DEPARTMENT OF ECONOMICS
OxCarre
Oxford Centre for the Analysis of Resource Rich Economies

Manor Road Building, Manor Road, Oxford OX1 3UQ
Tel: +44(0)1865 281281 Fax: +44(0)1865 271094
oxcarre@economics.ox.ac.uk www.oxcarre.ox.ac.uk

OxCarre Policy Paper 35

Cumulative Emissions, Unburnable Fossil Fuel, and the Optimal Carbon Tax

Frederick van der Ploeg

OxCarre

&

Armon Rezai*

Vienna University of Economics and Business

***OxCarre External Research Associate**

Direct tel: +44(0) 1865 281281 E-mail: oxcarre@economics.ox.ac.uk

CUMULATIVE EMISSIONS, UNBURNABLE FOSSIL FUEL,

AND THE OPTIMAL CARBON TAX

Frederick van der Ploeg, University of Oxford§

Armon Rezai, Vienna University of Economics and Business* ‡

Abstract

A stylised analytical framework is used to show how the global carbon tax and the amount of untapped fossil fuel can be calculated from a simple rule given estimates of society's rate of time impatience and intergenerational inequality aversion, the extraction cost technology, the rate of technical progress in renewable energy and the future trend rate of economic growth. The predictions of the simple framework are tested in a calibrated numerical and more complex version of the integrated assessment model (IAM). This IAM makes use of the Oxford carbon cycle of Allen et al. (2009), which differs from DICE, FUND and PAGE in that cumulative emissions are the key driving force of changes in temperature. We highlight the importance of the speed and direction of technological change for the energy transition and how time impatience, intergenerational inequality aversion and expected trend growth affect the time paths of the optimal global carbon tax and the optimal amount of fossil fuel reserves to leave untapped. We also compare these with the adverse global warming trajectories that occur if no policy actions are taken.

Keywords: energy transition, optimal carbon tax, unburnable fossil fuel, cumulative emissions, Oxford carbon cycle, trend growth

October 2016

---

§ Department of Economics, Manor Road Building, Oxford OX1 3 UQ, U.K. Also affiliated with St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg, 199034 Russia, And the VU University Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands. Email: rick.vanderploeg@economics.ox.ac.uk. Support from ERC Advanced Grant 'Political Economy of Green Paradoxes' (FP7-IDEAS-ERC Grant No. 269788) and the BP funded Oxford Centre for the Analysis of Resource Rich Economies is gratefully acknowledged.

* Department of Socioeconomics, Welthandelsplatz 1, 1020 Vienna, Austria, and IIASA, Schlossplatz 1, 2361 Laxenburg, Austria, email: Armon.Rezai@wu.ac.at, corresponding author. Support from the Austrian Science Fund (FWF): J 3633 and the OeNB Anniversary Fund (grant no. 15330) is gratefully acknowledged.

‡ We thank for Myles Allen and Elizabeth Baldwin for sharing their insights on the Oxford cycle and Spencer Dale for some helpful discussions.

1. Introduction

Climate scientists have warned that to have a 50-50 chance of limiting global warming to not more than 2 degrees Celsius above the average global temperature of pre-industrial times throughout the twenty-first century cumulative carbon emissions between 2011 and 2050 need to be limited to 1,100 Giga tonnes of carbon dioxide (Gt CO2) or 300 Giga tonnes of carbon (GtC) (Allen et al., 2009; Meinshausen et al., 2009; Clarke et al., 2014).[1] Recent calculations suggest that this necessitates one third of oil reserves, half of gas reserves and over four fifths of coal reserves to remain untapped from 2010 to 2050 (McGlade and Ekins, 2015). These calculations are based on an ad-hoc combination of the top-down model MAGICC to give a probability distribution of the temperature rise trajectories for a given carbon emissions profile taking macroeconomic trends as given and the bottom-up model TIAM-UCL to calculate how much of each fossil fuel can be burned in each region.

The integrated assessment model (IAM) most often used by economists and policy makers is DICE (Nordhaus, 2014).[2] This general equilibrium IAM has the advantage that it can explain macroeconomic trends and changes in the carbon cycle in a coherent and consistent manner. However, it supposes that all fossil fuel is abundant and thus cannot speak to the key question of how much fossil fuel to abandon in order to limit global warming. Most IAMs used in the policy debate such as PAGE (Tol, 2002ab), FUND (Hope, 2006) or DICE are quite complex and difficult to comprehend for the outsider (if accessible to the public at all). Furthermore, although figures for the optimal carbon tax derived from these IAMs deliver headline-grabbing numbers, it is less clear to the uninitiated where these numbers precisely come from and how reliable the underlying global damages used in these IAMs are from a scientific point of view (Pindyck, 2013). One IAM that does give estimates of the amount of fossil fuel to be locked up (McGlade and Ekins, 2015) does not perform an optimal tradeoff between locking up fossil fuel and the resulting curbing of global warming, on the one hand,

[1] According to the IPCC (2014), cumulative emissions have to be limited to an uncertainty range of 700-860 GtC if global warming is to remain below 2°C. With 520 GtC emitted by 2011, this gives a tight carbon budget range of 180-320 GtC. Recent research, however, increases this budget significantly, proposing a carbon budget of about 250 GtC to achieve the 1.5°C target (Allen and Rogelj, 2016).

