



Edinburgh School of Economics
Discussion Paper Series
Number 216

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climate change economics?*

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Date
January 2013

Published by
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A balance of questions: what can we ask of climate change economics?

David Comerford*

January 6, 2013 - preliminary, comments appreciated

Abstract

The standard approach to the economics of climate change, which has its best known implementation in Nordhaus's DICE and RICE models (well described in Nordhaus's 2008 book, *A Question of Balance* [11]) is not well equipped to deal with the possibility of catastrophe, since we are unable to evaluate a risk averse representative agent's expected utility when there is any significant probability of zero consumption. Whilst other authors attempt to develop new tools with which to address these problems, the simple solution proposed in this paper is to ask a question that the currently available tools of climate change economics are capable of answering. Rather than having agents optimally choosing a path (that differs from the recommendations of climate scientists) within models which cannot capture the essential features of the problem, I argue that economic models should be used to determine the savings and investment paths which implement climate targets that have been suggested in the physical science literature.

JEL Classification: Q54, Q43, E22, H23;

Keywords: Climate Change, Catastrophe, Optimal Policy, Alternative Energy Investment;

1 Introduction

This article argues that there are two different questions that an economic analysis of climate change could address when providing advice to policymakers using dynamic general equilibrium models. These questions are: '*What is the social cost of carbon given a climate change externality?*' and '*Given a cumulative emissions target, what carbon tax implements this target?*' Both these questions are important, but in giving policy advice, we can provide a much less uncertain answer to the second question than we can the first. The positive methodology employed in answering these two questions is the same. The normative question is different. The standard approach to climate change economics as pioneered by Nordhaus (see Nordhaus (2008) for a comprehensive summary) attempts to answer the first of these questions by evaluating the price of carbon (equal to the social cost of carbon) that a social planner would have to set, in order to implement the policy programme that maximises their lifetime CRRA utility objective function, in a world where high temperatures damage production or utility, and production in the absence of abatement technology causes high temperatures.

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In section 2 of this paper, I describe the climate change policy advice that comes from the climate-economy and climate science literatures and highlights differences between them. In section 3, I classify economic modelling efforts according to the assumptions about catastrophe that implicitly lie behind them, and place the physical science policy advice within this framework. This classification exercise highlights the fundamental reasons for the differences in policy recommendations that are discussed in section 2, and motivates a focus on the second question: ‘*What is the carbon tax required to implement a scientifically determined target?*’. Section 4 discusses the fact that, given current knowledge, and the currently accepted welfare framework, the only rigorous answer to the first question, ‘*What is the social cost of carbon?*’, is undefined. This section also describes some of the work that is being done on developing alternative welfare frameworks, which will eventually allow us to answer this first question. In section 5, I sketch a solution to the second question, and highlight the result that asking a different question can produce qualitatively different policy advice: I present a result on the timepath of carbon taxes that is implied by the simple model of this paper, that conflicts with many of the reported results from standard climate economy models. Section 6 concludes.

This paper therefore both makes clear the questions that are important in climate change economics, and provides an outline answer to the easier of the two. Despite being an easier question, it is a less researched and possibly more policy relevant question. Given a super-abundance of fossil fuels, and a backstop technology that is only available with large scale investment, what carbon price path should the policymaker implement to meet a cumulative emissions target? Questions like this have been addressed before, e.g. Nordhaus (2008) [11], talks of the application of the DICE 2007 model to binding temperature and CO_2 concentration limits; rather it is the discussion of the prominence that such questions are given, and the implications of answering different questions, that is the contributions of this paper.

2 Climate change policy advice

The Intergovernmental Panel on Climate Change (IPCC) in its 2007 report [4], stated and evidenced that there were “reasons for concern” that climate change greater than $2 - 3^\circ C$ may be dangerous. This “danger” is due to the possibility that there may be thresholds in the climate system that mean large changes, outwith the range of model predictions, are possible. Many climate scientists are coming to the belief that avoiding thresholds, or tipping points, in the climate system, is the crucial aspect of climate policy (see e.g. Alley et al (2003) [21], Overpeck and Cole (2006) [2], & Lenton et al (2008) [14]). In 2005 the European Union adopted a $2^\circ C$ temperature rise limit (above pre-industrial global temperatures) as a policy goal. Given central estimates of climate sensitivity to increases in CO_2 concentrations of $\sim 3^\circ C$ for a doubling of atmospheric CO_2 , this implies a CO_2 concentrations limit of $\sim 450ppm$ (given that pre-industrial concentrations were $\sim 280ppm$). However, as evidence accumulates, some have argued that the $450ppm$ target is too lenient, e.g. Hansen et al (2008) [25] recommend a target of, and describe a scenario whereby, atmospheric CO_2 levels are down to no more than $350ppm$ by 2100.

A particularly easy to express and communicate target is introduced by Allen et al (2009) [8] who note that climate models seem relatively insensitive to the timepath of emissions, and rather cumulative emission targets are much more useful. In keeping with the $2^\circ C$ limit, they suggest a cumulative emissions target of 1 trillion tonnes of carbon ($1TtC$). Given that historical emissions since the start of the industrial revolution are estimated at around 500 billion tonnes of carbon ($500GtC$), this means we are half way through our allowance, and have $500GtC$ left to burn. This is much less than the available fossil fuel resource (see Brandt & Farrell (2007) [5]).

This policy advice from the climate science community can be contrasted with that coming

from the climate-economy literature. To summarise this, I focus on Tol (2009) [15] which surveys prior literature. In surveying the economics of climate change field, Tol notes that an “area of agreement between these studies is that the welfare effect of a doubling of the atmospheric concentration of greenhouse gas emissions on the current economy is relatively small - a few percentage points of GDP. ... roughly equivalent to a year’s growth in the global economy - which suggests that over a century or so, the economic loss from climate change is not all that large.” This summary is borne out by the fact that the climate-economy studies do not deem it optimal to stick to a $2^{\circ}C$ temperature rise limit. This disagreement with the recommendations coming from the climate science community may seem strange given that many of these models include a simplified environmental model that has been calibrated to reproduce the temperature rises seen in climate models. For example, the DICE 2007 model described in Nordhaus (2008) has been calibrated to the MAGICC climate model¹. And the evidence for economic damages from a given level of warming, whilst highly uncertain, has been researched (see Nordhaus (2008)) and cannot be dismissed.

The disagreement in policy recommendations, ultimately arises from the possibility of catastrophe - from the possibility that the actual climate response to a large increase in CO_2 concentrations will be much greater than implied in the models. Beyond $2 - 3^{\circ}C$ ‘here be dragons’ and explore these regions at your peril. The climate-economy models surveyed by Tol (2009) agree with the central projections from the climate science models by construction, and it is likely that climate damages associated with these projections are low in the context of overall global output - but this is because no tipping points are breached, and catastrophic dynamics are not set in motion. The calibration of the climate side of climate-economy models to the central projection from models used in climate science, whilst clearly constraining the policy recommendations from the climate-economy literature, is not capturing the state of scientific knowledge of climate change. Climate science models have difficulty in matching some features of the known paleoclimate record, and of matching the tipping-point, threshold behaviour, suggested by paleoclimatic data (see Valdes (2011) [18]). The central IPCC climate projections contain no threshold effects at a $2^{\circ}C$ temperature rise and the accompanying warning of “reasons for concern” that climate change greater than $2 - 3^{\circ}C$ may be dangerous, is due to the sense that climate science practitioners have that the models’ central projections cannot be trusted for large climate forcings - largely because of this failure to match the paleoclimate record.

