is robust to quite large changes in estimates of the most uncertain input parameter, namely, the cost of unmitigated climate change under ‘business as usual’. In all simulations, the total cost of optimal mitigation is below 5 per cent of income, and in most cases substantially below this value.

The median target of 450 ppm is consistent with the stated goals adopted at the 16th Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) held at Cancun in 2010. In the course of international negotiations, national governments have made a variety of commitments regarding the medium term trajectory of emissions. As will be argued in more detail in this study, to achieve these goals, global emissions would need to peak by 2030 at the latest, with emissions in developed countries peaking well before that date. Emissions would then decline by 80–90 per cent, for developed countries by 2050, relative to current levels. Although there is no formal commitment to this effect, the assumption is that emissions per person for less developed countries would converge to the same level.

The gap between stated goals and actual policies is illustrated by the fact that the carbon price implied by the analysis is well above that prevailing in jurisdictions with an explicit carbon tax or tradeable permits scheme. For example, the Australian carbon price is initially set at \$23/tonne. The price of permits in the European Union to which Australia will be linked in 2015 has fluctuated, typically rising at the beginning of each trading period as the rules have been tightened, then declining as the cost of reducing emissions has

turned out lower than expected. At the time of writing, the price is around 7 euros/\$A9/tonne.

The analysis of Quiggin (2012) is essentially static in nature, except that the carbon price is assumed to be specified as a price path, increasing at a rate of 2 per cent per year. Thus, Quiggin (2012) does not address the question of what emissions trajectory would be consistent with stabilisation or consider the economic and political feasibility of alternative trajectories.²

The aim of this study is to present an analysis of feasible emissions trajectories that is sufficiently accessible to be useful to policymakers and the general public, and sufficiently robust to encompass a wide range of the uncertainties inherent in any attempt to assess the effects of policy choices over periods of decades or even longer.

The key simplification is to consider simple piecewise linear trajectories, in which net emissions initially increase, then decline to zero, at which point atmospheric concentrations of CO₂ stabilise. Trajectories of this form, with a known starting point can be characterised by three parameters. For present purposes, it is most useful to consider the rate of increase in emissions over the initial period, the date at which emissions peak and the date at which emissions are reduced to zero.

Much of the published work on emissions trajectories (for example, that of the IPCC 2007c) begins with scenarios regarding economic growth and climate policies from which projections of future emissions are derived. These emissions trajectories can then be used to predict the implications of the given scenario for changes in the global climate, which may be summarised by the change in global mean temperatures.

In this study, the modelling process is reversed. That is, starting from an objective specified as a maximum change in global mean temperature of 2°C, I derive a cumulative emissions target consistent with satisfying this objective. Given the target level of cumulative emissions, the analytical core of the exercise is to specify emissions trajectories that can reach this target, and to examine economic growth paths and policy settings consistent with those trajectories.

The discussion will focus primarily on trajectories required to achieve stabilisation of atmospheric concentrations of greenhouse gases at 450 ppm by 2050. For simplicity of exposition, but also because it is broadly consistent with the reasoning to be adopted here, I will focus on simple 'triangular' trajectories, in which emissions increase linearly up to some transition date, after which they decline linearly.

The study is organised as follows. Section 1 provides background information and a summary of the related work presented by Quiggin (2012). Section 2 describes the putty-clay model of capital substitution. Section 3 presents the model and simulation results. Section 4 deals with the

² I thank Andrew Steer, World Bank Special Envoy for Climate Change, for suggesting the need to address this question.

feasibility of decarbonising the economy, as projected in the model. Finally, some concluding comments are offered.

1. Background and previous work

The aim of reducing emissions of CO₂ and other greenhouse gases is to mitigate the change in the global climate, which may be summarised by the increase in global mean temperatures. As there is still considerable uncertainty about global climate sensitivity, it is more precise to say achievement of a given cumulative emissions target changes the probability distribution of the increase in global mean temperatures.

As noted by IPCC (2007b, WGII) Climate models differ in their estimates of the likely impact of stabilising atmospheric concentrations of CO₂ and other greenhouse gases. Estimates of the probability that equilibrium warming will exceed 2°C, conditional on stabilising atmospheric concentrations of greenhouse gases at 450 ppm CO₂e, range from 25 per cent to 75 per cent.