[2] Simulations based on DICE also supported the recommendations of the Stern Review (Stern, 2007).

and consumption sacrifices that have to be made to achieve this today and in the near future, on the other hand.

Our objective is to offer a simple framework to demonstrate how the global carbon tax and the amount of unburnable fossil fuel depend on ethical parameters such as the society's rate of time impatience and intergenerational inequality aversion, the extraction cost technology, the rate of technical progress in renewable energy and the estimate of the future trend rate of economic growth. Recently, simple rules for the global carbon tax have been developed to provide guidance for policy makers (Golosov et. al, 2014; Rezai and van der Ploeg, 2016; Allen, 2016). Two of these studies fix the weight current generations place on future well-being. Here, we also develop a rule that allows for general weights and also develop a rule for the optimal amount of fossil fuel to leave unburnt. We do not specify the carbon budget ex ante, but derive the climate policies that maximise social welfare and optimally trade off making sacrifices by current generations and those in the near future to limit global warming in the more distant future within a simple and transparent framework.

To back up our arguments, we put forward a new IAM of macroeconomic growth and climate change with three features that are not present in the DICE, FUND or PAGE models (Rezai and van der Ploeg, 2016). First, we allow extraction costs to increase as the finite stock of fossil fuel reserves is depleted. This creates a scarcity rent on fossil fuel and a motive not to burn all available reserves. Second, existing IAMs have used rather simple carbon cycles on coarse time grids with the implication that the amount that is left of burning one ton of carbon today at any future is independent of past or current stocks of carbon in the atmosphere. Others have shown that the carbon cycle of DICE can be well represented with a two- or three-box carbon cycle (Golosov et al., 2014; Gerlagh and Liski, 2013), but also abstract from history dependence. The Oxford carbon cycle (e.g., Allen et al., 2009) does give a role for memory and captures the carbon cycle and temperature changes much better and we therefore use this as our carbon cycle. For this cycle cumulative carbon emissions are the main driving force of changes in global mean temperature and this is why we focus on cumulative emissions too. Third, our IAM optimally determines the time at which fossil fuel is phased out and renewable energy is phased in. The transition to the carbon-free phase occurs at the moment that the rise in extraction costs as reserves are depleted plus the rise in the social cost of carbon together with the fall in the cost of renewable energy are sufficiently strong to price fossil fuel out of the market. Our IAM has a finer, annual grid than other IAMs so the timing of energy transitions can be pinpointed more precisely and accurately (Cai et al., 2012).

Other features of our IAM are more familiar. We have a Ramsey model of macroeconomic growth and convergence with capital, labor and energy fuel as factors of production, use the global warming damages of DICE, and suppose that renewable energy is not competitive today but will become so in the future as technical progress reduces their cost while the cost of fossil fuel increases with cumulative extraction. Overall technological progress proceeds along its historic average of roughly 2% per annum and world population continues to grow to a plateau of 12 billion. We will highlight the importance of different expectations about future trend growth for climate policy in our analytical results and in our numerical simulations.

2. Some simple insights into optimal climate policy

Recently, simple rules for the optimal global carbon tax τ (in dollars per ton of emitted carbon) at time *t* have been proposed by Golosov et al. (2014), Gerlagh and Liski (2014), Rezai and van der Ploeg (2016), and Allen (2016). They all share the form $\tau(t) = \Omega(r)\chi Y(t), \quad \Omega'(r) < 0,$ where χ is the damage flow as a fraction of world GDP corresponding to burning one gigatonne of carbon, Y is world GDP, and r is the growth-corrected rate used to discount global warming damages. With global warming damages proportional to world GDP (roughly as in DICE), the optimal global carbon tax is proportional to world GDP too. The function $\Omega(r)$ corresponds to the present discounted values of what is left at each point of time in the future of burning one ton of carbon today, suitably corrected for the lag between changes in the stock of atmospheric carbon and global mean temperature. This captures the DICE carbon cycle fairly well, but for the Oxford carbon cycle the history of emissions matters and thus the optimal global carbon tax should be written as

(1) $\tau(t) = \Omega\left(r, H(t)\right)\chi Y(t), \quad \Omega'(r) < 0,$

where $H(t)$ denotes the history of fossil fuel emissions at time *t*. The insight that the optimal global carbon tax is proportional to world GDP and decreases with the growth-corrected interest rate is thus unaffected. In economic growth models, the standard Keynes-Ramsey rule gives the growth-corrected social rate of interest

(2) $r = RTI + (IIA - 1)g,$

where $RTI > 0$ is the rate of time impatience, $IIA \geq 0$ the coefficient of relative intergenerational inequality aversion and *g* is the rate of trend growth. If there is little concern for the welfare of future generations (high RTI), the interest rate will be high and the global carbon tax low as future damages are discounted more heavily. Economic growth implies that future generations are richer and, provided $IIA > 1$, that current generations are less prepared to make sacrifices to curb global warming in the distant future especially if intergenerational inequality aversion is strong.[3] Higher growth then leads to a higher social rate of interest and to a lower carbon tax.