In addition to the treatment of catastrophe causing a problem in deriving an optimal policy in climate-economy studies (discussed further in the next section), there is a further problem with surveying the social cost of carbon (or equivalently the optimal carbon tax) across the economics of climate change literature and producing mean or median estimates that may be regarded as the considered view of the economics profession. Many articles make a methodological contribution or add some new feature to the climate-economy models. Their social cost estimate should therefore not be viewed as a data point towards what the economics profession think the optimal carbon price is, but rather as determining the marginal value of this new feature on the optimal carbon tax. For example, Lemoine & Traeger (2012) [16], and Brock et al (2012) [24] describe climate economy models with a non-catastrophic “tipping point” and so their contribution can be viewed as estimating the marginal value of this feature. Golosov et al (2011) [17] derive, under certain assumptions, a closed form optimal tax formulation that depends only on the parameters of the model rather than knowledge of the future evolution of the model’s endogenous variables, and so contribute to the climate change economist’s toolbox rather than providing a data point for a survey.

Golosov et al (2011) also report that carbon taxes should fall over time and that constant

¹Model for the Assessment of Greenhouse-gas Induced Climate Change. See <http://www.cgd.ucar.edu/cas/wigley/magicc/>

taxes have no effect on usage. This conclusion is due to Inada conditions on the use of energy together with no available alternative energy technologies - which are modelling simplification devices included to enable the study to address the question of ‘*What is the optimal carbon tax given a climate change externality?*’. Given the Allen et al (2009) conclusion that cumulative emissions are what matters and that some fossil fuels should be left in the ground, making these assumptions mean that the conclusions are not capable of being consistent with the climate science advice. By asking a different question, ‘*Given a cumulative emissions target, what carbon tax implements this target?*’, the model I present in Section 5 reaches a different conclusion on the time path of carbon taxes. If we ask different questions we get different answers.

3 Classifying approaches to climate change economics

I classify climate-economy studies into 4 groups depending on whether there is or is not a tipping point, whether avoiding crossing this tipping point on a CO_2 stabilisation path is technologically feasible, and whether crossing the tipping point is catastrophic or not. Before describing this classification, I shall first outline exactly what I mean by a tipping point and discuss some evidence that means that we cannot rule out tipping points being catastrophic for global civilisation.

A tipping point is a feature of dynamical systems with multiple steady states. As some forcing (like CO_2 from human emissions, or insolation (a measure of solar energy received on the Earth’s surface)) is applied to a system (like the Earth’s climate), the equilibrium state of the system may change smoothly, or it may change discontinuously across a tipping point. Reversing the forcing change need not reverse the movement across the tipping point. For example Zaliapin and Ghil (2010) [6] present a simple *energy balance* model of an water-world Earth-like system that is vulnerable to a catastrophic cooling to a *snowball Earth* state. The mechanism for this is that ice is much more reflective than water and so a world with intermediate levels of incoming solar radiation can be either cold or hot. If cold then the planet is ice-covered and heat reflecting (high albedo) which induces energy balance at a cold temperature, if warm then the planet is water-covered and heat absorbing (low albedo) which induces energy balance at a warm temperature i.e. two steady states. Suppose the system is in the cold, ice-covered steady state, then in order to transition to the warm steady state, incoming solar radiation has to be raised to a very high level to the point where ice cannot exist, at which point the cold steady state cannot exist and temperatures rise catastrophically as we cross the *tipping point*. The situation is well described by the bifurcation diagram, figure 1, taken from Zaliapin and Ghil (2010) which shows the equilibrium insolation and temperature combinations in their model.

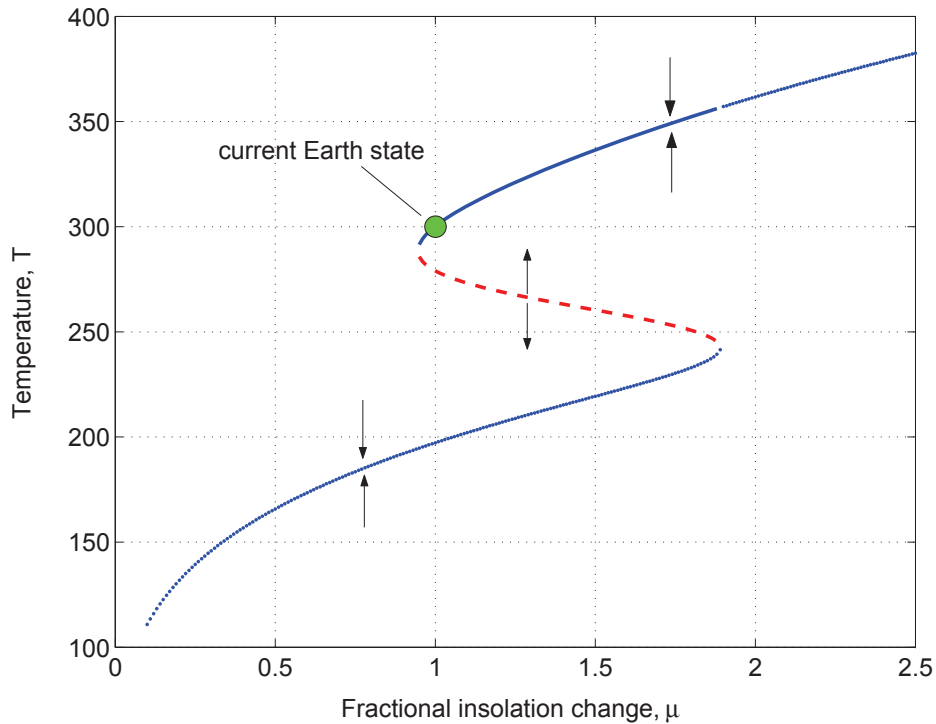


Figure 1: Energy Balance model of Snowball Earth from [6]

There are multiple sources of possible tipping points in the real Earth system including:

- The loss of polar ice at higher temperatures leading to a loss of albedo and a further rise in temperatures;
- Higher temperatures reducing ocean turnover, which reduces ocean productivity and carbon absorption and storage, causing a further rise in temperatures;
- Higher temperatures drying out peat bogs at high latitudes, melting methane hydrates in ocean sediments, and burning tropical forests, all causing carbon emissions from the natural environment, and hence a further rise in temperatures.

Each of these could lead to tipping points as the Earth transitions from one steady state to another. And once we hit a tipping point, change can be very fast: we have evidence (Alley (1993) [1]) that there were changes (at least at the regional, if not the global, level) of as much as $10^{\circ}C$ in as little as a decade, as Earth was coming out of the last ice age. Given our industrial society and economy, such rapid change could be very destabilising and damaging.