This process is complicated by a mixture of lags and both positive and negative feedbacks of various kinds. Detailed discussion is beyond the scope of this study. However, two critical points are:

- Lags mean that the equilibrium change in temperature will be reached some decades after atmospheric concentrations stabilise
- Feedback effects mean that reducing global mean temperatures after they have reached a new high equilibrium will be very difficult

These points are relevant if we wish to consider an ‘overshooting’ trajectory for atmospheric concentrations, in which the long-run target is initially surpassed; it is important to ensure that concentrations do not remain above the long-run target long enough for climate to equilibrate.

Given this discussion, a natural starting point is to consider an optimal target at which concentrations of greenhouse gases might be stabilised. This target will be expressed in terms of a weighted sum, referred to as ‘CO₂-equivalent’, which is designed to measure the total warming potential of the different gases. As discussed in more detail below, any such weighting scheme involves an arbitrary element. However, for the simple and robust approach used in Quiggin (2012) and developed further in this study, this will not prove problematic.

The simple benefit–cost framework in Quiggin (2012) yields an optimal pair consisting of a carbon price (or marginal abatement cost) and an optimal target level for atmospheric concentrations of CO₂ and other greenhouse gases. The crucial observation is that, given a quadratic loss function from uncontrolled climate change and a quadratic abatement cost curve, the optimal pair is robust to quite large changes in estimates of the most uncertain input parameter, namely, the cost of unmitigated climate change under business as usual (BAU).

The model is characterised by two equations, an abatement cost equation and a climate damage cost equation. In each case, the monetary cost is expressed as a quadratic function of the atmospheric concentration of CO₂ at which stabilisation is achieved.

The logic of this analysis is robust to substantial changes in parameter values and functional form, provided the crucial convexity properties of the model are maintained. For a wide range of parameter values, the optimal carbon price is between \$40 and \$75, and the optimal target is between 425 ppm and 475 ppm. In all simulations, the total cost of mitigation is below 5 per cent of income, and in most cases substantially below.

The key reasons for this robustness are easily stated. The marginal cost of abatement under BAU is zero by definition. By contrast, the marginal damage, while difficult to estimate precisely, is certainly substantial, given that the warming implied by BAU is well outside anything the human species has experienced. It follows that, with BAU as the initial position, there must exist substantial net gains from modest mitigation efforts. As the optimal point is that where marginal benefits and costs are equal, the average benefit–cost ratio for an optimal mitigation programme must be substantially greater than zero.

The key results of Quiggin (2012) are summarised in Table 1. The columns represent alternative values for $C_D(\text{BAU})$ the damage incurred under business as usual (BAU), expressed as a proportion of total income. The rows represent alternative values for the cost of mitigation, expressed in terms of current dollars per tonne of CO₂.

For values of $C_D(\text{BAU})$, ranging from 5 to 20 per cent of income and mitigation costs ranging from \$50/tonne to \$200/tonne, Table 1 shows the optimal target (ppm), carbon price (\$/ton) and welfare gain (per cent GDP). To guard against spurious precision, the optimal target is stated to the nearest 25 ppm, the price to the nearest \$5 and the welfare gain to the nearest 0.5 percentage points.

Table 1 Optimal CO₂ concentration, carbon price and welfare gain for varying damage and mitigation costs

Mitigation cost (\$/t)	Damage cost (per cent of income)			
	5	10	15	20
50	475 ppm	425 ppm	400 ppm	400 ppm
	\$30	\$35	\$40	\$40
	2.5%	7.5%	10.5%	17.5%
75	500 ppm	450 ppm	425 ppm	400 ppm
	\$40	\$50	\$60	\$65
	2.5%	7.0%	11.5%	16.5%
100	500 ppm	475 ppm	425 ppm	425 ppm
	\$50	\$60	\$75	\$75
	2.0%	6.0%	12.5%	15.5%
150	550 ppm	500 ppm	450 ppm	450 ppm
	\$50	\$75	\$100	\$100
	2.0%	5.5%	9.5%	14.0%

Because both abatement cost and the damage from climate change are strictly convex functions of the change in CO₂ concentrations, the optimal solution is fairly robust to substantial changes in key input parameters. For all but a few extreme assumptions, the optimal carbon price is between \$40 and \$75. Similarly, for a wide range of parameter values, the optimal target is between 425 ppm and 475 ppm. In all simulations, the total cost of mitigation is below 5 per cent of income, and in most cases substantially below this value.

