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Robustness of a simple rule for the social cost of carbon

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HIGHLIGHTS

- The social cost of carbon (SCC) is a hump-shaped function of world GDP.
- The SCC increases rapidly and peaks well into the post-carbon era.
- A proportional-to-GDP carbon tax rule approximates the first-best welfare closely.
- Such a rule errs in the amount of fossil fuel reserves to be locked-up *in situ*.

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ABSTRACT

The optimal social cost of carbon is in general equilibrium proportional to GDP if utility is logarithmic, production is Cobb–Douglas, depreciation is 100% every period, climate damages as fraction of production decline exponentially with the stock of atmospheric carbon, and fossil fuel extraction does not require capital. The time profile and size of the optimal carbon tax corresponding to this simple rule are not robust to more convex climate damages, smaller elasticities of factor substitution and non-unitary coefficients of relative intergenerational inequality aversion. The optimal timing of energy transitions and the amount of fossil fuel reserves to be locked up in the earth are also not accurately predicted by this framework. Still, in terms of welfare and global warming the simple rule for the optimal social cost of carbon manages to get quite close to the first best.

1. Introduction

A tractable model of the optimal carbon tax has been put forward by Golosov et al. (2014) based on a decadal Ramsey growth model and been extended by Hassler and Krusell (2012), Gerlagh and Liski (2012) and Iverson (2013). This model makes the following bold assumptions: logarithmic utility, Cobb–Douglas production, 100% depreciation of physical capital each period, relatively gradual marginal damages, and zero capital intensity of fossil fuel extraction. The assumption of full depreciation necessitates a coarse calibration grid, but with them it can be shown analytically that the *social cost of carbon* (*SCC*) is proportional to current GDP and independent of technology. We evaluate the robustness of this simple formula in a more general Ramsey growth model which relaxes these bold assumptions by introducing CES utility to allow for non-unitary coefficients of relative intergenerational inequality aversion, CES production with a much lower elasticity of factor substitution as suggested by Hassler and Krusell (2012), partial depreciation of physical capital and more convex climate damages as suggested by Weitzman (2010). Furthermore, with our integrated assessment model we want to speak to the issue of the optimal amount of fossil fuel to lock up in the earth and thus limit the cumulative amount of carbon emissions as this has been argued by climate scientists to be a crucial element of climate policy (e.g. McGlade and Ekins, 2015). To capture this, we allow in contrast to

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Golosov et al. (2014) for extraction costs that rise as fossil fuel reserves diminish and less accessible and more costly fields have to be explored and we also allow for a renewable backstop that is a perfect substitute for fossil fuel. These extensions allow us to have endogenous energy transition times for the switch to the carbon-free era and to determine the optimal and business-as-usual level of untapped fossil fuel reserves.

2. Ramsey growth and energy transitions

Let social welfare be utilitarian, with per capita utility U depending on per capita consumption C_t/L_t, where L_t is the exogenous population size and ρ the rate of time preference:

$$E_0\left[\sum_{t=0}^{\infty}\left(\frac{1}{1+\rho}\right)^t L_t U_t(C_t/L_t)\right] = E_0\left[\sum_{t=0}^{\infty}\left(\frac{1}{1+\rho}\right)^t L_t\left[\frac{(C_t/L_t)^{1-1/\eta}-1}{1-1/\eta}\right]\right], \quad \rho>0. \tag{1}$$

The elasticity of intertemporal substitution equals η. The ethics of climate policy depends on the weight given to future generations (and thus on how small ρ is) and on how small intergenerational inequality aversion is or how difficult it is to substitute current for future consumption per head (how low $1/\eta$ is). Optimal climate policy faces some constraints governing the global economy. First, output at time t, $Z(K_t, L_t, F_t, R_t)$, is produced using capital K_t, labor, L_t, fossil fuels (e.g., oil, natural gas and coal), F_t, and renewables (e.g., solar or wind energy), R_t. We allow for imperfect factor substitution, so both fossil fuel and renewable energy are essential in production. Fossil fuel extraction costs, $G(S_t)F_t$, rise as reserves, S_t, fall, $G' < 0$. Renewable energy is supplied infinitely elastically at exogenously decreasing cost, b_t. Technical progress increases productivity in both aggregate and renewable energy production. Climate damages curb output and are captured by the factor $1 - \Lambda(T_t)$, $\Lambda' < 0$. Production net of costs of energy production and climate damage is allocated to consumption C_t, investments in manmade capital and depreciation with δ the rate of depreciation:

$$K_{t+1} = (1-\delta)K_t + \Lambda(T_t)Z(K_t, L_t, F_t, R_t) - G(S_t)F_t - b_tR_t - C_t. \tag{2}$$

The dynamics of fossil fuel reserves are:

$$S_{t+1} = S_t - F_t = S_0 - \sum_{s=0}^{t} F_s, \qquad \sum_{t=0}^{\infty} F_t \le S_0. \tag{3}$$