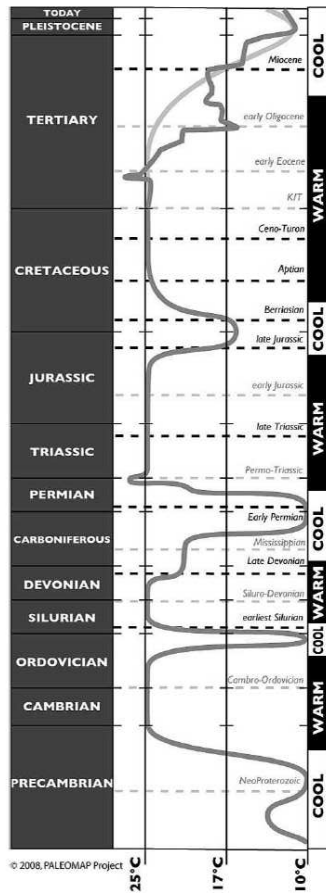


Figure 2: Approximate paleoclimate history, taken from <http://www.scotese.com/climate.htm>, created by Prof C Scotese, University of Texas at Arlington, Dept. Earth & Environmental Sciences

The geological record of global temperatures is suggestive of multiple steady states (see Figure 2). Further, there is evidence that the majority of the mass extinctions in the fossil record are associated with greenhouse warming events (see Ward (2006) [22] for a summary). It therefore seems clear that it is certainly possible that mechanisms exist such that sudden drastic warming is caused as a tipping point is passed, and that the impact of this warming is catastrophic - possibly enough to cause civilisational collapse or even human extinction. This may not be the central expectation, but many physical scientists are warning that catastrophe is possible: see Hansen (2009) [7] for a comprehensive account of the fears of one prominent climate scientist who clearly believes that human caused greenhouse gas emissions could lead to an extinction level catastrophe.

The 4 groups in the climate-economy study classification are described below. The charts accompanying these classifications have been created with the simple climate-economy model with tipping point outlined in the Appendix.

1. No tipping point: damages, however severe, are a smooth function of stabilisation CO_2

concentrations, and are never catastrophic. This is the case considered by Nordhaus (2008), Golosov et al (2011), and in the underlying papers of the Tol (2009) survey.

2. A non-catastrophic tipping point. The optimum may be before, at, or after the tipping point, and stabilisation before may or may not be feasible. This is the case that Brock et al (2012) and Lemoine & Traeger (2012) model. Figures 3 and 4 illustrates the cases with feasible stabilisation before the tipping point, and with optima at and after the tipping point.

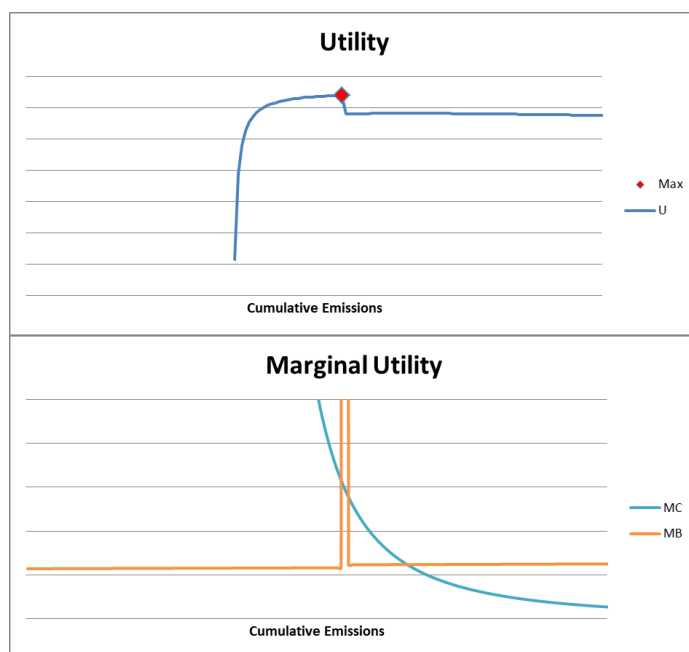


Figure 3: Utility & Marginal Utility with a non-catastrophic tipping point - stabilisation at the tipping point is optimal

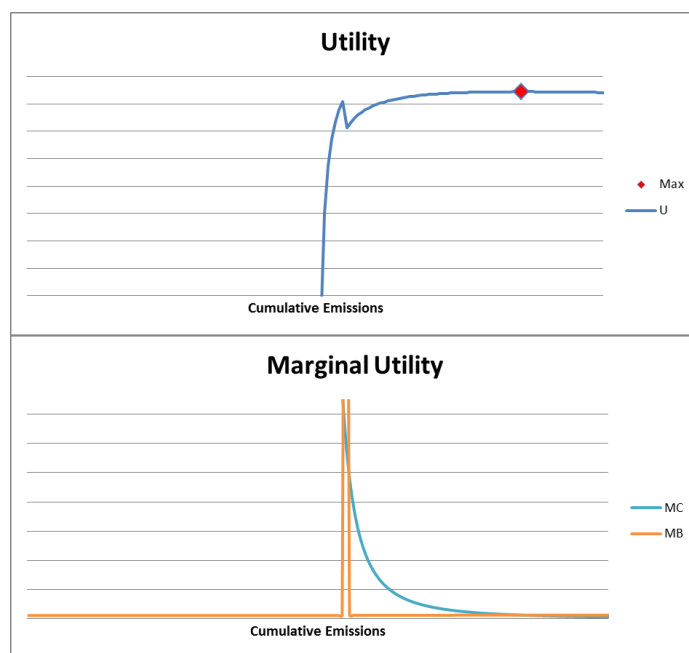


Figure 4: Utility & Marginal Utility with a non-catastrophic tipping point - stabilisation after the tipping point is optimal

3. There is a case where we cannot afford to stabilise before the tipping point (since the costs of doing this are greater than output in the policy period), but crossing the tipping point is catastrophic and corresponds to some civilisational collapse or extinction event as discussed above. This maximisation problem has no solution. Considering this to be one possible outcome in an *ex-ante* unknown problem, then any significant probability attached to this event will cause the optimisation under uncertainty to have no solution. This essentially is the case described in Weitzman (2009)'s *Dismal Theorem* [23]: whatever the level of unaffordable stabilisation costs, there is some small but non-zero probability (fat-tailed density) that a catastrophe occurs before this stabilisation level.
4. A catastrophic tipping point, but stabilisation before this tipping point is possible. There is infinite marginal benefit of climate policy implementation at the tipping point. Figures 5 and 6 illustrates this. This is the scenario that the climate science community is warning about: we cannot rule out tipping points being catastrophic, but it is likely that we can do something about the problem if we act quickly and decisively to implement climate policy. Stabilisation at or before the tipping point is optimal. Given uncertainty about exactly where the tipping point is, stabilisation exactly at the tipping point will be impossible. Assuming scientific advice to be erring on the cautionary side, following scientific advice is stabilisation before the tipping point. This is a realistic policy scenario.