The analysis undertaken by Quiggin (2012) is an exercise in comparative statics. For practical purposes, it is necessary to consider feasible emissions trajectories. This task is addressed in this study.

2. The putty–clay model

To determine feasible emissions trajectories, it is necessary to model the process of adjustment to the introduction of a price for carbon emissions. This is a special case of the general problem of modelling the adjustment of capital stocks and other inputs to a change in factor prices. The standard putty–clay model of capital adjustment is appropriate for this purpose.

The putty–clay model was originally developed by Johansen (1959), Solow (1962), and Phelps (1963) [the term ‘putty–clay’ was coined by Phelps], to examine capital–labour substitution in relation to the theory of economic growth. Under the putty–clay assumption, also called *ex ante* fixed proportions, a business can choose among a wide variety of possible ratios of capital to labour before capital is ordered (putty) but cannot alter that ratio once capital is put in place (clay).

A putty–clay assumption is clearly applicable in relation to the choice of fuel in many energy-using production processes. A coal-fired power station, once constructed, cannot in practical terms be converted to use nuclear or photovoltaic inputs, although there is scope for conversion between different fossil fuels.

The speed of conversion between fossil fuels may be illustrated by the rise and decline of oil-fired electricity generation. From 1960 to 1973, oil use increased rapidly, reaching a peak of 26 per cent of total OECD generation. After the oil price increase of 1973, investment in new oil-fired plant ceased and many existing plants were either scrapped or converted to other fuels. By 1990, the share of oil-fired generation had fallen to 10 per cent (Fried and Trezise 1993). The resurgence of oil prices after 2000 reduced oil-fired generation to negligible levels (US Energy Information Administration 2011).

For a given capital stock, the amount of carbon depends on the rate of capital utilisation, both in total and in the allocation of demand between plants of differing carbon intensity. So, the ‘clay’ component of responses to carbon prices consists of effects on final demand for energy and on the utilisation of different plants.

In the case of a centralised electricity supply industry, the utilisation of different plants is determined by the 'order of merit' in which orders are dispatched. In a pool market, such as that prevailing in Australia, the order of merit is determined by bids submitted by generators. In both cases, a carbon price will have the effect of moving carbon-intensive plants down the order of merit, and therefore reducing their utilisation.

Although determination of the appropriate pattern of capital utilisation is an important issue, particularly in matching variable supply and demand, changes in the pattern of capital utilisation cannot radically change the emissions associated with meeting a given demand from a given stock of capital. The aggregate stock of capital will ultimately be determined by total demand for energy, while the associated emissions will be determined primarily by the composition of the capital stock. In a putty-clay world, therefore, emissions are determined, up to a first approximation, by the capital stock.

The standard putty-clay model, in which the factors of production are labour and capital, must be modified to fit the case of carbon emissions, where investments reflect a discrete choice between techniques, rather than a choice from a smoothly varying range of optimal input ratios. In any given location, and with all other relevant conditions held constant, the optimal technique will be determined by the price of carbon.

At low or zero carbon prices, the most carbon-intensive technologies, such as coal-fired and oil-fired generation will be optimal. At high carbon prices, renewables, or perhaps nuclear, will be optimal. There will also be a range of prices for which gas-fired generation and other technologies with intermediate levels of emissions will be optimal. The critical point here is that there is a discrete switch from one technology to another, rather than a smooth process of substitution.

As conditions will vary over time and space, the price at which switching energy sources is optimal will also differ. Nevertheless, the range of carbon prices that favours a particular technology will be relatively narrow. It follows that the relationship between the carbon price and the share of renewables in generation will be better described by an S-shaped curve of the kind familiar from studies of innovation diffusion, rather than the hyperbolic curve that would be derived from a standard production technology.

The early stages of such a diffusion process may be approximated by a piecewise linear path in which the share of renewables grows slowly until a point of inflexion is reached, after which it grows rapidly. Conversely, reductions in energy use arising from improvements in efficiency may be expected to accelerate once they are embodied in capital stocks.

Further, the time at which emissions peak will be (approximately) the same as the time at which the stock of carbon-using capital peaks. This in turn will be the point at which, evaluated on a forward looking basis, investments in carbon-using capital cease to be attractive, relative to the best available alternative, which may be either an alternative energy source or an investment that increases the energy efficiency of the economy as a whole.