The cost of extracting fossil fuel increases as fewer reserves are left, so that the easiest accessible resources are explored first. Extraction cost at time *t* is thus $C\left(S(t)\right)$, $C' < 0,$ where $S(t)$ denotes reserves at time *t*. The optimal amount of fossil fuel to be locked up at the end of the fossil fuel phase follows from the economic condition that the marginal cost of fossil fuel extraction plus the carbon tax must equal the cost of renewable energy, since at the time of the energy transition, say *T*, the scarcity rent of fossil fuel vanishes. Hence, $C\left(S(T)\right) + \xi\tau(T) = b(T), \quad T > 0,$ where $\xi > 0$ denotes the carbon emission per unit of energy (the emission intensity) and $b(t)$ the unit cost of infinitely elastically supplied renewable energy at time *t*. Using the functional specification $C\left(S(t)\right) = \gamma_0\left(S(0)/S(t)\right)^{\gamma_1}$ together with (1) and (2), we derive the amount of unburnt fossil fuel as a function of fundamental ethical, technological and geophysical parameters:

[3] Golosov et al. (2014) and Allen (2016) fix *IIA* at 1 and 0, respectively. This creates potential problems of converges and is below the conventional range of *IIA* between 1 and 2.

$$(3) \qquad \frac{S(T)}{S(0)} = \left(\frac{\gamma_0}{b(T) - \xi\tau(T)} \right)^{\frac{1}{\gamma_1}} = \left(\frac{\gamma_0}{b(T) - \xi\Omega\big(RTP + (IIA-1)g, H(T)\big)\chi Y(T)} \right)^{\frac{1}{\gamma_1}}.$$

Since unburnt fossil fuel increases in the global carbon tax, a lower rate of time preference or less intergenerational inequality aversion lowers the rate used to discount damages and pushes up the carbon tax and thus leaves more of fossil fuel unburnt. A higher damage coefficient or a higher level of world GDP at the time of the switch to the carbon-free era also pushes up the carbon tax, so more of each fossil fuel is left in the ground. Also, more of a fossil fuel is left unburnt if the cost of extracting (γ_0) are high and the cost of its carbon-free alternative ($b(T)$) is low. Further, more fossil fuel is left unburnt if the emissions intensity (ξ) is large.[4] To the extent that solar energy is a cheap substitute for coal in, say, electricity generation, more of coal reserves must be left unused. The stock of untapped fossil fuel indicates how much fossil fuel is burned which translates into cumulative carbon emissions. It thus follows that cumulative emissions and global warming are curbed if the rate of time impatience (*RTI*), intergenerational inequality aversion (*IIA*) and (if *IIA* > 1) trend growth are lower, extracting fossil fuel is more expensive and renewable energy is cheaper. Finally, if σ units of fossil fuel are needed per unit of output, the optimal time of the energy transition is approximately

$$(4) \qquad T = \frac{1}{g}\ln\left(1 + g\,\frac{S_0 - S(T)}{\sigma Y(0)}\right), \quad g \neq 0, \qquad T = \frac{S_0 - S(T)}{\sigma Y(0)}, \quad g = 0.$$

Equation (4) shows that fossil fuel is abandoned more quickly if the economy and the associated demand for fossil fuel ($\sigma Y(0)$) are large, the total amount of burnt fossil fuel ($S_0 - S(T)$) is small, and the rate of economic growth (g) is high. Using (3), we see that a higher weight to the welfare of future generations (lower RTI) and less

[4] For example, the tar sands are expensive and have a high emissions intensity so it is best to keep as much (if not all) of these reserves unexploited. Conventional natural gas and shale gas are relatively cheap to extract and have lower emissions intensity than oil, coal or tar sands. This suggests that much less of gas reserves should be abandoned. Coal is very cheap to extract and has relatively high emissions intensity, so much of coal reserves will be used unless carbon is properly priced.

intergenerational inequality aversion (lower in IIA) lowers the amount of burnt fossil fuel and thus speeds up the transition to the carbon-free economy.

The basic dynamics of all IAMs are captured in equations (1)-(4). They illustrate how economic and geo-physical considerations (equation (1)) and ethical tradeoffs between current and future generations (equation (2)) drive the extent of climate policy. Technological possibilities determine the efficacy of climate policy. If alternative energy sources are available cheaply, substitutability across energy inputs is high and even cheap forms of fossil energy can be priced out of the market and locked up underground easily (see equation (3)). The smaller carbon budget translates into an earlier transition time to a carbon-free economy (equation (4)). This straightforward exposition of the logic underlying IAMs contrasts sharply with conventional IAMs which only produce simulated time paths for one particular set of parameters with the modelling assumptions often relegated to an appendix and occasionally not made available to the public at all. It is therefore hard to judge the plausibility of the numerical results, let alone of single assumptions. In the following section we will propose and simulate our own more complex and fully specified IAM in order to illustrate the plausibility of the proportionality feature of our simple carbon tax rule in equation (1) and demonstrate how predictions of the simple model bare out in the more elaborate and, arguably, fairly standard IAM.