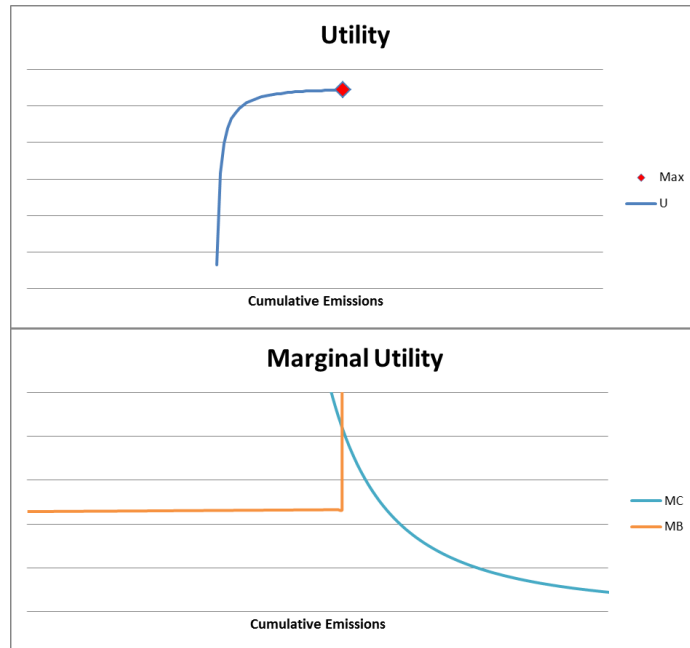


Figure 5: Utility & Marginal Utility with a catastrophic tipping point - stabilisation at the tipping point is optimal

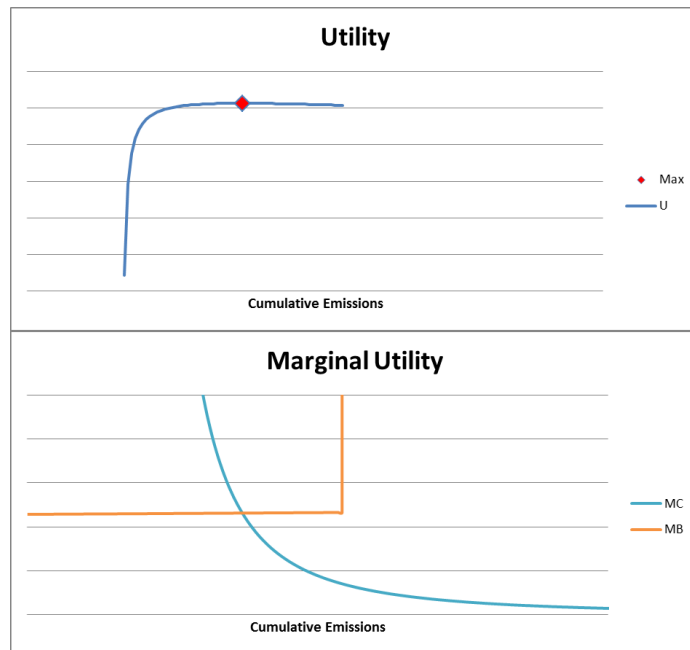


Figure 6: Utility & Marginal Utility with a catastrophic tipping point - stabilisation before the tipping point is optimal

Given this classification, we can see clearly where the divergence in policy advice between those arguing within the paradigm of case 4 (climate science recommendations), and those arguing within the paradigm of case 1 (the majority of climate change economics), comes from. However, this classification also reveals that the work of Brock et al (2012) and Lemoine & Traeger (2012), (case 2), does not help in bridging this divide: it may be optimal to stabilise at a point after a non-catastrophic tipping point, and Brock et al (2012) and Lemoine & Traeger (2012) merely discuss particulars of such models. The existence of non-catastrophic tipping points does affect optimising behaviour in ways related to the system dynamics and the degree of risk aversion of the agents, however these models do not help us at all in determining where the tipping points are, or how damaging they will be. Given that we cannot rule out catastrophic damages (and indeed suspect that they may exist), then unless we change the welfare framework (discussed in Section 4), we are, at least in a probabilistic sense, in case 3 (cue tearing of hair and gnashing of teeth, we're all doomed!) or case 4 (sensible but urgent policy advice). Stabilisation before any tipping point is likely (though not certainly) feasible and optimal. Climate models, being detailed models of the climate, are more appropriate than any climate-economy models (which necessarily have more approximation in order to facilitate optimisation) for determining where the tipping points are. These climate models have not answered this question yet, so the best we, as economists, can do is to trust what practitioners in this field say and recommend. For the economics of climate change, as Pindyck (2012) [13] says "it seems to me that a very detailed and complex modeling exercise is unlikely to be helpful", we should let the climate science community do the heavy modelling work, take their recommendations, and concentrate on modelling the economic impacts and determining the economic instruments that implement policy.

4 Dealing with the *First Question*

Nordhaus's standard approach to climate change economics, which (as discussed) is an effort to answer the '*What is the social cost of carbon?*' question, was extensively criticised by Weitzman in a series of papers (see principally Weitzman (2009)) in which he shows that, allowing for uncertainty, this carbon price is infinite. Weitzman's *Dismal Theorem* applies to problems which use an objective function with infinite marginal utility of consumption at the zero consumption level, combined with an effective probability mass² attached to catastrophe, which equates to this zero consumption level.

It is easy to object to this conclusion, which implies that society would optimally allocate an arbitrarily high share of current output to preventing tiny but non-zero risks of catastrophe or extinction. And while we may believe that society should devote more resources to climate change mitigation (or to developing asteroid or super-volcano protection systems etc) than it currently does, we are unlikely to believe that the resources so allocated should be approximately 100% of current output. However, on what grounds do we object to Weitzman's theorem? Which of the underlying assumptions do we disagree with?

According to Millner (2012) [9], there are three bottom-up grounds to object to Weitzman's methods and, therefore, conclusions: is it reasonable to attach a probability mass point to the possibility of catastrophe; is the assumption of infinite marginal utility of consumption at a zero consumption level reasonable; and, is this analysis under uncertainty relevant to a Cost Benefit Analysis (CBA) of climate policy? Millner concludes that only the infinite marginal utility of

²Weitzman's result is stronger than this in that it actually just relies on fat tails, either in the distribution of environmental outcomes or in the distribution of economic damages associated with a particular level of environmental outcome. Describing this result as applying due to a probability mass on catastrophic outcomes is intuitive though.

consumption critique has validity. Therefore, in order to evaluate the social cost of carbon we need to study how to (finitely) value catastrophe risks i.e. risks to civilisation or risks of extinction.

Weitzman (2009) discusses doing this by truncating the valuation attached to bad events, using a Value of Statistical Life (VSL) method. However this approach is shown to generate results in which the truncation becomes the dominant factor in the CBA calculation (so the size of the median impact does not really effect the calculation, the impact comes almost entirely from the choice of truncation methodology). Ikefuji et al (2011) [10] describe a stochastic climate economy model with non CRRA utility specifications chosen to produce robust policy prescriptions. This is an attempt to deduce a welfare framework on decision making under uncertainty about catastrophe from the axiom that ex-ante policy is both optimal and *reasonable* (i.e. not 100% of output). Millner (2012) is also a discussion the development of a welfare framework in which it is sensible to ask how we should value civilisation preserving policies, and which does not run into the Dismal Theorem's paradoxical infinities. This question is an interesting and important research question, but it is also a hard problem, and in the meantime, what advice do we give to policymakers on optimal climate change policy?

The answer proposed in this paper is to change the question: if we assume that following the advice of the climate science community eliminates the risk of catastrophe, then we could use a CRRA utility specification that exhibits infinite marginal utility at zero consumption, since we would only be using this welfare framework in its *natural setting* i.e. for consumption-savings decisions well away from the zero consumption level. We cannot strictly make this assumption, therefore we are not asking 'what is the optimal policy?', rather we are imposing scientific advice as a resource constraint and asking what price implements this constraint. The normative question is different - but still policy relevant and can be reconciled with the views of the climate science community.