3. Optimal trajectories

Carbon dioxide is the most important greenhouse gas [in a policy sense; that is, water vapour plays a critical role in climate, including greenhouse effects. However, the water vapour content of the atmosphere is endogenously determined by feedbacks that are ultimately driven by other greenhouse gases]. If emissions trajectories are used to predict global climate, it is necessary to take account of other gases, the most important of which is methane.

A requirement to compute aggregate trajectories poses significant problems, as methane and carbon dioxide have very different characteristics. Methane is a much more potent gas than CO₂ (about 70 times as potent, molecule for molecule). However, its residence time in the atmosphere is much shorter – an average of 12 years compared with an average of around 50 years for CO₂ (the number for methane is relatively precise, while that for CO₂ depends on a complex set of processes associated with the global carbon cycle).

It follows that any description of the time path of all greenhouse gas emissions in terms of a CO₂-equivalent trajectory relies on arbitrary conversion factors that cannot reflect real impacts over time. Given that it is impossible for any trajectory to give more than a broad indication of the time-path of emissions, it seems sensible to focus on giving the simplest representation of trajectories sufficient to capture the key policy issues.

Hence, the objective of the exercise presented here is to maximise simplicity and robustness, at the expense of precision and ‘realism’. These objectives are reflected in the choice of piecewise linear emissions trajectories, as illustrated in Figure 1.

Such trajectories incorporate a kink at the point where emissions peak, rather than a smooth curve in which emissions reach a plateau before declining. This approach is consistent, in conceptual terms, with the putty–clay model developed in the previous section.

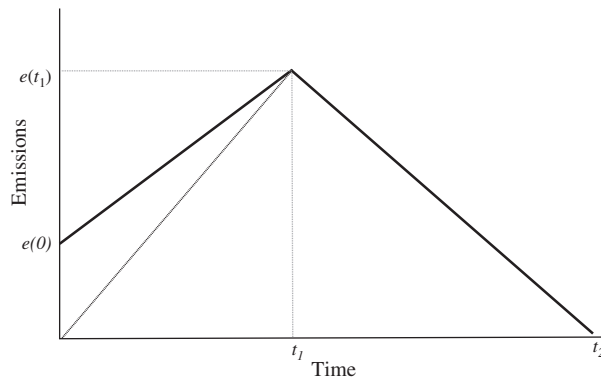


Figure 1 Piecewise linear emissions trajectory.

Formally, the trajectory for emissions may be described by a path of the form

$$e(t) = \begin{cases} e(0) + gt & 0 \leq t \leq t_1 \\ e(t_1) - d(t - t_1) & t_1 \leq t \leq t_2 \\ 0 & t \geq t_2 \end{cases} \quad (1)$$

where: t denotes years after the starting point (2010); t_1 is the date of peak emissions; t_2 is the date at which net emissions equal zero; $e(t)$ is emissions at date t in parts per million (ppm) of CO₂; g is the initial rate of increase of emissions; d is the rate of decline of emissions after t_1 .

Note that any path described by (1) must satisfy the identities

$$e(0) + gt_1 = e(t_1) = d(t_2 - t_1) \quad (2)$$

so that, for given $e(0)$, specifying any three of g , d , t_1 , t_2 and $e(t_1)$ determines the remaining two.

And, as illustrated in Figure 1, total cumulative emissions are given by the sum of two triangles, one with area $0.5e(0)t_1$ and one with area $0.5e(t_1)t_2$. So,

$$E = 0.5(e(0)t_1 + e(t_1)t_2) \quad (3)$$

The analysis that follows will be concerned with the problem of achieving a target E^* for the total level of emissions, given a known starting level $e(0)$. In this problem, specifying any two of g , d , t_1 and t_2 along with the target E^* is sufficient to determine the values of all the variables in the model.

As we are concerned with current policy, it is natural to focus on the increasing segment of the emissions trajectory, parametrised by g and t_1 . Tables 2 and 3 report the values of t_2 and d for alternative choices of g and t_1 , given a 2010 atmospheric concentration of 390 ppm CO₂e, a target of 450 ppm CO₂e. Initial emissions are set at 30 gigatonnes per year, corresponding to a growth rate of 1.5 ppm per year in CO₂e.³

Table 2 Implied decarbonisation date for 450 ppm target, given peak date and emissions growth rate

Emissions growth rate	Peak year			
	2020	2025	2030	2035
0.5	2070	2062	2055	2049
0.75	2066	2057	2050	2044
1	2063	2053	2046	2040
1.5	2057	2047	2040	***
2	2052	2043	2036	***

Note: *** denotes no feasible path.