Our focus in this section is simplicity and we have ignored many of the additional features which add to the realism of IAMs. Such extensions can include economic and technological aspects of our model such as more elaborate theories of economic growth and capital accumulation, technological progress in the fossil and renewable energy sectors as well as the economy in general, the substitutability of different forms of energy, and the role of energy in production and overall growth. Extensions of our model on the geophysical side can include the consideration of more elaborate and non-linear climate and temperature dynamics and catastrophic tipping points such as positive feed-backs from melting Siberian permafrost or the collapses of the Gulf stream. Some of these aspects can be readily included in our model: energy intensity can be modelled along an exogenously declining trend (as, for example, in DICE), differential rates of technological progress across energy sectors can illustrate the challenges of pricing fossil fuel out of the market, the consideration of learning curves in renewable energy introduce the need for renewable subsidies and extend the scope of economic policy, and catastrophic events can be represented by increasing the damage parameter χ in our model. Models like the TIAM-UCL break decisions about fossil fuel down to the regional level and allow for variations in the evolution of energy prices across regions. Given the long time horizon implied in climate change, we only consider here the world economy as a whole, assuming that persistent cost differentials would be arbitraged away by international trade.

3. Illustrative policy simulations

In our model in section 2 we left most of the functional relationships, most importantly the carbon tax rule unspecified. To demonstrate the robustness of our simple model and the insights obtained from equations (1)-(4), we present simulations for the optimal carbon tax and the business-as-usual (BAU) outcomes from our general equilibrium IAM with stock-dependent extraction costs and optimal energy transitions. While calibrated to real-world data, these simulations are meant to be illustrative in nature. The point is to demonstrate the proportionality of the optimal carbon relative to output as stated in equation (1). Our simulations are also the first where the Oxford carbon dynamics is implemented in an optimisation framework. In the baseline simulations we assume that the *RTI* is 0.1% per annum (Stern, 2007), *IIA* is 1.45 (Nordhaus, 2014) and productivity growth is 2% per annum (Barro, 2014). Table 1 presents these numbers and also a set of four sensitivity runs in which we analyse the effect of changes in the key parameters appearing in equations (1)-(4).

Insert table 1 here

We also present a 'conventional' scenario which meets the standard assumptions economists make about the social rate of time impatience, the degree of intergenerational inequality aversion, and the trend growth rate of productivity. Figure 1 reports the equilibrium trajectories for select key variables for the welfare-

maximizing case (left panel) and BAU where no policy action is taken, i.e., the carbon tax remains at zero (right panel).

Insert figure 1 here

We start with BAU (right panel) to illustrate the ruinous prospects for the world and highlight the need for climate policy. Without a carbon tax, firms are not forced to internalize the deleterious effects of fossil fuel and the market price of fossil fuel is sufficiently low for continued use of the dirty but cheaper input for most of the century. In the baseline BAU case 4,760 GtC are burnt and global temperature peaks above 5 °C. This is in sharp contrast with the social optimum where only an eighth as much carbon is burnt and temperature peaks slightly above 2°C (see discussion below). What is more, a maximal warming of 5°C and cumulative carbon emissions in excess of 4,500 GtC are a consistent feature of all our BAU simulations, regardless of the degree of RTI and IIA as these parameters mostly influence the carbon tax (which is zero in BAU). Under BAU the energy transition is driven solely by the cost differentials between fossil and renewable energy sources. Once the latter become competitive, fossil fuel use stops. The importance of climate policy is to drive an additional cost wedge between the two types of energy and bring forward the end of the carbon era. The trend growth rate does have a significant impact on BAU, but only on the timing of fossil fuel use in (4). As the economy grows more slowly, less fossil fuel is used in each period. This pushes out the time at which the economy switches to the carbon-free phase and allows technological progress in renewable energy generation to continue. Peak temperature is, however, only slightly lowered with cumulative emissions of about 4,000 GtC, which is still more than 10 times the carbon budget compatible with keeping global warming below 2 degrees Celsius. Given our simulations, BAU clearly is not an environmentally viable option. Fortunately, it is also very unattractive from a purely economic point of view not to adopt climate policy.

Optimal climate policy responds to the tradeoff between, on the one hand, locking up fossil fuel and curbing global warming, and, on the other hand, sacrificing consumption now and in the near future. Abstracting from the collective actions problems vexing current climate negotiations, in our model this reduces to trading off higher costs of energy in the near term and higher costs from climate change in the long term. Our illustrative simulations show that welfare is maximized under a complete decarbonisation of the economy by mid-century in the baseline scenario (red, solid) or by 2070 at the latest in our sensitivity runs. The left panel in figure 1 illustrates that in the baseline the optimal carbon tax is set to limit global warming to 2.2°C, starting at $82/tC and rising at about 3% per annum over the next two centuries. Stringent climate policy of this form increases the price of fossil fuels rapidly enough that fossil fuel is phased out and carbon-free alternatives are phased in mid-century. At this point, cumulative emissions amounting to 670 GtC will have been burnt and all remaining fossil fuel reserves will be abandoned. This favourable scenario contrasts starkly with the business-as-usual case discussed above where output losses of up to 35% are incurred.

Given the assumptions about RTI, IIA and g, we can compute the equilibrium interest rate in (1). For the baseline scenario, r is 1% per annum. The rules in (1) and (2) allow us to predict the effects of changes in parameter values on the optimal carbon tax, cumulative emissions, and peak temperature. Increasing the RTI to 1% per annum increases the interest rate with which damages are discounted from 1% to 1.9% per annum and, consequentially, lowers the carbon tax. Fossil fuel therefore remains competitive for longer, leading to increased cumulative emissions and higher peak warming. The simulations in figure 1 confirm this prediction, with the initial tax falling to $45/tC, cumulative emissions and maximal warming rising to 1,010 GtC and 2.6°C, respectively.