Golosov et al. (2014) introduce a two-stock carbon cycle where emissions lead to a permanent component E_1 and a transient component E_2 of the stock of carbon in the atmosphere:

$$E_{1t} = E_{1t-1} + \varphi_L F_t, \tag{4}$$

$$E_{2t} = \varphi E_{2t-1} + \varphi_0(1-\varphi_L)F_t, \tag{5}$$

where ϕ_L denotes the fraction of emissions that stays permanently in the atmosphere, ϕ the speed at which the temporary stock of carbon decays, and ϕ_0 a coefficient to calibrate how much of carbon is returned to the surface of the oceans and earth within a decade. We define temperature, T_t, as deviations from pre-industrial temperature in degrees Celsius. The climate sensitivity, ω, corresponds to the rise in temperature ensuing from a doubling of the total stock of carbon in the atmosphere, E_t:

$$T_t = \omega \ln\left(\frac{E_t}{\bar{E}}\right)/\ln(2), \quad E_t \equiv E_{1t} + E_{2t}, \tag{6}$$

where $\bar{E} = 596.4$ GtC is the IPCC figure for the pre-industrial stock of atmospheric carbon. Using (6) we redefine damages as $D(E_t) \equiv \Lambda\left(\omega \ln\left(\frac{E_t}{\bar{E}}\right)/\ln(2)\right)$. This formulation ignores lags between atmospheric carbon and global warming and the improvements that result from a three-stock carbon cycle, but with these features one still gets a linear formula for the SCC (Gerlagh and Liski, 2012).

The social planner maximizes (1) subject to (2)–(6). The Lagrangian is defined as:

$$\begin{aligned} L \equiv & \sum_{t=0}^{\infty}(1+\rho)^{-t}\left[L_tU_t(C_t/L_t) - \lambda_t\left(K_{t+1} - (1-\delta)K_t - D(E_t)Z(K_t, L_t, F_t, R_t) + G(S_t)F_t + b_tR_t + C_t\right)\right] \\ & + \sum_{t=0}^{\infty}(1+\rho)^{-t}\left[\nu_{1,t}(E_{1,t+1} - E_{1,t} - \varphi_L F_t) + \nu_{2,t}\left(E_{2,t+1} - (1-\varphi)E_{2,t} - \varphi_0(1-\varphi_L)F_t\right) - \mu_t(S_{t+1} - S_t + F_t)\right], \end{aligned}$$

where λ_t denotes the shadow value of capital, ν_{1t} and ν_{2t} the shadow disvalue of the permanent and transient stocks of atmospheric carbon, and μ_t the shadow value of in-situ fossil fuel. The efficiency conditions for a social optimum are (Appendix A):

$$\frac{C_{t+1}/L_{t+1}}{C_t/L_t} = \left(\frac{1+r_{t+1}}{1+\rho}\right)^{\eta}, \quad r_{t+1} \equiv D(E_{t+1})Z_{K_{t+1}} - \delta, \tag{7}$$

$$D(E_t)Z_{F_t} \le G(S_t) + s_t + \tau_t, \quad F_t \ge 0, \text{ c.s.}, \tag{8}$$

$$D(E_t)Z_{R_t} \le b_t, \quad R_t \ge 0, \text{ c.s.}, \tag{9}$$

$$s_t = -\sum_{\varsigma=0}^{\infty}\left[G'(S_{t+1+\varsigma})F_{t+1+\varsigma}\Delta_{t+\varsigma}\right], \tag{10}$$

$$\tau_t = -\sum_{\varsigma=0}^{\infty}\left[\{\varphi_L + \varphi_0(1-\varphi_L)(1-\varphi)^{\varsigma}\}\Delta_{t+\varsigma}D'(E_{t+1+\varsigma}) \times Z(K_{t+1+\varsigma}, L_{t+1+\varsigma}, F_{t+1+\varsigma}, R_{t+1+\varsigma})\right] \tag{11}$$

with compound discount factors $\Delta_{t+\varsigma} \equiv \prod_{\varsigma'=0}^{\varsigma}(1+r_{t+1+\varsigma'})^{-1}$, $\varsigma \ge 0$.

Eq. (7) is the Euler equation, where the positive effect of the return on capital (r_{t+1}) on consumption growth is bigger if intertemporal substitution is easier (high η). If fossil fuel is used, Eq. (8) indicates that its marginal product should equal marginal extraction cost plus the scarcity rent, $s_t \equiv \mu_t/\lambda_t$, plus the SCC, $\tau_t \equiv [\varphi_L\nu_{1t} + \varphi_0(1-\varphi_L)\nu_{2t}]/\lambda_t$. If the marginal product of fossil fuel is below total marginal cost, it is not used. Eq. (9) states the equivalent condition for renewable use. Eq. (10) follows from the Hotelling rule and gives the scarcity rent of keeping an extra unit of fossil fuel unexploited as the present discounted value of all future reductions in fossil fuel extraction costs. Eq. (11) defines the SCC as the present discounted value of all future marginal global warming damages from burning an additional unit of fossil fuel.[2]

The SCC is proportional to GDP if utility is logarithmic, $\delta = 1$, $D(E_t) = e^{-\gamma(E_t-\bar{E})}$ with $\gamma > 0$ the climate damage parameter, Cobb–Douglas production function for capital, labor and energy, and extraction does not require capital inputs. This leads to what we will refer to as the *simple* rule:

$$\tau_t = \gamma\left[\left(\frac{1+\rho}{\rho-n}\right)\varphi_L + \left(\frac{1+\rho}{1+\rho-\varphi(1+n)}\right)\varphi_0(1-\varphi_L)\right]GDP_t \tag{11'}$$

[2] One unit of carbon released from burning fossil fuel affects the economy in two ways: the first part remains in the atmosphere for ever and the second part gradually decays over time at a rate corresponding to roughly 1/300 per year.