³ The total mass of the atmosphere is approximately 5 million Gt, and the relative density of CO₂ is 1.5, so that 1 ppm of CO₂ by volume is approximately 7.5 Gt. Since about 60 per cent of gross emissions are absorbed by sinks such as the ocean, 1 additional ppm of CO₂ by volume results from every 20 Gt of emissions. It follows that the total 'budget' of allowable emissions for a 450 ppm target is 1200 Gt.

Table 3 Required rate of emissions reduction for 450 ppm target, given peak date and emissions growth rate

Emissions growth rate	Peak year			
	2020	2025	2030	2035
0.5	2	2.7	4	7.2
0.75	2.2	3.1	5	11.3
1	2.4	3.5	6.3	20
1.5	2.7	4.5	10	***
2	3.1	5.7	17.5	***

Note: *** denotes no feasible path.

The stated aims agreed at the Cancun Conference correspond to the cells in the top left of Tables 2 and 3. If the current rate of growth of emissions is around 1Gt per year were continued up to a peak in 2020, the required rate of linear decline in emissions would imply zero net emissions by 2063, broadly consistent with the stated objectives for 2050 proposed by the European Union and others. A similar outcome could be achieved with a slower rate of emissions growth and a peak in 2025.

Unfortunately, while these trajectories are consistent with stated objectives, the policy measures currently adopted by governments do not imply an emissions peak in 2020 or even 2025. If the peak is delayed until 2030, the required rate of decline in emissions, shown in Table 3, is higher than could be achieved simply by reliance on price measures. On these projections, the capital stock adjustment required would not be consistent with the putty–clay model.

The situation is even worse if a peak is not reached until 2035, as implied by projections of energy use prepared by the International Energy Agency and other bodies. Even with slow growth in emissions over this period, the required rate of reduction is implausibly high. For higher rates of emission growth, stabilisation would not even be logically feasible, as indicated by the asterisks in the final two rows of the column. Emissions by 2035 would already have exceeded the total consistent with stabilisation at 450 ppm.

In summary, achievement of stabilisation at 450 ppm will require either an effective agreement to cap global emissions in the relatively near future or a rapid reduction in emissions after a peak is reached. Although neither of these outcomes appears likely at present, there are some reasons for optimism, as will be discussed in the following section.

A different picture emerges when we consider a goal of stabilisation at 475 ppm, as shown in Tables 4 and 5. As a first approximation, an additional 25 ppm corresponds to additional 500 Gt of CO₂ emissions, or between 15 and 20 years at current rates. Not surprisingly, therefore, stabilisation at 475 ppm can be achieved even if peak emissions are delayed by a decade or more relative to those required to achieve stabilisation at 450 ppm.

With emissions growing at an average of 1.5 tonnes over the next two decades, a peak emissions date of 2030 would still be consistent with stabilisation at 475 ppm if the economy could be decarbonised before 2060.

Table 4 Implied decarbonisation date for 475 ppm target, given peak date and emissions growth rate

Emissions growth rate	Peak year			
	2020	2025	2030	2035
0.5	2099	2089	2080	2072
0.75	2093	2082	2072	2064
1	2088	2076	2066	2058
1.5	2079	2066	2057	2049
2	2072	2059	2050	2043

Table 5 Required rate of emissions reduction for 475 ppm target, given peak date and emissions growth rate

Emissions growth rate	Peak year			
	2020	2025	2030	2035
0.5	1.3	1.6	2	2.7
0.75	1.4	1.8	2.4	3.4
1	1.5	2	2.8	4.3
1.5	1.7	2.4	3.8	7
2	1.9	2.9	5	12.3

With slower growth in emissions of 1 tonne per year over the period of continued increase, even a peak date of 2035 would not preclude stabilisation at 475 ppm.

According to estimates in IPCC (2007a, Chapter 10), the median estimate of the probability of temperatures exceeding 2C rises from 50 per cent, with stabilisation at 450 ppm to around 60 per cent with stabilisation at 475 ppm. Similar estimates can be derived for the probability of higher values for the ultimate temperature increase on the assumption that the relevant parameter (typically reported as climate sensitivity⁴) is normally distributed with a known variance. This is left as an exercise for the reader.