Figure 1 also reports the effect of lowering the degree of intergenerational inequality aversion to 1. This reduces the social interest rate r to 0.1% per annum, and therefore increases the carbon tax (to $408/tC), curbs cumulative emissions (to 30 GtC) and lowers global warming (to 1.2°C). More pessimism about future growth prospects, say, lowering g to 1%, roughly halves the social interest rate which leads to a near doubling of the initial carbon tax to $153/tC but also flattens the growth trajectory of the carbon tax (to roughly 2% per annum). The overall effect is still a reduction in cumulative emissions to 440 GtC and of peak temperature to 1.9°C.

We also report the outcomes for what we deem the ‘conventional’ parameter set in the economics profession (e.g., Weitzman, 2007). In the presence of positive productivity growth, the higher discount rate and the higher degree intergenerational aversion lead to a significantly higher interest rate of 3% per annum. The economic intuition behind this is that with a lower *RTI* and higher *IIA,* current generations are less willing to sacrifice their own economic well-being which is at a lower level than that of future generations which are expected to be significantly wealthier due to persistent growth in productivity and living standards. The higher social interest rate lowers the carbon tax to $22/tC as future damages are discounted more heavily. The price of fossil fuel remains below that of renewable energy for longer and cumulative emissions increase to 1,430 GtC, inducing temperature to peak at 3°C.

Insert figure 2 here

Van den Bijgaart et al. (2016) and Rezai and van der Ploeg (2016) test rules based on Nordhaus (1991) and similar to (1) for simple carbon cycles. In figure 2 we present similar results. The carbon tax follows the proportional rule (2) for most of the scenarios, performing worse if the transitional dynamics are slow (Rezai and van der Ploeg, 2016). In particularly, for baseline and conventional parameter specifications, the optimal carbon tax is essentially a constant fraction of output. The rule therefore seems to perform well even in the more complex Oxford carbon cycle where the history of carbon emissions also matters.

4. Conclusions

The failure of markets to price carbon emissions appropriately leads to excessive fuel use and global warming. Climate policy corrects this planetary market failure and imposes the social cost of deleterious carbon emissions on the users of fossil fuel by levying a global carbon tax (or setting up a market for tradable emission permits), thereby limiting cumulative carbon emissions. Most of climate economics tries to calculate the social cost of carbon, or the optimal carbon tax, using large, intransparent numerical IAMs, which are unable to shed light on the optimal amount of fossil fuel to leave unburnt. We have given some simple formulae to show how the global carbon tax and the amount of untapped fossil fuel can be calculated on the back-on-the-envelope given estimates of society's rate of time impatience and intergenerational inequality aversion, the extraction cost technology, the rate of technical progress in renewable energy and the future trend rate of economic growth.

Our numerical general equilibrium IAM with stock-dependent extraction costs, endogenous energy transitions and Oxford carbon dynamics shows that with business as usual global warming leads to unacceptable degrees of peak global warming, around 5°C. This highlights the urgency and scale of the climate policy challenge. Our estimates of the optimal time paths for the carbon tax significantly curb cumulative fossil fuel use to 670 GtC. As a consequence, peak temperature reduces to 2.2°C in our baseline scenario but ranges between 1.2°C and 3°C across scenarios with cumulative emissions ranging from 30 to 1430 GtC. These results illustrate how previous estimates of the carbon budget for 2°C (usually cited at around 300 GtC) have been too pessimistic. Our findings are consistent with the more elaborate climate science presented in Allen and Rogelj (2016) who place the lower bound for hitting the 1.5°C target by the end of the century at 250 GtC.

Climate policy is more ambitious if future generations get more weight, intergenerational inequality aversion is less, and the expected trend rate of economic growth is lower. We confirm that for conventional parameter ranges, the optimal carbon tax is proportional to world GDP so that future development in the productive capacity of the economy is a crucial driver of the optimal carbon tax.

In as far as our optimal climate policy based on the DICE estimates of global warming damages lead to more than 2°C global warming more climate adjustments need to be made. An obvious one is that a rising carbon tax will in itself increase the rate of technical progress in renewable energy production and speed up the transition away from fossil fuel. To the extent that there is learning by doing, a renewable energy subsidy is called for (Rezai and Van der Ploeg, 2014). Another one is that a rising carbon tax induces additional carbon capture and sequestration. This may well be an essential component of assuring that global warming remains below 2°C (Allen et al., 2009).

A crucial research question is how markets will respond to a 2°C world with stringent climate policy. In the absence of viable sequestration options, cumulative emissions of 300-670 GtC should be compared with existing reserves of the 7 big international oil companies. Carbon Tracker and The Guardian have highlighted the issue in a recent fossil disinvestment campaign.[5] However, any economic disconnect between the planetary carbon budget constraint and existing reserves depends on the current book value of these reserves. We believe that contemporary accounting practices are guarding against an artificial overvaluation of international oil companies and it does not seem appropriate to warn about stranded assets of oil companies. However, we leave this for future research and conclude that, notwithstanding, the planet should get used to the idea that large chunks of fossil fuel reserves should remain untapped.