5 Sketching a solution to the *Second Question*

In this section, I set out to answer the second question that practitioners within the economics of climate change should be addressing: '*Given a cumulative emissions target, what carbon tax implements this target?*'. I base the model I use to answer this question, to a limited extent, on Golosov et al (2011), not because I intend to argue with this paper in particular, but because it is a recent paper with a clear calibration that I can use. However, the main purpose of showing this exercise, as well as highlighting those features that should be included within such a model (and which are often not included in climate-economy models that attempt to answer the first question), is that Golosov et al (2011) makes a strong claim about the time paths of carbon taxes which this answer to the second question does not support. This highlights the fact that asking different questions can produce different answers!

Golosov et al (2011) is a standard, smooth damages, climate economy general equilibrium model that has a number of interesting features, but whose main contribution is the derivation, under certain assumptions, of a closed form optimal tax formulation that depends only on the parameters of the model rather than knowledge of the future evolution of the model's endogenous variables. The *optimum* level of carbon emissions in their results is much greater than the 500GtC future cumulative emissions limit that Allen et al (2009) recommend. Their optimal policy is determined by balancing the marginal costs of climate change against marginal benefits of energy use (non carbon energy sources are not available in their model until after the model's time horizon of more than a century). Their model does not consider the development of, and investment in, the alternative energy technologies needed for the post fossil fuel world. The

focus therefore of the Golosov et al (2011) model (in common with most such models) is on the environmental side which, as previously argued, climate economy models are poorly equipped to deal with, and not at all on the investment side which economic models have comparative advantage in addressing.

I develop a simple two energy sector economy model with an available stock of carbon energy resources, and also the technological possibility of building non carbon energy infrastructure. The model is calibrated so that the social planner, faced with a resource constraint of using only those resources used in the Golosov et al (2011) optimum, sets a carbon tax equal to that derived in the initial period of Golosov et al (2011) i.e. $\$56.9/tC$. Using this calibration, I can then estimate the carbon tax needed to implement a resource restriction consistent with Allen et al (2009). Climate damages do not enter the model: if we were to include climate damages that were very low before the tipping point but infinite after it, instead of implementing this via a resource constraint, then the results would not be much altered. The details of the model and the solution algorithm are outlined in Appendix 2, but broadly the social planner has logarithmic preferences over consumption, energy is essential for production and energy itself can be produced from some stock S_0 of fossil fuel or from some *green-tech energy capital* stock. The social planner's problem is to maximum lifetime utility by choosing consumption, investment in capital, and investment in green-tech energy capital, subject to the available fossil fuel energy resources.

We can determine the social planner's optimum solution to the saving and investment problem given various different values for S_0 . The path for marginal product of energy gives the path for prices that the final goods sector pays the fossil fuel sector for its energy supply. There is some *true* value for S_0 (i.e. the S_0 that pertains in a laissez-faire world). A carbon tax can be applied in this world so that the total payment made by the final goods sector is the corresponding marginal product from the restricted S_0 world, and the payment received by the fossil fuel sector (marginal product of energy less carbon tax) equalises the rate of return for the representative fossil fuel supplier, between supplying fuels and leaving them in the ground where their value can appreciate or depreciate. At time T the energy sector is entirely decarbonised and for all times $t > T$ the carbon tax must be (greater than or) equal to the marginal product of energy so that the final goods sector's net payment to the fossil fuel industry is zero. The value of the remaining fossil fuel resources at this point is also zero (though the marginal value of increasing the amount of fossil fuels that we are willing to burn is most definitely not zero). We can therefore implement a restriction on the total allowable burnable fossil resource even in the presence of a super-abundance. We proceed as follows (again full details in Appendix 2):

- Assume the calibration of Golosov et al (2011) and calibrate production function so that current global capital stock and energy usage produces current global GDP.
- Use the Golosov et al (2011) carbon budget (substantially greater than $500GtC$) under their optimum policy as a resource constraint, and use their initial carbon tax of $\$56.9/tC$ as a further calibration target to fully calibrate the model. We label the model run with $S_0 \equiv$ Golosov et al (2011) carbon budget as "Calibration" in Figures 7, 8 & 9.
- The policy we cost here, from Allen et al (2009), is restricting S_0 to $500GtC$, to get the $1TtC$ cumulative emissions. This model run is labelled as "1TtC" in Figures 7, 8 & 9.
- The required carbon tax in the $1TtC$ policy scenario is found to be $\$94.0/tC$ at the outset.