Of arguably greater interest, but harder to express in probabilistic terms, is the risk of a catastrophic outcome, arising, for example, from a runaway feedback process leading to climatic changes that might render much of the planet uninhabitable. These risks are small, but even a probability of a few per cent would more than outweigh the costs of mitigation estimated above.

Although it is hard to estimate the costs of delay, it is possible to state with reasonable confidence that the marginal benefits of mitigation are increased as a result of delay, since the damage function is convex. Assuming some induced innovation arising from existing policies, the marginal costs of mitigation should decline over time. So, the delays arising from the

⁴ Climate sensitivity is the equilibrium response of the climate system to a doubling in CO₂-equivalent concentrations. Since the pre-industrial level was around 280 ppm, this corresponds to a value of 560 ppm.

limitations of past international agreements strengthen the case for action in the future.

4. The feasibility of zero net emissions

The relatively optimistic projections presented here reflect the fact that the trajectories modelled here involve a reduction of net emissions to zero over a period of decades. This modelling assumption, as it applies to fossil fuel use, is based on the putty-clay model presented in Section 2. In this model, new investment in fossil-fuel using capital will cease when the expected lifetime cost exceeds that of alternative energy sources. Consumption of fossil fuels will then decline as capital wears out and is scrapped.

The analysis of Quiggin (2012) adopts, for the median case, the assumption that a carbon price trajectory beginning at \$50 tonne and rising to \$100/tonne by 2050 would be sufficient to achieve decarbonisation. With existing technology and prices, a carbon price of \$100 tonne (equivalent to \$100/MWh for coal-fired power) would be sufficient to displace coal from electricity generation and heating uses. The US EIA (2010) estimated the 2011 levelised cost of coal-fired power at \$100/MWh, while that of renewables such as wind and solar PV is estimated at less than \$200/MWh.⁵ With a continuation of recent technical progress, a carbon price of \$100/tonne would make renewables cheaper than gas.

It is less clear that such a price would be sufficient to displace fossil fuels in transportation. However, on current technology it would be possible to use electric vehicles for most transportation, with only a modest increase in capital costs and a reduction in operating costs. Regulation may be the most practical way of achieving this outcome.

The analysis presented here also incorporates the assumption that net emissions of other greenhouse gases can be reduced to zero, or even below. It is useful to contrast the modelling approach here with that of Hamilton (2010), who draws on the work of Anderson and Bows (2008). The primary differences arise because, in Anderson and Bows' projections, net emissions of greenhouse gases remain substantial after 2050 regardless of policy action to reduce fossil fuel use.

In particular, Anderson and Bows assume that

1 net deforestation continues until 2100.

2 methane and other non-CO₂ emissions stabilise at 2000 levels.

By contrast, in the present analysis, it is assumed that there is no net loss of forest cover between now and 2100, and that forest cover increases in the later part of the century. Similarly, it is assumed that emissions of methane and

⁵ Coal prices would presumably fall in response to a decline in demand, thereby reducing the levelised cost of coal-fired power. However, the effect would be modest and bounded by the cost of coal extraction and transport.

other non-CO₂ GHGs peak at the same time as CO₂ emissions and decline thereafter, with the result that atmospheric concentrations of these relatively short-residence gases will be declining in the later part of this century. These effects are assumed to offset any residual net emissions from fossil fuel use, and thereby justify the use of projected trajectories in which net emissions are reduced to zero.

The differences between the assumptions used here and those of Anderson and Bows account for around 800 GT of emissions (or 40 ppm) between now and 2100, equal to 25 years of emissions at current rates.

5. Concluding comments

The objective of stabilising atmospheric concentrations of CO₂ and other greenhouse gases at 450 ppm (CO₂ equivalent) has been generally accepted by world governments. The analysis of Quiggin (2012) shows that, for a wide range of assumptions about damage and mitigation costs, the optimal global policy would require stabilisation in the range 400–500 ppm.

Consideration of feasible trajectories suggests that if the current pace of mitigation efforts is sustained, the likely outcome will be in the upper end of this range. Such an outcome will imply a higher than 50 per cent probability of substantial damage from climate change, and an enhanced risk of a catastrophic outcome.

There is still time to achieve stabilisation at or below 450 ppm. However, achievement of such an outcome will require more serious efforts at the achievement of an effective international agreement than have been observed so far.

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