References

Allen, M. (2016). Drivers of peak warming in a consumption-maximizing world, Nature Climate Change, forthcoming.

Allen, M., D. Frame, C. Huntingford, C. Jones, J. Lowe, M. Meinshausen and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458, 7242, 1163-1166.

Barro, R.J. (2014). Convergence and modernization, mimeo., Harvard University, Cambridge, Mass.

Bijgaart, Inge van den, Reyer Gerlagh, Luuk Korsten, and Matti Liski. 2016. A simple formula for the social cost of carbon. Journal of Environmental Economics and Management, 77, 75-94.

Cai, Y., K. Judd and T. Lontzek (2012). Open science is necessary. Nature Climate Change, 2, 299.

Gerlagh, R. and M. Liski (2014). Carbon taxes for the next thousand years, mimeo., Tilburg University.

[5] Carbon Tracker (2013) claims that to limit global warming to 2°C 60-80% of coal, oil and gas reserves of international oil companies would have to be abandoned. Total reserves of listed companies are 762 GtCO2, which is a quarter of total global reserves (roughly 3000 GtC02).

Golosov, M., J. Hassler, P. Krusell and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium, Econometrica, 82, 1, 41-88.

Hope, C. (2006). The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern, Integrated Assessment, 6, 1, 19-56.

IPCC (2014). Climate Change 2014, AR5 Synthesis Report. Accessed 24 May 2015 at http://www.ipcc.ch/pdf/assessment-report/ar5/syr/syr_ar5_final_spm.pdf.

McGlade, C. and P. Ekins (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2^0 C, Nature, 517, 187-190.

Meinshausen, M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame and M.R. Allen (2009). Greenhouse gas emission targets for limiting global warming to 2^0 C, Nature, 458, 1158-1162

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches, Journal of the Association of Environmental and Resource Economists, 1, 273-312.

Pindyck, R.S. (2013). Climate change policy: what do the models tell us?, Journal of Economic Literature, 51, 3, 860-872.

Rezai, A. and F. van der Ploeg (2014). Abandoning fossil fuel: how fast and how much?, Research Paper 123, OxCARRE, University of Oxford.

Rezai, A. and F. van der Ploeg (2016). Intergenerational inequality aversion, growth and the role of damages: Occam's rule for the global carbont tax, Journal of the Association of Environmental and Resource Economics, 3, 493-522.

Stern, N. (2007). The Economics of Climate Change: The Stern Review, Cambridge University Press.

Tol, R.S.J. (2002a). Estimates of the damage costs of climate change, part I: benchmark estimates, Environmental and Resource Economics, 21, 1, 47-73.

Tol, R.S.J. (2002b). Estimates of the damage costs of climate change, part II: dynamic estimates, Environmental and Resource Economics, 21, 2, 135-160.

Weitzman, M.L. (2007). A review of the Stern Review on the economics of climate change, Journal of Economic Literature, 45, 3, 703-724.

Appendix

Our IAM is effectively the one presented in Rezai and van der Ploeg (2016), but with the Oxford carbon cycle instead of the carbon cycle of DICE or Golosov et al. (2014). The economic part of our IAM is calibrated to data for 2010: world GDP is 63 trillion US $, the initial capital stock is 150 trillion US $ and initial energy use is 9.44 GtCe. The world population is 6.5 billion in 2010 and is assumed to rise to 10 billion at the end of the century and to stabilize at 12 billion. We assume a depreciation rate for capital of 10% per annum and a Cobb-Douglas technology with 30% and 70% as the shares of capital and labor, respectively. We assume that for each trillion of output that is produced $\sigma = 0.15$ GtC of fossil fuel is needed, which is in line with a Leontief technology. The initial cost of renewable energy $b(0)$ is initially $800/tCe. The rate of technical progress in renewable energy is initially 1% per annum and then slows down to 0.5% per annum during the first 50 years and to below 0.1% per annum in 150 years. The cost function for oil extraction has $350/tC $(\gamma_0 = 0.35)$ which gives the share of energy in output of about 5%. Extraction costs evolve with $\gamma_1 = 0.5$ and the initial stock of fossil fuel reserves is 10,000 GtC. This means that initially renewable energy is more than twice as expensive as fossil energy. Since we measure fossil fuel use in GtC, the emissions intensity is $\xi = 1$.