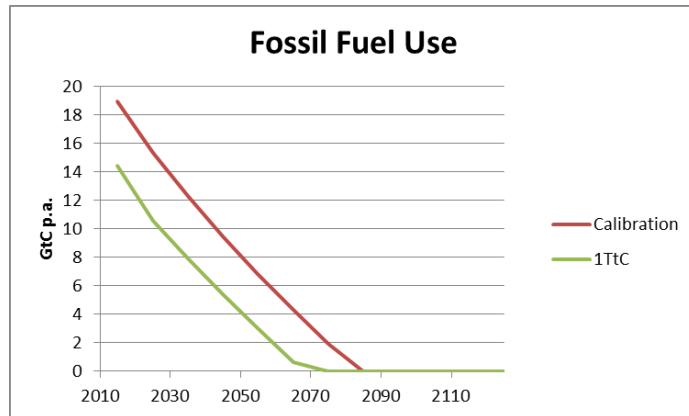


Figure 7: Fossil fuel use, in $1GtC$, vs time

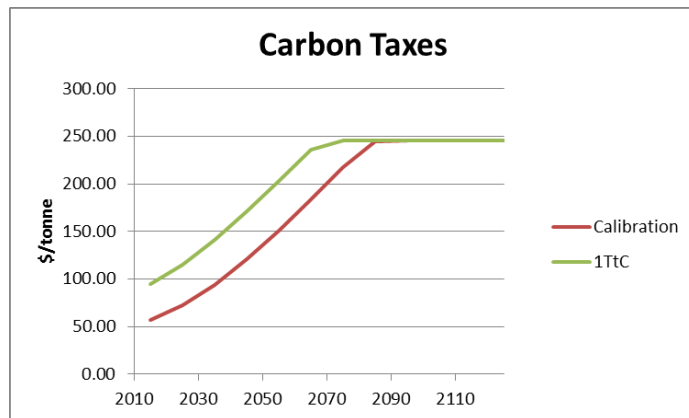


Figure 8: Carbon taxes, in $\$/tC$, vs time

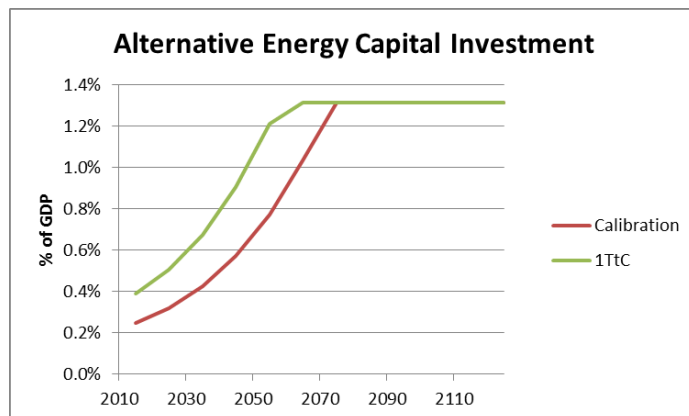


Figure 9: Investment in alternative energy capital, as % of GDP , vs time

As well as reporting a higher tax needed to implement an emissions target that we already know to be tighter than the optimum reported in Golosov et al (2011) (not a surprising result), it is also interesting to report the time path of taxes. In common with much of the economics of climate change literature, it is asserted in Golosov et al (2011) that “A constant value-added tax does not affect the intertemporal decisions of the firm, and hence has no effect on allocations, no matter how high this tax is.” This is true only in a model in which there is no alternative energy supply (which does not pay the tax) and in which policy is to manage the time profile of emissions rather than the cumulative total of emissions. In a world where we are relatively energy constrained in the no-fossil fuels future compared with today, the ultimate carbon tax will be fairly high (because the marginal product of energy will be high). Initially there is relative energy abundance and the marginal product of energy (which is the price that the final goods sector pays for its energy), is lower than it will be in long run steady state (which relies entirely on the backstop technology). We want to allow some fossil fuel use in this early period to fund the transition to the backstop technology i.e. we want a carbon tax that is less than a low energy price, rising over time so that at the point at which we have made the transition, the carbon tax is equal to the higher steady state energy price. The carbon price is rising in the result generated here, however, so long as the ultimate carbon price is greater than or equal to the marginal product of renewable energy in steady state then this is a carbon tax that will eliminate fossil emissions leaving remaining resources in the ground. On the way to this level the tax can be high and falling (extremely stringent climate policy), constant, or low and rising (less stringent climate policy). The level of long run renewable energy output is a key determinant of this steady state carbon tax level.

The energy transition model as sketched out in this section has been contrasted throughout against the climate economy model of Golosov et al (2011). This comparison was for rhetorical effect in order to make a point about the policy conclusions that we can draw from such models in giving advice to policymakers. To fully answer the question of what is the optimal carbon price to implement a cumulative emissions target, we should include a more complete model of the energy sector. Such a model would include features such as fossil fuel extraction costs, inelastic demand for energy, and technological progress. A full study would build upon the work of e.g. Hassler et al (2011) [12] who provide evidence that energy saving technical progress does respond to the energy price, and that the elasticity of substitution between energy and other factors of production is substantially less than 1; and David & van Zon (2012) [19] which is an example of a transition model which incorporates endogenous growth. I believe the study of the transformation and decarbonisation of the energy sector (and the interaction that this transition with the rest of the economy) is the central question of climate change economics, rather than the trade off between climate damages and the benefit flow from emitting carbon.

6 Conclusion

This article has argued that the reason for the dichotomy in policy advice between the climate science and economics literatures is fundamentally due to the treatment of catastrophic outcomes. To proceed, we can:

1. ignore the possibility of catastrophe, as much of the economics literature has done, and make policy recommendations that are far too light;
2. allow for catastrophe within our current welfare framework and recommend that we devote 100% of output to climate change mitigation (and another 100% of output to prevent other unlikely catastrophes!);

3. develop a new welfare framework in which we can sensibly evaluate policies that payoff only in preventing civilizational collapse or human extinction, and in the meantime, try not to muddy the waters with our half formed views of what appropriate policy is for climate change mitigation;
4. take the cumulative emissions limits, given to us by the climate science community, as resource constraints, and evaluate optimal policy conditional on staying within these constraints. The only way for the answer to this question to also be the answer to the “what is the optimal policy” question, is for scientists to be able to guarantee that following their advice would prevent catastrophe. Of course no such guarantees can be offered.

Whilst both options 3 and 4 above are sensible, this article is an appeal for more efforts to be put into 4. The minimal features that a model which can address 4 must exhibit are an alternative energy infrastructure technology and an ability for agents to leave resources in the ground. Such models could be used to provide highly relevant input that could inform the debate as to optimal climate change mitigation strategies.

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Appendix 1

The very simple climate-economy model presented in this appendix is used to generate the utility and marginal utility charts in Section 3. The tipping point is generated with a methane hydrate reservoir of size \bar{M} with an emission process given by:

$$\begin{aligned} \dot{M}_t &= -\max[0, T_t - T_M^*]M_t \\ M_t &\in [0, \bar{M}] \end{aligned}$$

Where T_M^* is the destabilisation temperature for the methane hydrate stocks. There are two possible stable states for this system:

- If human emissions cause a temperature rise of less than T_M^* then methane hydrate stocks are not destabilised and ultimate CO_2 levels are just given by pre-industrial levels and those human emissions that remain in the atmosphere.
- If human emissions cause a temperature rise of more than T_M^* then methane hydrate stocks are destabilised and ultimate CO_2 levels are given by pre-industrial levels, remaining atmospheric human emissions and \bar{M} .

Figure 10 illustrates this model given a particular parameter set. It shows equilibrium CO_2 levels against pre-industrial plus remaining atmospheric human emissions, generated using a logarithmic relationship between temperature change and CO_2 increases with a climate sensitivity of $3^\circ C$ for a doubling of CO_2 ³, $T_M^* = 3^\circ C$ (above pre-industrial temperatures), and $\bar{M} = 500ppm$ (which is assumed either to all remain in the atmosphere or to be the remaining atmospheric amount from the methane hydrate reservoir).

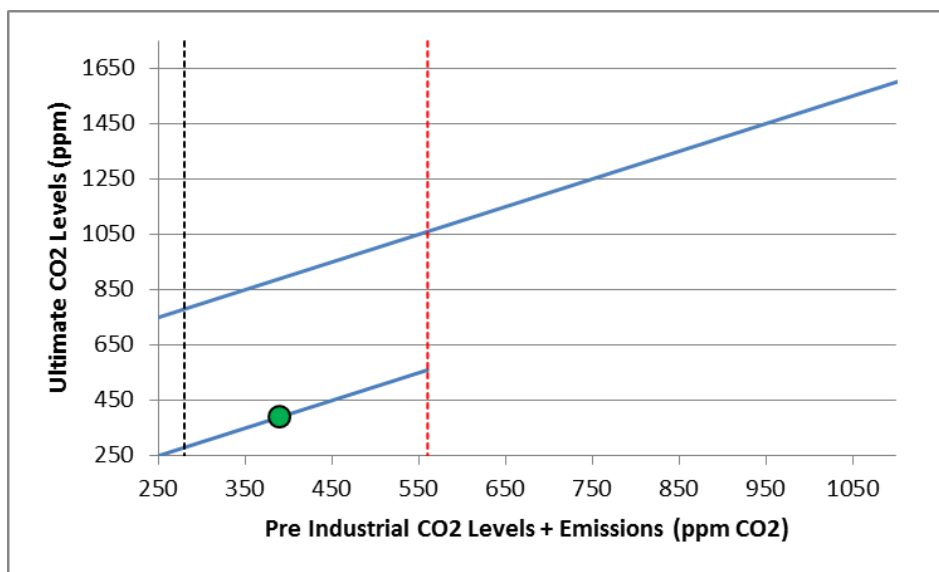


Figure 10: Simple Tipping Point Model with Methane Hydrates

Using this model (though not necessarily the above parameterisation), we can impose a modified version of the climate damages function from Golosov et al (2011)⁴. The Golosov et al

³This fixes the climate sensitivity parameter, $\kappa = (3^\circ C)/\ln(2)$

⁴Which was calibrated to reproduce the damages from the DICE 2007 model described in Nordhaus (2008)

