Technological Forecasting & Social Change 116 (2017) 216–222

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Cumulative emissions, unburnable fossil fuel, and the optimal carbon tax☆

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ARTICLE INFO

Article history:
Received 21 July 2016
Received in revised form 17 October 2016
Accepted 19 October 2016
Available online 2 November 2016

Keywords:
Energy transition
Optimal carbon tax
Unburnable fossil fuel
Cumulative emissions
Oxford carbon cycle
Trend growth

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.

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 1100 Gigatonnes of carbon dioxide (Gt CO_2) or 300 Gigatonnes of carbon (GtC) (Allen et al., 2009; Meinshausen et al., 2009).[3] 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).[4] 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, 2002a,b), 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

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

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[1] 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.

[2] Support from the Austrian Science Fund (FWF): J 3633 and the OeNB Anniversary Fund (grant no. 15330) is gratefully acknowledged.

[3] 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.

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

http://dx.doi.org/10.1016/j.techfore.2016.10.016

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, 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 optimal global carbon tax and the optimal 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, 2016a; 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 maximize 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, 2016a). 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 1 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, 2016), 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 (2016a), and Allen (2016). They all share the form $\tau(t)=\Omega(r)\chi Y(t)$, $\Omega'(r)<0$, where χ is the damage flow as a fraction of world GDP corresponding to burning 1 GtC, 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 1 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

$$\tau(t) = \Omega(r, H(t))\chi Y(t), \quad \Omega'(r) < 0, \tag{1}$$

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

$$r = RTI + (IIA-1)g, \tag{2}$$

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.[5] 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 $C(S(t)), C' < 0$, 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, $C(S(T)) + \xi\tau(T) = b(T)$, $T > 0$, 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 $C(S(t)) = \gamma_0(S(0)/S(t))^{\gamma_1}$ together with Eqs. (1) and (2), we derive the amount of unburnt fossil fuel as a function of fundamental ethical, technological and geophysical parameters:

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

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 fossil fuel is left unburnt if the cost of extracting (γ_0) is high and the cost of its carbon-free alternative ($b(T)$) is low. Further, more fossil fuel is left unburnt if the emissions

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[5] 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.