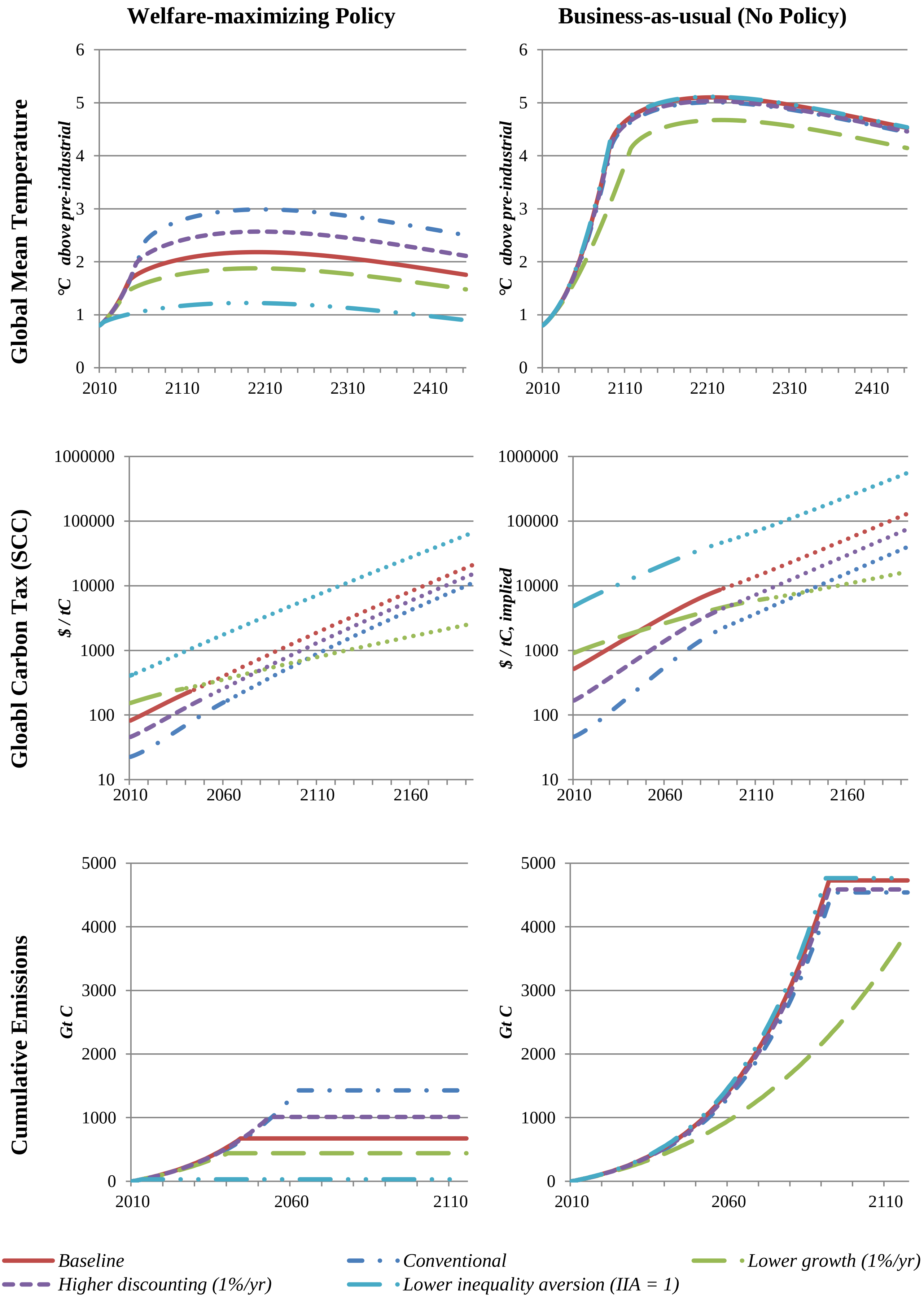
A detailed description of the IAM including objective functions and transitions equations can be found under:

http://www.oxcarre.ox.ac.uk/images/stories/papers/ResearchPapers/oxcarrerp2015150.pdf