(2011) damage function is $D(S) = 1 - \exp(-\gamma(S - \bar{S}))$, with $\bar{S} = 280ppm$ being pre-industrial atmospheric CO_2 concentrations, and D expressed as the percentage of output lost due to high temperatures. This specification is modified to allow for the possibility that the tipping point is catastrophic i.e. in some circumstances we set $D(S > S_{tp}) = 100\%$. Economic output is assumed to be constant and entirely consumed, except in the first period when some is spent on climate policy, such that costs are hyperbolic in the stabilisation level. Utility is assumed to be CRRA, and climate policy is undertaken in the first period to achieve some stabilisation level of atmospheric CO_2 concentrations. This first period is assumed to be long enough to fully implement emissions elimination at some stabilised level of atmospheric CO_2 concentrations, and for the climate system to reach equilibrium. Utility as a function of the target CO_2 stabilisation level (S , expressed in $ppm CO_2$), and the other equations of this simple model are:

$$\begin{aligned}
U(S) &= \frac{(Y - C(S))^{1-\theta} - 1}{1-\theta} + \sum_{t=1}^{\infty} \frac{(Y(1 - D(S)))^{1-\theta} - 1}{1-\theta} \left(\frac{1}{1+r}\right)^t \\
\text{where, } C(S) &= \frac{A}{S - 394} \quad , \quad S > 394 \\
D(S) &= \begin{cases} D_{NC}(S_{ult}(S)) & \text{if the tipping point is not catastrophic,} \\ D_{Cat}(S_{ult}(S)) & \text{if the tipping point is catastrophic.} \end{cases} \\
D_{NC}(S_{ult}(S)) &= 1 - \exp(-\gamma(S_{ult}(S) - \bar{S})) \\
D_{Cat}(S_{ult}(S)) &= \begin{cases} D_{NC}(S_{ult}(S)) & \text{if } \kappa \ln\left(\frac{S}{280}\right) < T_M^*, \\ 100\% & \text{if } \kappa \ln\left(\frac{S}{280}\right) > T_M^*. \end{cases} \\
\text{and, } S_{ult}(S) &= \begin{cases} S & \text{if } \kappa \ln\left(\frac{S}{280}\right) < T_M^*, \\ S + \bar{M} & \text{if } \kappa \ln\left(\frac{S}{280}\right) > T_M^*. \end{cases}
\end{aligned}$$

We can represent the utility maximisation problem as a comparison between the marginal costs of implementing climate policy and the marginal benefits of implementing climate policy. Targetting CO_2 stabilisation at the tipping point S_{tp} (defined by $T(S_{tp}) = T_M^*$) is always (at least a one sided local) utility maximum and at this point there is a singularity in the marginal benefit of implementing climate policy.

Appendix 2

Details and solution methods of the model used in Section 5. Variable definitions:

Y_t	\equiv	Output
C_t	\equiv	Consumption
L	\equiv	Population (assumed constant)
E_t	\equiv	Energy
R_t	\equiv	Renewable energy infrastructure
F_t	\equiv	Fossil fuels used
K_t	\equiv	Other physical capital
S_t	\equiv	Stocks of fossil fuels
I_t	\equiv	Investment in renewable energy infrastructure
$0 < \alpha < 1$	\equiv	Capital share of total income
$0 < \nu < 1$	\equiv	Energy share of total income
$0 < \gamma < 1$	\equiv	Returns to scale in renewable energy production
$0 < \beta < 1$	\equiv	Discount Factor
$0 < \delta < 1$	\equiv	Depreciation rate (of both R & K)
A'	\equiv	Total factor productivity (assumed constant)
A	$=$	$A' L^{1-\alpha-\nu}$
B	\equiv	Renewable energy infrastructure productivity (assumed constant)

Technologies and resource constraints:

$$\begin{aligned}
 Y_t &= A' L^{1-\alpha-\nu} K_t^\alpha E_t^\nu = AK_t^\alpha E_t^\nu \\
 E_t &= F_t + BR_t^\gamma \\
 R_{t+1} &= R_t(1 - \delta) + I_t \\
 K_{t+1} &= K_t(1 - \delta) + AK_t^\alpha (F_t + BR_t^\gamma)^\nu - C_t - I_t \\
 S_{t+1} &= S_t - F_t \\
 F_t &\leq S_t \quad , \quad \forall t
 \end{aligned}$$

Preferences - use log utility, so that the value function:

$$V_t(K_t, R_t, S_t) = \log C_t + \beta V_{t+1}(K_{t+1}, R_{t+1}, S_{t+1})$$

First Order Conditions:

$$\begin{aligned}
 \text{w.r.t. } C_t, \quad \beta \frac{\partial V_{t+1}}{\partial K_{t+1}} &= \frac{1}{C_t} \\
 \text{w.r.t. } I_t, \quad \frac{\partial V_{t+1}}{\partial K_{t+1}} &= \frac{\partial V_{t+1}}{\partial R_{t+1}} \\
 \text{w.r.t. } F_t, \quad \mu_t &= \beta \nu AK_t^\alpha (F_t + BR_t^\gamma)^{\nu-1} \frac{\partial V_{t+1}}{\partial K_{t+1}} - \beta \frac{\partial V_{t+1}}{\partial S_{t+1}}
 \end{aligned}$$

Envelope Theorem Conditions:

$$\begin{aligned}
\text{w.r.t. } K_t, \quad \frac{\partial V_t}{\partial K_t} &= \beta(1 + \alpha AK_t^{\alpha-1}(F_t + BR_t^\gamma)^\nu - \delta) \frac{\partial V_{t+1}}{\partial K_{t+1}} \\
\text{w.r.t. } R_t, \quad \frac{\partial V_t}{\partial R_t} &= \beta \nu \gamma A B R_t^{\gamma-1} K_t^\alpha (F_t + BR_t^\gamma)^{\nu-1} \frac{\partial V_{t+1}}{\partial K_{t+1}} + \beta(1 - \delta) \frac{\partial V_{t+1}}{\partial R_{t+1}} \\
\text{w.r.t. } S_t, \quad \frac{\partial V_t}{\partial S_t} &= \beta \frac{\partial V_{t+1}}{\partial S_{t+1}} + \max(\mu_t, 0)
\end{aligned}$$

such that:

$$\begin{aligned}
F_t < S_t &\Rightarrow \mu_t = 0 \\
F_t = S_t &\Rightarrow \mu_t > 0
\end{aligned}$$

Eliminate marginal values to derive difference equations to characterise the system. 6 equations in 6 unknowns, $K_t, R_t, S_t, C_t, F_t, \mu_t$. We know K_0, R_0, S_0 . We shall need to construct an algorithm to determine $C_0, F_0 \leq S_0$. Then (assuming $F_0 < S_0$) for times $1 \leq t < T$:

$$\begin{aligned}
S_t &= S_{t-1} - F_{t-1} \\
K_t + R_t &= (K_{t-1} + R_{t-1})(1 - \delta) + AK_{t-1}^\alpha (F_{t-1} + BR_{t-1}^\gamma)^\nu - C_{t-1} \\
C_t &= C_{t-1} \beta (1 + \alpha AK_t^{\alpha-1} (F_t + BR_t^\gamma)^\nu - \delta) \\
\frac{\alpha}{K_t} &= \frac{\nu \gamma BR_t^{\gamma-1}}{F_t + BR_t^\gamma} \\
\mu_t &= 0 \\
\left(\frac{K_t}{K_{t-1}}\right)^\alpha \left(\frac{F_t + BR_t^\gamma}{F_{t-1} + BR_{t-1}^\gamma}\right)^{\nu-1} &= 1 + \alpha AK_t^{\alpha-1} (F_t + BR_t^\gamma)^\nu - \delta
\end{aligned}$$