Figures and Tables

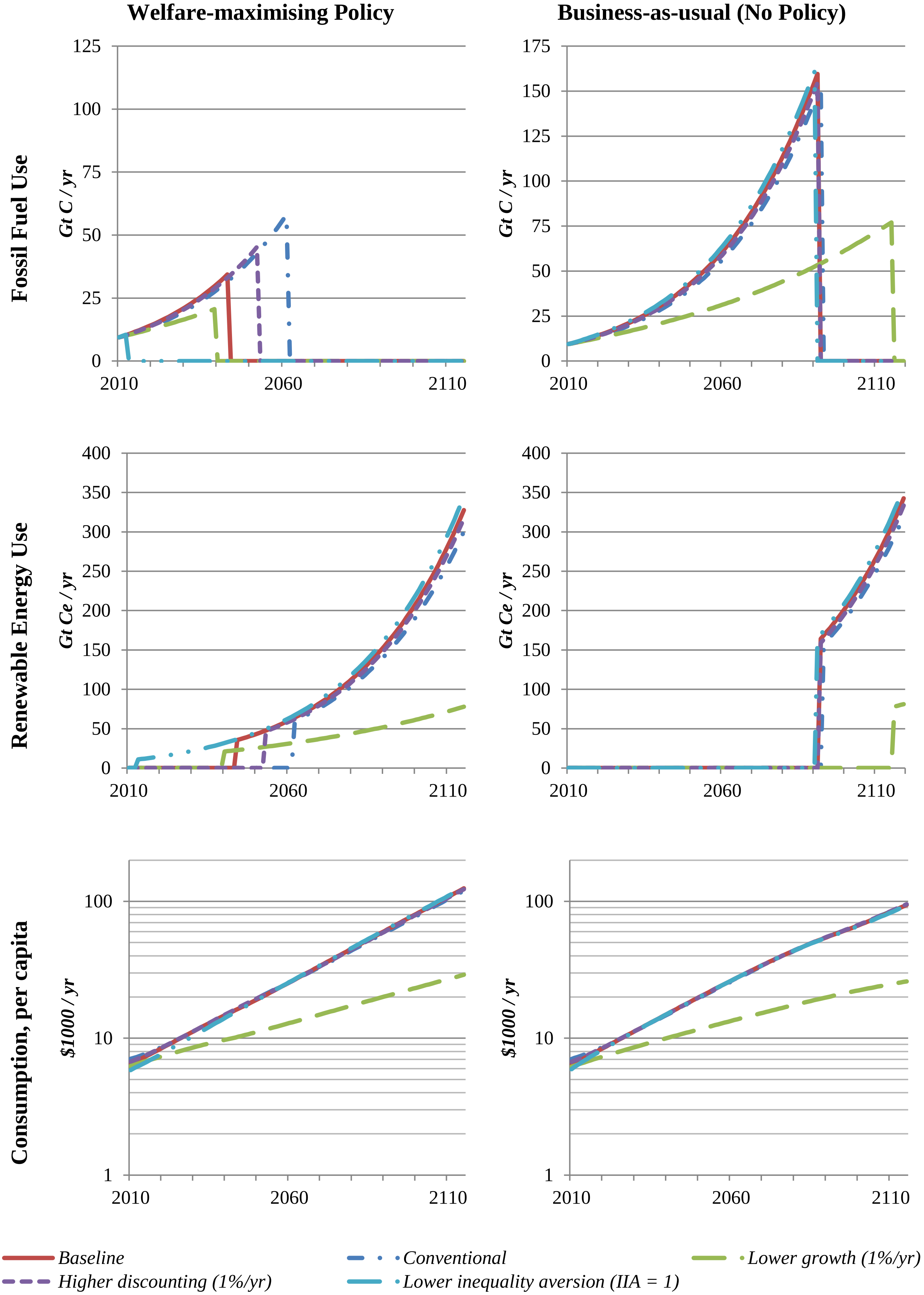
Scenario	Color	*RTI*	*IIA*	*g*	*r*	Cumulative emissions	Maximum temperature
Baseline		0.1%	1.45	2%	1%	670 GtC	2.2 °C
Lower IIA		0.1%	1	2%	0.1%	30 GtC	1.2 °C
Lower trend growth		0.1%	1.45	1%	0.55%	440 GtC	1.9 °C
Higher Discounting		1%	1.45	2%	1.9%	1,010 GtC	2.6 °C
Conventional		1%	2	2%	3%	1,430 GtC	3.0 °C

Table 1: Policy Scenarios, equilibrium interest rates, and cumulative emissions



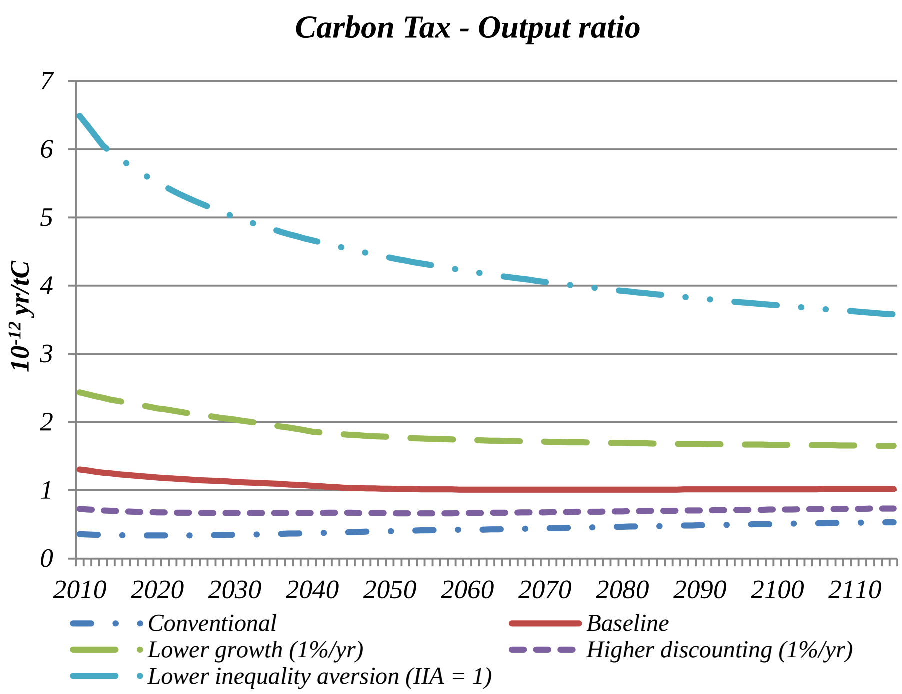
Key Baseline (RTI = 0.1%, *IIA* = 1, *g* = 2%) *yields rapid decarbonization mid-century, limiting global warming to slightly above 2°C. Conventional economic parameters (RTI* = 1%, *IIA* = 2, *g* = 2%) *delay the transition by one decade and lead to temperature increases of 3°C.*

Figure 1: Sensitivity analysis for the optimal *SCC* and cumulative emissions



Key: Business-as-usual leads consistently to high temperature deviations of 5°C. Only lower expected growth in living standards reduces cumulative demand for fossil fuel.

Figure 1 (cont'd): Sensitivity analysis for the optimal *SCC* and cumulative emissions



Key: Carbon tax as a constant fraction of output if transitional dynamics are short.

Figure 2: Carbon Tax as a fraction of output.