Time T is defined as the point, t , at which the first system above generates $F_t > S_t$. From $t \geq T$ the system is specified by:

$$\begin{aligned}
F_t &= S_t \\
S_t &= S_{t-1} - F_{t-1} \\
K_t + R_t &= (K_{t-1} + R_{t-1})(1 - \delta) + AK_{t-1}^\alpha (F_{t-1} + BR_{t-1}^\gamma)^\nu - C_{t-1} \\
C_t &= C_{t-1} \beta (1 + \alpha AK_t^{\alpha-1} (F_t + BR_t^\gamma)^\nu - \delta) \\
\frac{\alpha}{K_t} &= \frac{\nu \gamma BR_t^{\gamma-1}}{F_t + BR_t^\gamma} \\
\mu_t &= \nu A \left(K_t^\alpha (F_t + BR_t^\gamma)^{\nu-1} \frac{1}{C_t} - \beta K_{t+1}^\alpha (F_{t+1} + BR_{t+1}^\gamma)^{\nu-1} \frac{1}{C_{t+1}} \right)
\end{aligned}$$

The time t value of each asset K_t, R_t, S_t is:

$$\begin{aligned}
\frac{\partial V_t}{\partial K_t} &= (1 + \alpha AK_t^{\alpha-1} (F_t + BR_t^\gamma)^\nu - \delta) \frac{1}{C_t} \\
\frac{\partial V_t}{\partial R_t} &= (1 + \nu \gamma A B R_t^{\gamma-1} K_t^\alpha (F_t + BR_t^\gamma)^{\nu-1} - \delta) \frac{1}{C_t} \\
\frac{\partial V_t}{\partial S_t} &= \nu AK_t^\alpha (F_t + BR_t^\gamma)^{\nu-1} \frac{1}{C_t}
\end{aligned}$$

Therefore we calculate the total return on each asset over period $(t, t + 1)$. By a no arbitrage argument these total returns should all be the same, and since there is no uncertainty, their value

should be $1/\beta$.

$$\begin{aligned}
TR(K_t) &= \left[(1-\delta) \frac{\partial V_{t+1}}{\partial K_{t+1}} + \frac{\alpha A K_t^{\alpha-1} (F_t + BR_t^\gamma)^\nu}{\beta C_t} \right] \bigg/ \frac{\partial V_t}{\partial K_t} \\
TR(R_t) &= \left[(1-\delta) \frac{\partial V_{t+1}}{\partial R_{t+1}} + \frac{\nu \gamma A B R_t^{\gamma-1} K_t^\alpha (f_t + BR_t^\gamma)^{\nu-1}}{\beta C_t} \right] \bigg/ \frac{\partial V_t}{\partial R_t} \\
TR(S_t) &= \frac{\partial V_{t+1}}{\partial S_{t+1}} \bigg/ \frac{\partial V_t}{\partial S_t}
\end{aligned}$$

Steady state can be calculated:

$$\begin{aligned}
S^* &= 0 \\
F^* &= 0 \\
K^* &= \left(\frac{\alpha A B^\nu (\gamma \nu / \alpha)^{\gamma \nu}}{1/\beta + \delta - 1} \right)^{\frac{1}{1-\alpha-\gamma \nu}} \\
R^* &= \frac{\gamma \nu}{\alpha} K^* \\
C^* &= A B^\nu (K^*)^\alpha (R^*)^{\gamma \nu} - \delta (K^* + R^*) \\
\mu^* &= \frac{\nu A B^{\nu-1} (K^*)^\alpha (R^*)^{\gamma(\nu-1)} (1-\beta)}{C^*} \\
E^* &= B (R^*)^\gamma
\end{aligned}$$

The algorithm to determine $C_0, F_0 \leq S_0$

- Given F_0 , adjust C_0 so that C_t is arbitrarily close to C^* at some suitably large t (i.e use the *forward shooting* method)
- If the total return on fossil fuels over the final period of their use is too high then they are in too short supply and should be conserved at the outset i.e. F_0 is too high and should be lowered. Vice versa for total returns that are too low.

We proceed as follows (full details):

- Assume the calibration of Golosov et al (2011) i.e. $\alpha = 0.3$, $\nu = 0.03$, $\beta = 0.985$ (per annum), $\delta = 1$. Time step = 10 years. Therefore still have 3 unknown parameters: A, B , & γ .
- Estimate initial global capital stock, $K_0 + R_0$ ⁵. Take the percentage of global primary energy supply from fossil fuels from data ($\sim 80\%$) and combine with initial carbon usage from the laissez-faire version of Golosov et al (2011), $128GtC$, so that $E_0 = 128/80\%$ and such that the production function produces current global GDP, Y_0 . Assume that $E_0 = 2E^*$ i.e. we assume that a future world which uses non-fossil energy resources will be more energy constrained than our current world (this may or may not be a reasonable assumption, and it is important for the timepath of carbon taxes discussed below). For a given choice of γ these assumptions give us A & B , i.e. using these 2 relationships, we can fix 2 of the 3 unknown parameters.
- Following Golosov et al (2011) let $S_0 = 1400$ in laissez-faire ($400GtC$ from oil and $5000GtC$ from coal which has an efficiency of 0.2 and convert to energy units (1GtC of oil gives 1

⁵1990 estimate of global capital stock taken from [3], rolled up to 2011 using Gross World Product from Wikipedia

energy unit) rather than units of carbon). The Golosov et al (2011) *optimum* uses 691 energy units of fossil fuel and is implemented using an initial carbon tax of $\$56.9/tC$. We choose γ to match this initial tax rate i.e. this further relationship pins down the remaining unknown parameter. This model run is labelled as “Calibration” in Figures 7, 8 & 9.

- The policy we cost here, from Allen et al (2009), is restricting S_0 to 420 energy units (400GtC of oil and 100GtC from coal at 0.2 efficiency, to get the $1TtC$ cumulative emissions)⁶. This model run is labelled as “1TtC” in Figures 7, 8 & 9.
- The required carbon tax in the $1TtC$ policy scenario is found to be $\$94.0/tC$ at the outset.

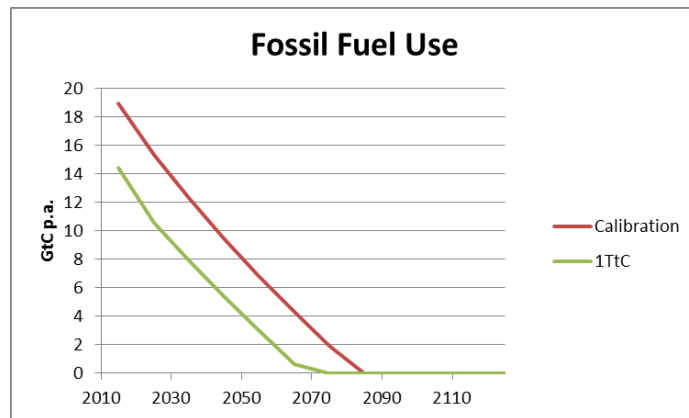


Figure 11: Fossil fuel use, in energy units such that $1EU$ is provided by $1GtC$ of oil or $5GtC$ of coal, vs time. The caption on Figure 7 in the main body of the text does not describe this complication.

⁶The model actually produces fossil energy taxes applied to energy units and does not differentiate between oil and coal. This is not too inappropriate for the $1TtC$ run since coal is not much used, it is less appropriate the more coal that is in the mix.